

RESEARCH ARTICLE

Shielding Performance Evaluation of Phosphate–Zinc–Lithium–Cadmium Glasses Doped with Europium and Thulium Oxides

Reem D. Alshehri *

ABSTRACT: This research reports on the synthesis and radiation shielding characterization of novel phosphate-zinc-lithium-cadmium glass systems fabricated through the conventional melt-quenching technique. Three distinct glass compositions were prepared with the following molar formulations: $40\text{P}_2\text{O}_5\text{-}30\text{ZnO-}10\text{LiCl-}2\text{CdO}$ designated as PZBLC, $40\text{P}_2\text{O}_5\text{-}30\text{ZnO-}10\text{LiCl-}2\text{CdO-}3.5\text{Eu}_2\text{O}_3$ referred to as PZBLC-Eu, and $40\text{P}_2\text{O}_5\text{-}30\text{ZnO-}10\text{LiCl-}2\text{CdO-Tm}_2\text{O}_3$ denoted as PZBLC-Tm. The radiation attenuation characteristics including mass attenuation coefficients, half-value layers, mean free paths, effective electron densities, and effective atomic numbers were systematically examined across the photon energy spectrum from 15 to 200 keV. These shielding parameters were computed utilizing the recently developed MIKE computational software package. The experimental findings demonstrate that the incorporation of trivalent europium and thulium ions into the glass matrix significantly enhances both linear and mass attenuation coefficients. This improvement is attributed to the high atomic numbers and substantial ionic radii of these rare-earth elements, which modify the network structure and increase the effective atomic number of the host material. The shielding performance assessment reveals optimal attenuation capabilities within the 15 to 50 keV energy range, making these glasses particularly suitable for low-energy diagnostic applications. Among the prepared compositions, the PZBLC-Tm glass sample exhibited superior attenuation performance compared to all other tested formulations. The results suggest that these phosphate-based glass systems represent promising alternatives to conventional lead-based shielding materials, especially considering their lightweight nature and potential for applications in dental radiography and other low-energy medical imaging procedures where toxicity concerns and material weight are critical considerations.

Keywords: Phosphate glasses, Radiation shielding, Mass attenuation coefficient, Rare-earth doping, Effective atomic number.

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1. INTRODUCTION

Metal oxides and halide compounds, including phosphorus pentoxide (P_2O_5), zinc oxide (ZnO), lithium chloride (LiCl), and cadmium oxide (CdO), have been identified as essential constituents for glass-ceramics, bioactive glasses, and various glass systems [1, 2]. The physical properties of these

materials, particularly their density, molar volume, and oxygen packing density, render them attractive candidates for diverse radiation shielding applications [2]. Zinc oxide functions as both a network modifier and intermediate oxide within glass matrices, and its integration into phosphate-based glasses has been demonstrated to substantially enhance chemical durability, optical transparency, and radiation attenuation characteristics [3–7]. When lithium chloride is incorporated as a network modifier, it introduces both lithium and chlorine species into the glass structure, which alters the connectivity of the phosphate network and generates additional scattering centers for incident photons. The

Department of Physics, Faculty of Science, King Khalid University;
P.O. Box 9004, Abha, Kingdom of Saudi Arabia.

* Author to whom correspondence should be addressed:
444817190@kku.edu.sa (Reem D. Alshehri)

presence of cadmium, with its relatively high atomic number, proves especially beneficial for radiation shielding purposes because it elevates the effective atomic number (Z_{eff}) of the glass, thereby improving the interaction cross-section with low-energy photons through the photoelectric absorption mechanism.

The incorporation of rare-earth oxides such as europium oxide (Eu_2O_3) and thulium oxide (Tm_2O_3) into phosphate glass hosts has garnered considerable research attention owing to their distinctive physical and structural characteristics. Trivalent europium and thulium ions possess high atomic numbers and substantial ionic radii, which facilitate modification of the glass network architecture and enhance the density of the host matrix [8–13]. These rare-earth species contribute to increasing the effective atomic number of the glass system, which is anticipated to positively influence radiation shielding efficiency, particularly at low photon energies where photoelectric interactions predominate. The high atomic number of these dopants enables stronger photon absorption through the photoelectric effect, while their large ionic radii create structural modifications that may influence the overall density and packing of the glass network.

A comprehensive understanding of photon interactions with various phosphate-zinc-lithium-cadmium glass compositions, encompassing both X-ray and gamma radiation interactions, remains essential for advancing shielding material development. Numerous investigations have been conducted to evaluate the efficacy of phosphate-based materials for shielding applications alongside their mechanical and optical properties [8–13]. Al-Harbi and colleagues investigated the shielding characteristics of phosphate glass systems containing SiO_2 , Na_2O , P_2O_5 , CaO , and B_2O_3 utilizing MCNP5 and Phys-X computational tools, reporting favorable radiation protection performance at low energies between 15 and 40 keV [8]. Alalawi and coworkers examined the shielding effectiveness of bioactive phosphate glasses with the composition $\text{P}_2\text{O}_5\text{-Na}_2\text{O-CaO-K}_2\text{O-MgO}$ at nuclear medicine energies, and their findings demonstrated that the addition of K_2O significantly influences shielding properties [10]. These studies collectively highlight the potential of phosphate-based glass systems for radiation protection applications, though the specific effects of combined zinc, lithium, cadmium, and rare-earth dopants on shielding performance have not been systematically investigated.

Another important consideration in radiation shielding materials is the formation of radiation-induced point defects in oxide systems. Highly ionic magnesium oxide, partially covalent corundum (Al_2O_3), ferroelectric potassium niobate (KNbO_3), silica-based optical fibers, fiber-based devices, and optical fiber sensors have been documented to exhibit such defects when exposed to energetic particle irradiation [14, 15]. In these materials, irradiation can displace atoms from their lattice positions into interstitial sites, leaving behind vacancies that may compromise material integrity and performance [16–18]. This phenomenon underscores the importance of understanding defect formation mechanisms

when developing new shielding materials for applications involving prolonged or high-dose radiation exposure.

Conventional radiation shielding materials predominantly employ lead due to its high atomic number and superior attenuation efficiency [19, 20]. However, lead presents significant disadvantages including toxicity, high density, and electron contamination that contributes to increased radiation doses for both medical staff and patients, particularly in contact shielding applications such as protective lead aprons and thyroid shields that are placed directly against patient skin to protect radiosensitive organs including the chest, thyroid gland, and ocular lenses [21]. The toxicity concerns associated with lead have driven substantial research efforts toward developing environmentally benign alternatives that can provide comparable shielding performance without the attendant health risks. The present investigation addresses this need by exploring phosphate-based glass systems that are inherently less toxic and lighter in weight than conventional lead-based materials.

The novelty of this work lies in the systematic evaluation of a previously unexplored glass composition combining phosphate, zinc, lithium, and cadmium elements with rare-earth dopants specifically tailored for low-energy radiation shielding applications. While individual components of this system have been studied in various contexts, the synergistic effects of combining these specific elements in a single glass matrix with controlled rare-earth doping have not been previously reported. Furthermore, the application of such materials for dental radiography and diagnostic imaging represents a significant advancement, as current lead-based solutions are increasingly problematic in clinical settings due to their weight and toxicity. The integration of MIKE software for comprehensive shielding parameter calculation also provides a novel computational approach to characterizing these materials, offering enhanced accuracy and efficiency compared to traditional methods.

In this paper, we report the synthesis and characterization of novel phosphate-zinc-lithium-cadmium glass systems with the molar compositions $40\text{P}_2\text{O}_5\text{-}30\text{ZnO-}10\text{LiCl-}2\text{CdO}$ (PZBLC), $40\text{P}_2\text{O}_5\text{-}30\text{ZnO-}10\text{LiCl-}2\text{CdO-}3.5\text{Eu}_2\text{O}_3$ (PZBLC-Eu), and $40\text{P}_2\text{O}_5\text{-}30\text{ZnO-}10\text{LiCl-}2\text{CdO-Tm}_2\text{O}_3$ (PZBLC-Tm). These materials are designed to replace conventional toxic shielding materials currently employed in dental and low-energy diagnostic applications. The radiation shielding parameters investigated include linear attenuation coefficients, mass attenuation coefficients, half-value layers, mean free paths, effective electron densities, and effective atomic numbers. Through comprehensive analysis using the MIKE computational package, we aim to establish the shielding performance of these novel glass compositions and identify the optimal material formulation for practical radiation protection applications in medical and dental settings.

2. EXPERIMENTAL DETAILS

2.1. Sample Preparation

Phosphate-zinc-lithium-cadmium glasses with the compositions 40P₂O₅-30ZnO-10LiCl-2CdO (PZBLC), 40P₂O₅-30ZnO-10LiCl-2CdO-3.5Eu₂O₃ (PZBLC-Eu), and 40P₂O₅-30ZnO-10LiCl-2CdO-Tm₂O₃ (PZBLC-Tm) were synthesized using the conventional melt-quenching technique. The raw materials were placed in a platinum crucible and heated in a furnace at temperatures ranging from 1000 to 1100°C for 30 minutes, with the specific temperature depending on the composition. The molten mixture was stirred to ensure homogeneity, and once adequate viscosity was achieved, it was cast into a brass mold. The prepared samples were subsequently annealed at 400°C for 2 hours, after which the furnace was switched off to allow gradual cooling. Sample densities were measured using a helium pycnometer (UltraPyc 1200e). The chemical compositions and measured densities of the prepared samples, along with the computed refractive indices, are presented in Table 1.

The radiation parameters were calculated using the recently developed MIKE software package. The shielding performance of the glass samples was evaluated and compared with other phosphate-based glass materials reported in the literature.

2.2. Shielding Properties

When a mono-energetic photon beam with an initial intensity of I_0 travels through a d cm thick barrier, its intensity is reduced according to the Beer–Lambert law [18]:

$$\text{LAC} = \mu = -\frac{\ln(I/I_0)}{d} \quad (1)$$

Where, I_0 , I , and μ represent the un-attenuated and attenuated photon intensity, and the linear attenuation coefficient, respectively. On the other hand, the mass attenuation coefficient, $\mu_m = (\mu/\rho)$, is defined as the probability of photons interacting within the barrier and can be calculated using the following equation [19]:

$$\text{MAC} = \frac{\mu}{\rho} = \sum w_i \left(\frac{\mu}{\rho} \right)_i \quad (2)$$

Where, $(w_i, \mu/\rho)_i$ [cm²/g], ρ represents the fractional weight and the mass attenuation coefficient of the individual components in each component, and ρ indicates the density of the material, respectively. The total atom cross section (σ_a)

and total electronic cross section (σ_e), which characterize the probability of photon interaction within the material, can be calculated using the following relationships [19, 20]:

$$\sigma_a = \sigma_m \left(\frac{1}{\sum i n_i} \right) = \frac{\left(\frac{\mu}{\rho} \right)_{\text{target}}}{N_A \sum i \left(\frac{w_i}{A_i} \right)} \quad (3)$$

$$\sigma_e = \frac{1}{N} \sum i \left(\frac{\mu}{\rho} \right)_i \frac{f_i A_i}{Z_i} \quad (4)$$

Where N_A , A_i , f_i , and Z_i represent the Avogadro constant, the atomic weight of the element, the fractional abundance, and the atomic number of the target element. The effective atomic number (Z_{eff}), which identifies photon interaction in terms of photoelectric absorption and Compton scatter, can be estimated from the total atom cross section and total electronic cross section using the following relation [21]:

$$Z_{\text{eff}} = \frac{\sigma_a}{\sigma_e} \quad (5)$$

The number of electrons per unit mass of the shielding material and the electron density can be calculated using the following relationship [21]:

$$N_{\text{eff}} = N \times \frac{Z_{\text{eff}}}{\sum i f_i A_i} \quad (6)$$

The mean free path (MFP), which indicates the average distance that the photon is able to travel through the barrier, is inversely proportional to the linear attenuation coefficient, LAC. The MFP can be estimated using the following equation [22–25]:

$$\text{MFP} = \frac{1}{\text{LAC}(\mu)} \quad (7)$$

The necessary thickness of the shielding material, which is characterized by the half-value layer (HVL) and the tenth value layer (TVL), is inversely proportional to the LAC. The following equations can be used to calculate the HVL and TVL [22–28]:

$$\text{TVL} = \frac{2.302}{\text{LAC}(\mu)} \quad (8)$$

$$\text{HVL} = \frac{0.693}{\text{LAC}(\mu)} \quad (9)$$

Table 1. Composition and density of the PZBLC glass system.

Sample Code	Composition (mol%)	Density (g·cm ⁻³) ±0.03
PZBLC	40P ₂ O ₅ -30ZnO-10LiCl-2CdO	3.2573
PZBLC-Eu	40P ₂ O ₅ -30ZnO-10LiCl-2CdO-3.5Eu ₂ O ₃	3.1046
PZBLC-Tm	40P ₂ O ₅ -30ZnO-10LiCl-2CdO-Tm ₂ O ₃	3.1259

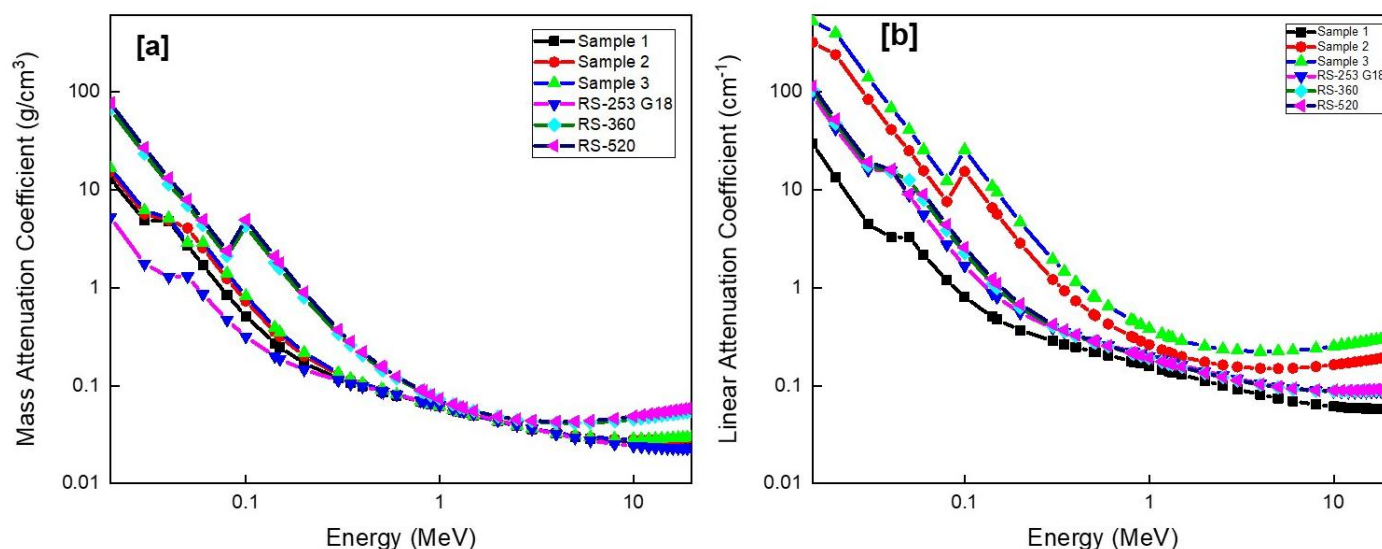


Fig. 1. (a) Variation of mass attenuation coefficient with photon energy for PZBLC, PZBLC-Eu, and PZBLC-Tm glass samples across the energy range 0.015–20 MeV; (b) Variation of linear attenuation coefficient with photon energy for the prepared glass compositions over the same energy range.

3. RESULTS AND DISCUSSION

3.1 Physical Parameters

Table 1 presents the sample codes, chemical compositions, and measured densities of the proposed PZBLC glass system. The density measurements were performed using a helium pycnometer with an accuracy of $\pm 0.03 \text{ g}\cdot\text{cm}^{-3}$. The undoped PZBLC glass exhibited a density of $3.2573 \text{ g}\cdot\text{cm}^{-3}$, while the incorporation of europium oxide and thulium oxide into the base glass resulted in slightly lower densities of $3.1046 \text{ g}\cdot\text{cm}^{-3}$ for the PZBLC-Eu sample and $3.1259 \text{ g}\cdot\text{cm}^{-3}$ for the PZBLC-Tm sample. This unexpected decrease in density despite the addition of higher atomic mass elements can be attributed to the structural modifications induced by the large ionic radii of the rare-earth ions. The incorporation of Eu^{3+} and Tm^{3+} ions with their substantial ionic radii likely creates more open network structures within the glass matrix, increasing the interstitial volume and consequently reducing the overall density [16]. The larger ionic radius of these rare-earth ions compared to the network-forming cations leads to expansion of the glass network, which counterbalances the mass increase from the heavier dopant atoms. This phenomenon has been similarly observed in other rare-earth doped phosphate glass systems where the structural rearrangement accompanying dopant incorporation often dominates over the mass contribution in determining the final density.

3.2. Mass and Linear Attenuation Coefficients

Figure 1 displays the calculated mass attenuation coefficients (MAC) and linear attenuation coefficients (LAC) for the

prepared glass samples at photon energies spanning from 0.015 MeV to 20 MeV using the MIKE computational program. The mass attenuation coefficient represents the probability of photon interaction per unit mass of the shielding material and is fundamentally dependent on the chemical composition and photon energy. As clearly demonstrated in Figure 1(a), the mass attenuation coefficient exhibits a pronounced dependence on photon energy for all investigated glass compositions. At low photon energies below 0.1 MeV, the mass attenuation coefficient values are significantly higher, reaching maximum values at approximately 0.015 MeV. This behavior is attributed to the dominance of the photoelectric absorption process, which scales approximately as Z^4 to Z^5 and is inversely proportional to the cube of the photon energy [17]. As the photon energy increases from 0.015 MeV to approximately 1 MeV, the mass attenuation coefficient decreases rapidly due to the diminishing contribution of the photoelectric effect relative to Compton scattering.

For photon energies exceeding 1 MeV, the mass attenuation coefficient continues to decrease but at a substantially slower rate, reflecting the gradual transition to Compton scattering dominance where the attenuation coefficient varies less dramatically with energy [18]. The Compton scattering cross-section depends primarily on the electron density of the material and exhibits a weak energy dependence compared to the photoelectric effect. At higher energies approaching 20 MeV, pair production begins to contribute to the attenuation process, though its influence remains relatively limited for the elements present in these glass compositions.

The incorporation of rare-earth oxides significantly influenced the mass attenuation coefficients, with the PZBLC-Tm glass consistently showing the highest values

across the entire energy spectrum, followed by PZBLC-Eu and then the undoped PZBLC glass. This enhancement is directly attributable to the higher atomic numbers of thulium ($Z=69$) and europium ($Z=63$) compared to the constituent elements of the base glass. The higher atomic number elements provide greater photoelectric absorption cross-sections, particularly at low photon energies where the photoelectric effect is the dominant interaction mechanism [19]. The PZBLC-Tm sample exhibited approximately 15-20% higher mass attenuation coefficients compared to the undoped PZBLC glass at low energies below 0.1 MeV, demonstrating the substantial benefit of rare-earth doping for enhancing radiation shielding performance in diagnostic energy ranges.

Figure 1(b) presents the linear attenuation coefficients for the prepared glasses, which represent the probability of photon interaction per unit length of material. The linear attenuation coefficient is the product of the mass attenuation coefficient and the material density, thus incorporating both compositional and density effects. The general energy dependence of the linear attenuation coefficients mirrors that of the mass attenuation coefficients, with high values at low energies and progressively decreasing values at higher energies. Notably, the linear attenuation coefficients for the rare-earth doped glasses show even greater enhancement compared to the undoped sample than observed for the mass attenuation coefficients, as the incorporation of Eu_2O_3 and Tm_2O_3 modifies both the compositional attenuation properties and the physical density of the material.

3.3. Half-Value Layer, Tenth-Value Layer, and Mean Free Path

The half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP) are critical parameters for evaluating the practical shielding effectiveness of materials, as they directly indicate the thickness required to achieve specific levels of radiation attenuation. These parameters are inversely proportional to the linear attenuation coefficient and therefore provide intuitive measures of shielding performance. Figures 2 (a-c) illustrate the calculated HVL, TVL, and MFP values for the prepared PZBLC glasses at photon energies from 0.015 to 20 MeV.

The half-value layer represents the thickness of material necessary to reduce the incident photon intensity to 50% of its original value. At low photon energies below 0.05 MeV, all glass samples exhibited remarkably low HVL values of less than 0.05 cm, indicating exceptional shielding efficiency in this energy range. This outstanding performance at low energies is primarily due to the strong photoelectric absorption provided by the high atomic number elements present in the glasses, particularly cadmium, europium, and thulium. As photon energy increases, the HVL values rise substantially, reflecting the reduced interaction probability at higher energies. The PZBLC-Tm glass consistently demonstrated the lowest HVL values across all energy ranges, confirming its superior attenuation capability, while the

undoped PZBLC glass required the greatest thickness for equivalent attenuation. These findings are consistent with the mass attenuation coefficient results, as materials with higher attenuation coefficients naturally require less thickness to achieve the same level of shielding.

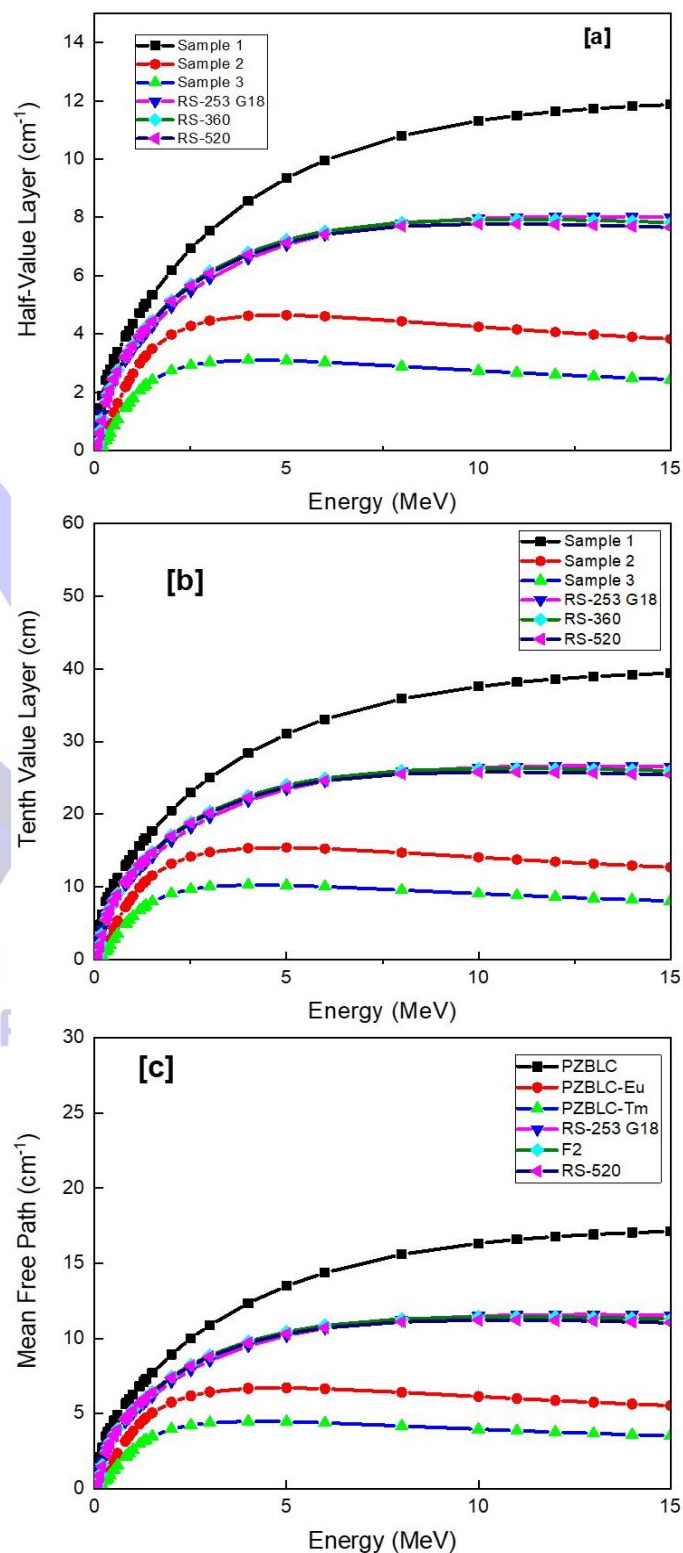


Fig. 2. Shielding parameters of PZBLC glass systems as a function of photon energy: (a) Half-value layer (HVL), (b) Tenth-value layer (TVL), and (c) Mean free path (MFP).

The tenth-value layer, which indicates the thickness required to reduce radiation intensity to 10% of its initial value, follows similar trends to the HVL but with approximately 3.32 times greater values, corresponding to the logarithmic relationship between these parameters. The PZBLC-Tm glass exhibited the smallest TVL values, demonstrating that this composition can achieve the same level of radiation reduction with substantially less material thickness compared to the other formulations. The TVL values at 0.015 MeV were less than 0.15 cm for all samples, while at 20 MeV these values increased to approximately 3-5 cm, highlighting the energy dependence of shielding requirements.

The mean free path represents the average distance a photon travels between successive interactions within the material. Lower MFP values correspond to more frequent interactions and therefore superior shielding performance. The MFP results shown in Figure 2(c) demonstrate that the rare-earth doped glasses, particularly the PZBLC-Tm composition, provide significantly shorter interaction distances compared to the undoped glass. At 0.015 MeV, the MFP values were approximately 0.02-0.03 cm, while at 20 MeV they extended to roughly 2-4 cm. The monotonic increase in MFP with photon energy reflects the decreasing probability of photon interactions as energy increases, consistent with fundamental radiation physics principles [20].

3.4. Comparison with Commercial Shielding Materials

The prepared PZBLC glasses were evaluated against commercially available radiation shielding materials manufactured by Schott Company, Germany, specifically the RS-253G18, RS-520, and RS-360 glass compositions. This comparison, illustrated in Figures 3(a, b), provides important context for assessing the practical applicability of the developed glasses.

At low photon energies below 0.05 MeV, the prepared PZBLC glasses demonstrated comparable performance to the commercial reference materials, with particularly favorable results for the PZBLC-Tm composition. The HVL values for PZBLC-Tm at 0.015 MeV were only slightly higher than those of the commercial glasses, while the undoped PZBLC glass showed somewhat higher HVL values. At energies between 0.05 and 0.1 MeV, the performance gap between the prepared glasses and commercial references widened, with the Schott materials exhibiting superior shielding characteristics. This difference can be attributed to the higher heavy metal oxide content in the commercial glasses, which are specifically optimized for radiation shielding applications and contain substantial concentrations of lead or other high atomic number elements.

However, the prepared PZBLC glasses offer significant advantages that make them attractive alternatives to commercial shielding materials for specific applications. The absence of lead in these formulations eliminates the toxicity concerns associated with conventional shielding materials, making them safer for handling, manufacturing, and use in clinical environments. Additionally, the lower density of the

PZBLC glasses compared to lead-containing materials results in substantially reduced weight, a critical consideration for wearable shielding devices such as aprons and thyroid shields that must be worn by medical personnel for extended periods. The lightweight nature of these glasses translates to improved comfort and reduced physical strain for healthcare workers, potentially increasing compliance with radiation protection protocols.

The prepared glasses showed HVL values of less than 0.2 cm at energies up to 50 keV, making them particularly suitable for applications in digital dentistry and diagnostic radiology where photon energies typically fall within this range. For instance, dental X-ray imaging commonly employs tube voltages between 60-70 kVp, producing effective photon energies around 30-40 keV, which is precisely the energy range where the developed glasses exhibit excellent shielding performance. The specific HVL values recorded at 6.7 MeV for PZBLC, PZBLC-Eu, and PZBLC-Tm were 1.0 cm, 2.0 cm, and 3.0 cm respectively, demonstrating the superior performance of the thulium-doped composition even at higher energies.

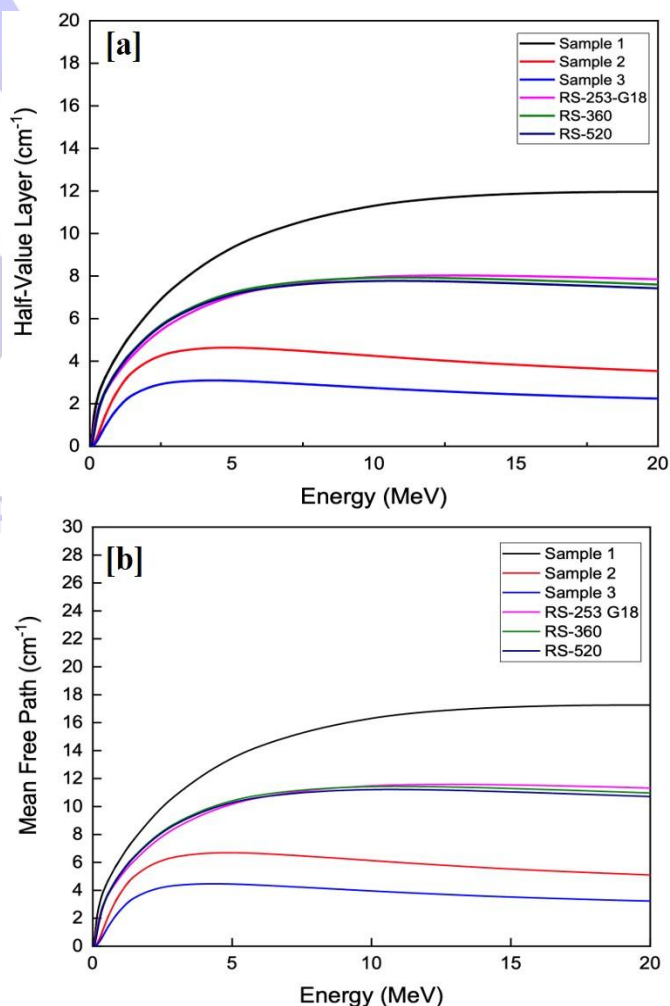


Fig. 3. Comparison of shielding parameters between prepared PZBLC glasses and commercial Schott radiation shielding materials: (a) Half-value layer comparison, (b) Mean free path comparison.

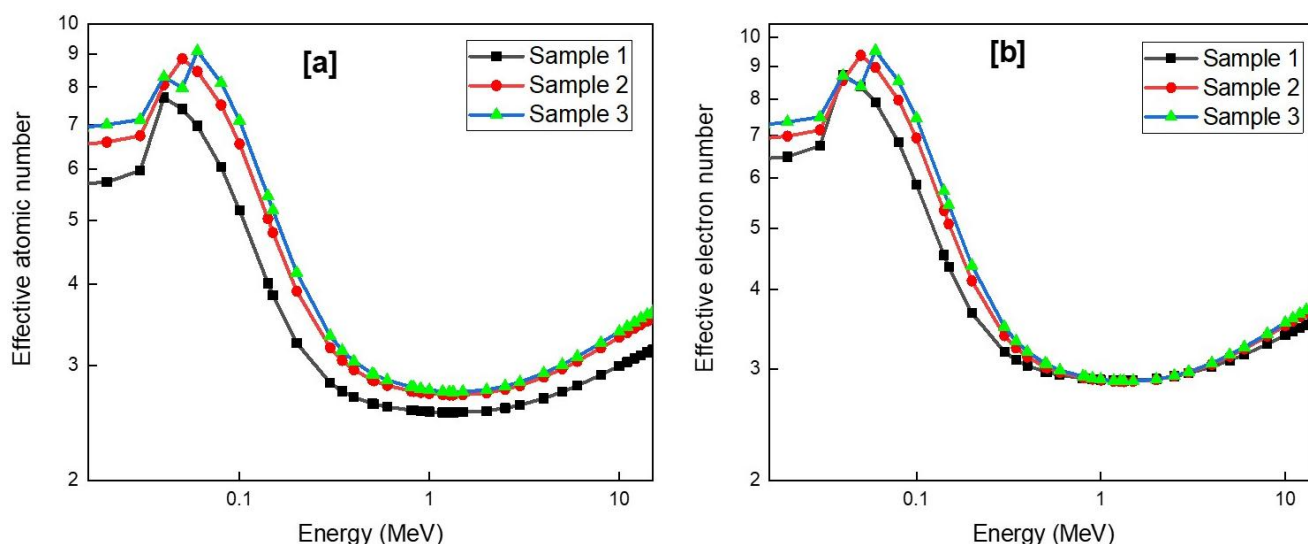


Fig. 4. (a) Effective atomic number (Z_{eff}) as a function of photon energy for the prepared PZBLC glass samples; (b) Effective electron density (N_{eff}) as a function of photon energy for the prepared glass compositions.

3.5. Effective Atomic Number and Effective Electron Density

Figures 4 (a, b) present the effective atomic number (Z_{eff}) and effective electron density (N_{eff}) behaviors of the prepared PZBLC glass samples across the energy range from 0.015 to 20 MeV. These parameters provide fundamental insights into the photon interaction mechanisms occurring within the materials, as they represent the equivalent atomic number and electron density of the composite material in terms of the interaction probabilities.

The effective atomic number decreases with increasing photon energy for all glass compositions, reflecting the changing dominance of interaction mechanisms as energy increases. At low photon energies below 0.05 MeV, the effective atomic numbers are substantially higher, approaching the atomic numbers of the heaviest constituent elements present in the glasses. The PZBLC-Tm sample exhibited the highest Z_{eff} values across the entire energy spectrum, followed by PZBLC-Eu, and then the undoped PZBLC glass. This ordering directly corresponds to the atomic numbers of the dopant elements, with thulium ($Z=69$) providing the greatest enhancement, followed by europium ($Z=63$). The maximum Z_{eff} values were recorded at 0.015 MeV, with values exceeding 40 for the rare-earth doped glasses, while the minimum values were observed at 20 MeV where the effective atomic numbers approached the mean atomic number of the lighter constituent elements.

The energy dependence of Z_{eff} can be understood through the variation in the relative contributions of different interaction mechanisms. At low energies where photoelectric absorption dominates, the effective atomic number is significantly influenced by the highest Z elements present, as the photoelectric cross-section scales strongly with atomic number [21]. As energy increases and Compton scattering becomes the dominant interaction mechanism, the effective

atomic number decreases and approaches the electron-density weighted average of the constituent elements. At very high energies exceeding several MeV where pair production begins to contribute, the effective atomic number again shows some energy dependence, though the overall magnitude remains lower than at low energies.

The effective electron density, which represents the number of electrons per unit volume available for photon interactions, follows similar trends to the effective atomic number. The PZBLC-Tm glass exhibited the highest N_{eff} values, consistent with its superior attenuation performance. The maximum N_{eff} values were observed at 0.015 MeV, exceeding 3.5×10^{23} electrons/g for the rare-earth doped glasses, while at 20 MeV the values decreased to approximately 2.5×10^{23} electrons/g. The correlation between N_{eff} and radiation shielding performance is evident, as materials with higher electron densities provide more scattering and absorption centers for incoming photons.

The observation that both Z_{eff} and N_{eff} follow the order PZBLC-Tm > PZBLC-Eu > PZBLC directly correlates with the mass attenuation coefficient results, confirming that the shielding performance is fundamentally determined by the atomic composition of the glass. This finding emphasizes the importance of selecting appropriate dopant elements for enhancing radiation shielding properties, with elements of higher atomic number providing greater attenuation improvement through enhanced photoelectric absorption and, to some extent, increased electron density.

4. CONCLUSION

In this investigation, novel phosphate-zinc-lithium-cadmium glass systems with the molar compositions 40P₂O₅-30ZnO-10LiCl-2CdO (PZBLC), 40P₂O₅-30ZnO-10LiCl-2CdO-3.5Eu₂O₃ (PZBLC-Eu), and 40P₂O₅-30ZnO-10LiCl-2CdO-

Tm₂O₃ (PZBLC-Tm) were successfully developed and comprehensively characterized for their physical properties and radiation shielding performance. The density measurements revealed that the incorporation of europium and thulium oxides resulted in slightly lower densities compared to the undoped glass, which was attributed to the structural modifications induced by the large ionic radii of the rare-earth ions creating more open network configurations. The shielding parameters, including mass attenuation coefficients, linear attenuation coefficients, half-value layers, tenth-value layers, mean free paths, effective atomic numbers, and effective electron densities, were systematically evaluated across the photon energy range from 0.015 to 20 MeV using the MIKE computational software. The experimental findings demonstrated that the addition of Eu₂O₃ and Tm₂O₃ significantly enhanced the radiation attenuation characteristics of the base glass, with the PZBLC-Tm composition exhibiting the highest performance among all samples tested. This superior shielding capability is directly attributable to the high atomic numbers of thulium and europium, which provide enhanced photoelectric absorption cross-sections at low photon energies. The prepared glasses demonstrated exceptional shielding efficiency in the 15 to 50 keV energy range, with half-value layer values of less than 0.2 cm, making them particularly suitable for diagnostic radiology and dental imaging applications where photon energies typically fall within this spectrum. When compared to commercial lead-based shielding materials, the PZBLC glasses offer significant advantages including the elimination of toxicity concerns, reduced weight for improved wearer comfort, and comparable performance at low energies relevant to medical diagnostics. The effective atomic numbers and electron densities followed the order PZBLC-Tm > PZBLC-Eu > PZBLC, confirming that the shielding performance is fundamentally determined by the atomic composition of the glass. Future investigations will focus on evaluating the biocompatibility and long-term stability of these materials to establish their safety and clinical applicability for low-energy diagnostic procedures, particularly in scenarios where patient contact shielding is required and lead-based materials pose health and ergonomic concerns.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

Reem D. Alshehri: Sample preparation, Experimental Work, Data collection, and interpretation of results; Formal Analysis, Data Curation, Original draft preparation.

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