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Lead-Free and Lightweight Radiation Shielding Materials: A Radiology-Centric Review

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Abstract- Background: The requirement for efficient, ergonomic, and ecologically friendly shielding systems is highlighted by the fast expansion of diagnostic and interventional radiology, which has increased worker and patient exposure to ionising radiation. Despite its great performance, traditional lead-based protective gear is linked to toxicity, disposal issues, and severe musculoskeletal strain in healthcare personnel.

Methods: This review is based on a structured search of peer-reviewed studies published between 2018 and 2025, retrieved from databases such as PubMed, ScienceDirect, and SpringerLink.

Results: With a focus on their use in diagnostic and interventional radiology, recent developments in lead-free polymer-based shielding materials are reviewed. Composites based on tungsten, bismuth, tin, and hybrid fillers show encouraging attenuation efficiency in addition to increased flexibility, decreased weight, and enhanced ergonomic performance.

Conclusion: Lightweight, lead-free shielding materials provide a useful substitute for traditional lead-based protection. In addition to resolving environmental issues, their adoption promotes worker safety and is in line with Indian and international radiation safety priorities. To enable its broader clinical adoption, more research is essential.

Key-words -Lead-free shielding, Radiation protection, Diagnostic radiology, Polymer composites, X-ray attenuation, Occupational safety

I. INTRODUCTION

A key tenet of interventional radiology and medical imaging is radiation protection [20]. Concerns about cumulative radiation exposure among patients and medical personnel have grown as a result of the expanding use of computed tomography, mobile radiography, and fluoroscopy-guided procedures [10,23].

Because of its large atomic number and superior attenuation characteristics in diagnostic energy ranges, lead (Pb) has historically been the material of choice for radiation shielding [18]. However, there are a number of well-known drawbacks of lead-based shielding, such as toxicity, difficulties with disposal, and excessive weight, which may cause radiology staff members' musculoskeletal discomfort [12,16].

The development of lead-free, lightweight shielding substitutes that preserve sufficient attenuation performance while enhancing ergonomics, usability, and environmental safety in clinical practice has thus become a major focus of material science research [1,4,6].

II. SCOPE AND OBJECTIVES OF THE REVIEW

In the context of diagnostic and interventional radiology, the current review focuses on assessing recent advancements in lightweight, lead-free radiation shielding materials. Material performance, clinical applicability, and relevance to current radiation protective methods are highlighted.

III. GLOBAL AND INDIAN PERSPECTIVE ON RADIATION PROTECTION

Radiation safety in medical imaging has been designated by the World Health Organization (WHO) as a global public health concern, especially in areas where diagnostic and interventional radiology services are rapidly expanding [20]. In addition to encouraging safer imaging conditions and occupational dose reduction techniques, WHO guideline highlights the fundamental concepts of rationale, optimisation, and dose limits [21,23]. These suggestions emphasise the significance of ecologically friendly medical technology that reduce dependency on dangerous substances like lead [21].

The Atomic Energy Regulatory Board (AERB) in India oversees radiation safety in diagnostic radiology under national regulatory frameworks [30]. Ageing lead aprons, inadequate quality assurance procedures, incorrect disposal of lead-containing protective equipment, and growing procedural workloads are just a few of the practical issues that radiology departments in India still have to deal with [10,27]. Lightweight and lead-free shielding materials are especially important in this situation because they provide superior ergonomics, better adherence to safety regulations, and alignment with both environmental sustainability objectives and occupational health standards [18].

IV. RATIONALE FOR LITERATURE REVIEW

The increasing demand for safer, lightweight, and environmentally sustainable radiation shielding solutions has necessitated a structured review of recent literature. This approach helps in identifying clinically relevant advancements and existing research gaps.

V. METHODOLOGY AND LITERATURE SELECTION

To find pertinent research on lead-free shielding in diagnostic radiology, an organised literature study was carried out utilising electronic databases such as PubMed, ScienceDirect, and Google Scholar. Research released between 2018 and 2025 was taken into account.

To guarantee thorough coverage of the subject, the search method included terms like lead-free shielding, radiation protection, diagnostic radiology, polymer composites, X-ray attenuation, and occupational safety. To find more pertinent research, the reference lists of the chosen publications were also screened.

Experimental, simulation-based, and clinical research assessing radiation shielding materials in the diagnostic energy range (20–150 keV) were among the inclusion criteria. To preserve clinical relevance and data quality, studies concentrating on industrial, nuclear, or high-energy radiation applications were eliminated, along with non-English and duplicate papers.

Initially, titles and abstracts were used to filter all recognised documents. Only studies that satisfied the inclusion criteria were included in the final analysis after full-text publications were evaluated for eligibility. PRISMA reporting criteria served as the inspiration for the structured screening method used in the research selection process.

PRISMA 2020 principles were followed during the study selection process to guarantee methodological consistency, reproducibility, and transparency.

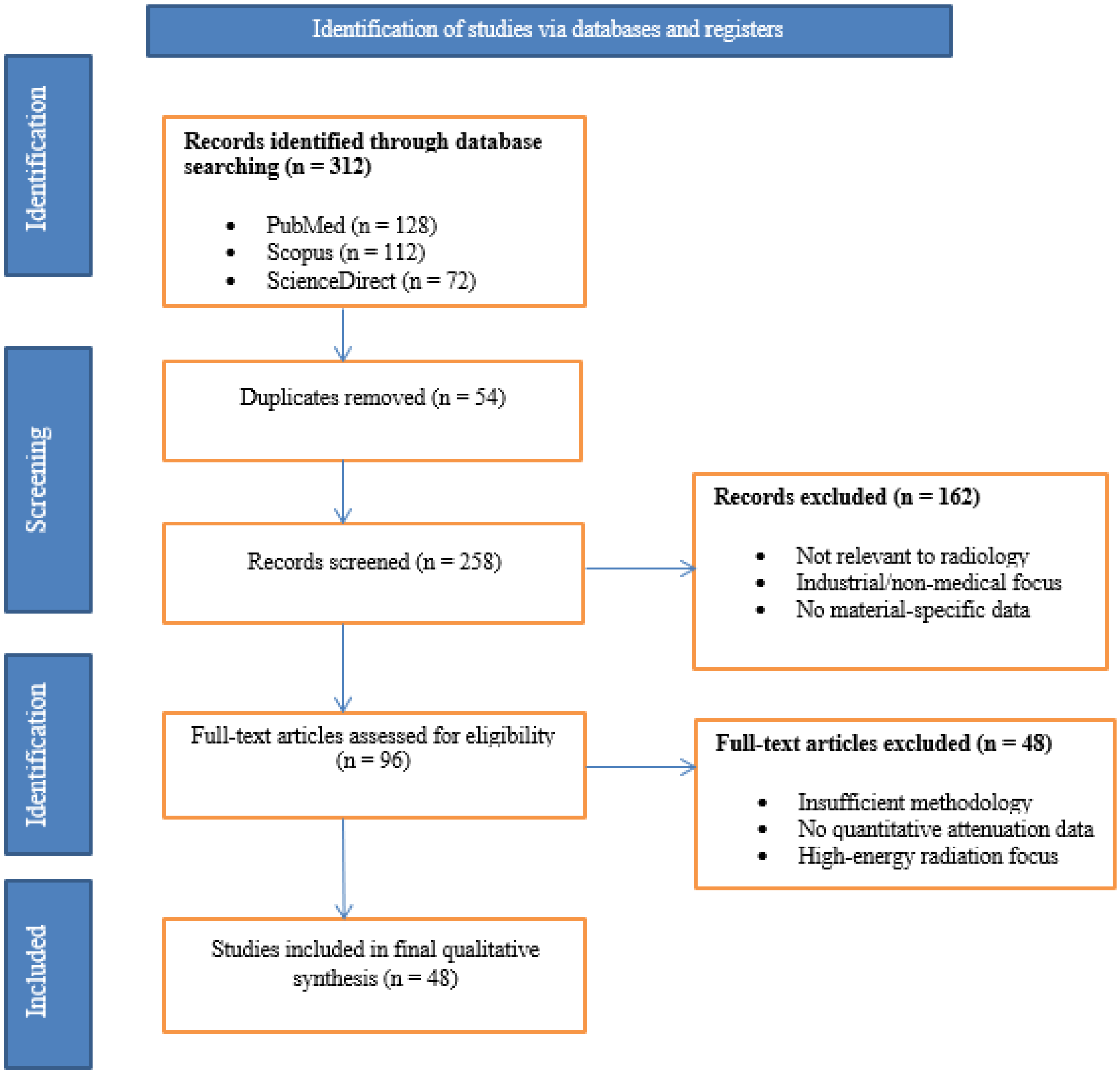

Figure1: PRISMA 2020 flow diagram showing the selection process

VI. LEAD-FREE MATERIAL SYSTEMS FOR RADIATION SHIELDING

1. Tungsten-Based Polymer Composites

Because tungsten has a large atomic number and good mass attenuation capabilities in diagnostic X-ray energy ranges, tungsten-filled polymer composites are among the most researched lead-free radiation shielding materials [2,6]. Tungsten-polymer systems can provide clinically meaningful lead-equivalent shielding while retaining better mechanical flexibility than traditional lead sheets, according to experimental and simulation-based (Monte Carlo) research [6,12]. By raising the likelihood of photon contact while maintaining wearer comfort, multilayer and layered composite structures further improve attenuation efficiency, making them appropriate for mobile shielding applications in fluoroscopy suites and protective aprons [1,9].

2. Bismuth-Based Composites

Because of their high atomic number, non-toxicity, and lower density than lead, bismuth oxide (BiO_3)–polymer composites have drawn a lot of interest for low-to-medium diagnostic energy applications [3,15]. These materials are frequently investigated for thyroid shields, gonadal protection, and patient-contact shielding devices because they effectively attenuate dispersed radiation. However, excessive bismuth content or incorrect filler dispersion can cause beam hardness and picture artefacts, especially in computed tomography applications, necessitating clinical validation and optimal formulation [28].

3. Hybrid and Multi-Filler Systems

For particular radiological applications, hybrid polymer composites with mixtures of tungsten, bismuth, tin, and barium sulphate fillers provide customised optimisation of attenuation performance, mechanical flexibility, and cost-effectiveness [5,14]. According to studies, multi-filler systems can lower total material weight while improving attenuation behaviour over a wide diagnostic energy range [29]. In interventional radiology settings, where extended fluoroscopy times necessitate both efficient radiation shielding and operator comfort, these hybrid materials are being investigated more and more [10,27].

VII. ERGONOMIC AND OCCUPATIONAL CONSIDERATIONS

The gradual switch from traditional lead-based aprons to lightweight, lead-free radiation shielding devices is primarily motivated by occupational health concerns. Long-term usage of conventional lead aprons has been repeatedly linked to musculoskeletal conditions, such as persistent shoulder and neck pain, lumbar spine issues, and overall exhaustion in radiologists, radiographers, and interventional cardiologists [12,16]. In high-volume fluoroscopy and interventional treatments, where extended standing and static postures are frequently necessary, these problems are especially important.

Lead-free aprons made of tungsten-, bismuth-, or hybrid polymer composites can reduce overall garment weight by about 20–40% when compared to conventional lead aprons while still maintaining clinically acceptable radiation attenuation performance, according to recent clinical and survey-based studies [11,13]. This weight loss supports long-term labour productivity and occupational health sustainability by improving posture, increasing mobility, and reducing cumulative occupational strain.

Improved ergonomic design is crucial for increasing adherence to radiation safety procedures from the standpoint of workflow. Particularly during mobile radiography, emergency imaging, and extended interventional procedures, when discomfort from heavy aprons might result in less compliance, lighter and more comfortable protective clothing are more likely to be used consistently [10,27]. These ergonomic advantages are consistent with worldwide radiation protection guidelines advised by groups like the WHO and ICRP, which stress that radiation safety plans should take into account healthcare professionals' occupational well-being in addition to dose reduction [20,29]. In this regard, Figure 2 compares a traditional lead apron with a lead-free polymer apron, emphasising variations in weight, flexibility, and ergonomic comfort that have a direct impact on clinical practice occupational safety and compliance.

Figure2: Comparison of conventional lead apron and lead-free polymer apron[31].

Environmental and Regulatory Considerations

In contemporary radiology practice, environmental sustainability has grown in importance. Toxicity, recycling, and end-of-life disposal are major issues with conventional lead-based shielding materials, especially in low- and middle-income nations with potentially inadequate medical waste management systems [11,18]. Lead is generally acknowledged as a hazardous material, and inappropriate disposal of worn-out or broken lead aprons may increase the danger of occupational exposure as well as environmental contamination.

Regulatory and health organisations around the world have placed a greater emphasis on reducing or getting rid of dangerous materials in medical equipment. As part of its larger patient safety and sustainable healthcare programs, the World Health Organization (WHO) supports ecologically friendly medical imaging methods [20]. Simultaneously, the progressive shift toward safer, lead-free alternatives in radiation protection systems has been aided by international legislative constraints on hazardous compounds in manufacture.
The Atomic Energy Regulatory Board (AERB) oversees radiation protection regulations and equipment safety in India under national regulatory frameworks [30]. The use of lead-based shielding is still permitted by current regulations, but quality control, routine inspections, and the secure disposal of radiation protective equipment are becoming increasingly important. Lead-free and polymer-based shielding materials provide useful benefits within this context by lowering the production of toxic waste and streamlining end-of-life management without sacrificing diagnostic performance [21].

According to recent research, environmentally friendly polymer composites with fillers made of tungsten, bismuth, or barium sulphate can effectively attenuate radiation in diagnostic radiography while also increasing recyclability and lowering environmental impact [17,18]. These advancements are consistent with the idea of "green radiology," which incorporates environmental sustainability, occupational safety, and radiation safety into standard clinical practice.

VIII. CLINICAL RELEVANCE IN INTERVENTIONAL RADIOLOGY

Because of the extended fluoroscopy duration, frequent cine captures, and near operator contact to the radiation source, interventional radiology (IR) is one of the greatest occupational exposure settings in diagnostic imaging. Both structural and personal shielding are crucial elements of radiation safety methods in interventional suites because scatter radiation is the main cause of staff dose during these operations [4,12].

In this regard, lightweight and lead-free shielding materials are becoming more and more important. Within diagnostic energy ranges commonly used in interventional procedures (60–120 kVp), non-lead aprons, thyroid collars, and protective drapes made from tungsten- and bismuth-based polymer composites can provide attenuation performance comparable to conventional lead shielding, according to clinical and phantom-based studies [1,6]. These materials are particularly beneficial in prolonged procedures such as angioplasty, embolization, and other endovascular interventions, where cumulative occupational dose and operator fatigue are important concerns.

Reduced apron weight enhances operator mobility and procedural efficiency from a workflow standpoint, enabling physicians to maintain ideal posture without sacrificing radiation protection. More frequent use of supplementary protective equipment, such as table-mounted drapes and ceiling-suspended shields, which further aid in dose reduction in clinical practice, is further supported by improved comfort [10,27].

In order to reduce occupational exposure in interventional settings, international radiation protection guidelines from the ICRP and WHO emphasise a multi-layered strategy that include engineering controls, personal protective equipment, and procedural optimisation [20,29]. According to this framework, lead-free shielding materials are well suited for contemporary interventional radiology practice because they combine sufficient attenuation performance with enhanced usability and ergonomic benefits.

IX. COMPARATIVE PERFORMANCE AND WEIGHT CONSIDERATIONS

Understanding the performance characteristics and clinical application of lead-free radiation shielding materials in diagnostic and interventional radiology requires a systematic comparison of representative studies. The material composition, research type, and reported radiation attenuation performance are highlighted in Table 1, which summarises the main conclusions from a few experimental and evaluation investigations.

Table 1. Representative studies on lead-free radiation shielding materials

Author (Year)	Material Type	Study Type	Key Outcomes
Li et al. (2021)	Tungsten–polymer multilayer composite	Experimental study	Achieved attenuation comparable to lead with reduced weight and improved flexibility
Kuo et al. (2021)	Flexible multilayer polymer composite	Experimental study	Demonstrated high-efficiency shielding with enhanced flexibility and wearability
El-Khatib et al. (2021)	Bismuth oxide–polymer composite	Experimental study	Provided effective attenuation at low photon energies suitable for diagnostic applications
Gilys et al. (2022)	Lead-free multilayer composite	Experimental study	Showed efficient attenuation across diagnostic energy range with optimized structure
Kassim et al. (2023)	Tungsten carbide nanocomposite	Experimental study	Improved attenuation efficiency through nanomaterial incorporation
Wu et al. (2024)	Flexible polymer composite	Experimental study	Demonstrated high flexibility and suitability for wearable shielding applications
Kim (2024)	Tungsten–polymer layered composite	Experimental study	Effective attenuation across diagnostic and gamma radiation ranges
Park et al. (2023)	Commercial lead-free materials	Clinical evaluation	Comparable radiation protection to conventional lead under clinical conditions

A direct comparison between conventional lead-based shielding and emerging lead-free polymer composites is essential for radiology-focused evaluation. Table 2 summarizes key performance parameters relevant to diagnostic and interventional radiology, including attenuation efficiency, weight, flexibility, toxicity, environmental impact, and clinical usability.

Table 2. Comparative characteristics of radiation shielding materials in diagnostic radiology

Parameter	Lead	Tungsten Composite	Bismuth Composite	Hybrid Composite
Atomic number	82	74	83	Composite (variable composition)
Attenuation efficiency	Excellent	Comparable to lead	High (low–medium energy dependent)	Optimized across energy range
Weight	High	Moderate	Moderate	Low–moderate
Flexibility	Poor	Good	Good	Very good
Toxicity	High	Low	Low	Low
Environmental impact	High	Low	Low	Low
Clinical usability	Standard	Suitable for wearable aprons	Primarily patient shielding	Highly suitable for clinical applications

X. DISCUSSION: CURRENT CHALLENGES AND RESEARCH GAPS

Although lead-free and lightweight radiation shielding materials have advanced significantly, a number of technical and clinical obstacles still prevent their broad clinical use. The lack of standardised testing procedures for various photon energy ranges and clinical settings is a significant drawback. Direct comparison between published studies and commercially available products is challenging due to differences in beam quality, irradiation geometry, and measurement techniques [10].

Another significant issue is long-term mechanical durability. In clinical settings, polymer-based shielding materials are frequently subjected to cycles of flexing, folding, and cleaning. However, there is no data on their long-term structural stability, thermal resistance, and compatibility with widely used disinfectants, which raises questions about long-term performance [13,18].

Additionally, due to variations in filler composition, particle size distribution, and production processes, stated lead-equivalency values exhibit significant fluctuation. This discrepancy emphasises the necessity of independent validation and standardised reporting frameworks prior to the clinical application of novel shielding materials [14].

Advanced nanocomposites' cost-effectiveness and large-scale manufacturability continue to be significant obstacles, especially in healthcare systems with limited resources where adoption decisions are heavily influenced by procurement costs and lifecycle sustainability [23].

To ensure the safe, standardised, and clinically dependable application of lead-free radiation shielding technologies, coordinated multidisciplinary collaboration between material scientists, medical physicists, clinicians, manufacturers, and regulatory authorities will be necessary to address these limitations.

XI. FUTURE DIRECTIONS

In order to ensure that laboratory-based innovations can be consistently applied in actual radiology settings, future research should concentrate on enhancing the clinical translation of lead-free radiation shielding materials. To guarantee uniformity in testing procedures, performance evaluation, and reporting across studies, the creation of standardised evaluation frameworks in line with international standards, such as those from the International Electrotechnical Commission (IEC) and the International Commission on Radiological Protection (ICRP), is a top priority [20,29].

With the potential to improve fit, comfort, and protective effectiveness in clinical practice, emerging technologies like additive manufacturing (3D printing) present significant options for the creation of personalised and patient-specific shielding solutions. Simultaneously, a significant and developing field of study is the creation of adaptive or "smart" shielding materials that can react dynamically to changing radiation exposure conditions [6,29].

Clinically speaking, long-term multicenter studies are necessary to assess important performance metrics, such as mechanical durability, resistance to frequent cleaning and disinfection, and practical dose reduction efficacy in various clinical settings [13,18]. To objectively measure the sustainability advantages of lead-free shielding materials over traditional lead-based systems, environmental life-cycle assessment studies should also be included [17,18].

To support the safe, standardised, and efficient adoption of lead-free radiation shielding technologies in the Indian healthcare context, more focus should be placed on cost-effective manufacturing strategies, regulatory alignment with Atomic Energy Regulatory Board (AERB) standards, and structured training programs for radiology personnel [24, 30].

Implications for Radiology Practice

In contemporary radiology departments, the use of lead-free shielding materials has the potential to enhance both environmental sustainability and occupational safety. An important development in radiation protection is their incorporation into clinical practice.

XII. CONCLUSION

In diagnostic and interventional radiology, lead-free and lightweight radiation shielding materials offer a practical and sustainable substitute for traditional lead-based protection. Tungsten-, bismuth-, and hybrid polymer composites can reach attenuation performance comparable to lead while greatly reducing weight, toxicity, and environmental effect, according to evidence from current studies (2018–2025) [1,6,11,18].

By lowering musculoskeletal strain and increasing adherence to radiation safety procedures, especially in interventional radiology settings, these materials also address significant occupational health issues [12,16,27]. Additionally, their role in encouraging safer, more sustainable, and ecologically conscious radiology practice is supported by compliance with national regulatory frameworks and international recommendations [20,24,30].

The successful large-scale clinical implementation of these emerging shielding technologies will require ongoing multidisciplinary collaboration among clinicians, medical physicists, material scientists, and regulatory authorities, despite ongoing challenges with standardisation, long-term durability, and cost-effectiveness.

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