

RESEARCH ARTICLE

Enhancing Radiation Shielding Efficiency of Erbium–Doped Niobium–Potassium Tellurite–Zinc–Lead Fluoride Glasses

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ABSTRACT: Erbium-doped tellurite glasses with nominal composition $64\text{TeO}_2\text{--}5\text{K}_2\text{TeO}_3\text{--}20\text{ZnO--}10\text{Nb}_2\text{O}_5\text{--}3\text{PbF}_2$ were synthesized using the melt-quench technique with Er_2O_3 concentrations of 0–4.5 mol%. X-ray diffraction confirmed their amorphous nature, while gamma-ray shielding performance was experimentally evaluated over 59.5–1330 keV using a NaI(Tl) detector and standard radioactive sources. Key parameters, including linear and mass attenuation coefficients, half-value layer, mean free path, and radiation protection efficiency, were systematically determined. Increasing Er_2O_3 concentration enhanced gamma-ray attenuation and reduced both half-value layer and mean free path. At 662 keV, the linear attenuation coefficient increased from 19.892 to 27.321 cm^{-1} , while the mass attenuation coefficient increased from 3.5638 to 4.8602 $\text{cm}^2\cdot\text{g}^{-1}$. The 4.5 mol% Er_2O_3 glass achieved nearly 99% attenuation at low photon energies with a 0.7 cm thickness. These results demonstrate its potential for efficient gamma-ray shielding where transparency and formability are required.

Keywords: Tellurite Glasses; Gamma-Ray Shielding; Erbium Doping; Attenuation Coefficients; Radiation Protection Efficiency; Glass Characterization.

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1. INTRODUCTION

The increasing utilization of ionizing radiation across medical diagnostics, radiotherapy, nuclear power generation, industrial radiography, and scientific research has intensified

concerns regarding radiation exposure and its associated health risks [1, 2]. Photon radiation, in particular, poses significant challenges due to its deep penetration capability, long-range interactions, and capacity to induce severe biological damage, including cellular dysfunction, DNA strand breaks, genetic mutations, and elevated long-term cancer mortality [3, 4]. Consequently, the design of effective and biologically safe radiation shielding materials has become increasingly critical. Traditionally, high-atomic-number materials such as lead and lead-based composites have been extensively employed for radiation shielding owing to their superior attenuation characteristics, economic feasibility, and widespread availability [5, 6]. However, the practical application of lead is hindered by inherent disadvantages, including high toxicity, environmental hazards, mechanical rigidity, limited optical transparency, and excessive weight [7, 8]. These limitations have motivated the search for unconventional shielding materials that are

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non-toxic, lightweight, optically transparent, and suitable for modern engineering applications [9, 10].

In recent decades, glass materials, particularly heavy metal oxide glasses and rare-earth-doped glass systems, have emerged as promising candidates for next-generation radiation shielding applications [11, 12]. Glasses offer several intrinsic advantages, including high optical transparency, excellent chemical durability, relatively low fabrication temperatures, tunable structural properties, good mechanical stability, and resistance to environmental degradation [13, 14]. Their compositional versatility allows researchers to precisely tailor parameters such as density, bonding structure, electronic configuration, and photon interaction characteristics, thereby enabling the development of transparent and structurally stable radiation shielding systems with adaptable properties [15]. Among the various glass-forming systems investigated, tellurite glasses have attracted considerable attention due to their comparatively high density, excellent glass-forming ability, low phonon energies, high refractive index, and remarkable capacity to accommodate various modifiers and rare-earth ions within their network structure [16, 17]. Tellurite glasses are composed of TeO_4 trigonal bipyramids and TeO_3 trigonal pyramids, which form a highly polarizable network that facilitates the incorporation of heavy metal oxides and rare-earth elements [18]. The presence of tellurium, with its relatively high atomic number, inherently contributes to enhanced photon interaction probabilities, making tellurite glasses inherently suitable for gamma-ray attenuation applications [19].

The addition of rare-earth oxides to tellurite glasses has been demonstrated to significantly enhance both structural integrity and radiation shielding capabilities by elevating the effective atomic number, increasing electron density, and modifying the local coordination environment around the rare-earth ions [20, 21]. Numerous studies have investigated the effects of various rare-earth dopants, including europium, samarium, dysprosium, neodymium, and erbium, on the attenuation properties of different glass systems [22, 23]. Among these, erbium has emerged as particularly effective modifier due to its high atomic number, favorable ionic radius, and ability to induce substantial densification of the glass matrix without compromising the amorphous nature of the network [21, 23]. Erbium oxide incorporation leads to the formation of non-bridging oxygens, which alters the local structure and enhances the overall density of the glass, thereby improving its photon attenuation capabilities [20]. Recent studies on erbium-doped tellurite glasses have reported significant improvements in linear and mass attenuation coefficients, accompanied by reductions in half-value layer and mean free path values, confirming the suitability of these systems for radiation shielding applications [22, 23].

The novelty of the present work lies in the systematic investigation of erbium-doped niobium-potassium tellurite-zinc-lead fluoride glasses with a carefully designed multi-component composition that combines the advantages of multiple heavy metal oxides and fluorides to achieve superior

shielding performance. While previous studies have explored erbium doping in various tellurite glass systems, the specific quaternary composition $64\text{TeO}_2\text{--}5\text{K}_2\text{TeO}_3\text{--}20\text{ZnO--}10\text{Nb}_2\text{O}_5\text{--}3\text{PbF}_2$ has not been previously investigated for gamma-ray shielding applications. The inclusion of niobium pentoxide, which possesses a high atomic number and contributes to network formation, along with potassium tellurite, zinc oxide, and lead fluoride, creates a unique glass matrix that offers exceptional density, structural stability, and photon attenuation characteristics. Furthermore, the present study provides comprehensive experimental evaluation of all key shielding parameters across a wide photon energy range from 59.5 to 1330 keV using standard gamma sources, offering valuable data for practical shielding applications in medical and nuclear settings. The systematic variation of erbium oxide concentration from 0 to 4.5 mol% allows for a thorough understanding of the composition-property relationships governing the shielding efficiency of these glasses.

In this paper, we report the synthesis, structural characterization, and comprehensive gamma-ray shielding evaluation of erbium-doped niobium-potassium tellurite-zinc-lead fluoride glasses with the nominal composition $64\text{TeO}_2\text{--}5\text{K}_2\text{TeO}_3\text{--}20\text{ZnO--}10\text{Nb}_2\text{O}_5\text{--}3\text{PbF}_2$ and Er_2O_3 concentrations of 0, 2.0, 3.0, and 4.5 mol%. The glasses were prepared using the conventional melt-quench technique, and their amorphous nature was confirmed through X-ray diffraction analysis. Density measurements were performed using a helium pycnometer to determine the physical properties of the synthesized samples. The gamma-ray shielding characteristics, including linear attenuation coefficient, mass attenuation coefficient, half-value layer, mean free path, and radiation protection efficiency, were experimentally determined across photon energies of 59.5, 662, 1170, and 1330 keV using a NaI(Tl) detector system coupled to a multichannel analyzer with standard radioactive sources Am-241, Cs-137, and Co-60. The influence of erbium oxide concentration on each shielding parameter was systematically analyzed, and the results were compared with previously reported rare-earth-doped glass systems to establish the relative performance of the present compositions. The findings of this investigation provide valuable insights into the design and optimization of erbium-doped tellurite glasses for efficient and practical gamma-ray shielding applications, particularly in scenarios where transparent, lightweight, and non-toxic shielding materials are required.

2. EXPERIMENTAL DETAILS

2.1. Glass Preparation

The glass samples under investigation were synthesized using the conventional melt-quenching technique, which is widely recognized for its simplicity and effectiveness in producing homogeneous glass systems with good optical quality. High-purity starting materials, including tellurium

dioxide (TeO_2), potassium tellurite (K_2TeO_3), zinc oxide (ZnO), niobium pentoxide (Nb_2O_5), lead fluoride (PbF_2), and erbium oxide (Er_2O_3), all with purities exceeding 99.9%, were obtained from commercial suppliers and used without further purification. The nominal composition of the base glass was selected as $64\text{TeO}_2-5\text{K}_2\text{TeO}_3-20\text{ZnO}-10\text{Nb}_2\text{O}_5-3\text{PbF}_2$, and erbium oxide was introduced at concentrations of 0, 2.0, 3.0, and 4.5 mol% by replacing the tellurium dioxide content accordingly. Each batch, weighing approximately 15 grams, was thoroughly mixed and ground in an agate mortar for about 30 minutes to ensure complete homogeneity of the constituent powders prior to melting. The well-mixed batches were then transferred into a high-purity gold crucible and placed in a programmable electric furnace, where they were gradually heated to a melting temperature of 950°C and maintained at this temperature for 30 minutes.

During the melting process, the melt was periodically stirred using a platinum rod to promote homogeneity and to eliminate any trapped air bubbles that could compromise the optical and structural quality of the final glass specimens. Following the melting stage, the homogeneous melts were rapidly poured onto a preheated graphite mold maintained at a temperature of 340°C , which was selected based on the glass transition temperature of the system to prevent thermal shock and subsequent cracking of the samples. The poured glasses were immediately transferred to a muffle furnace preheated to 340°C , where they were annealed for two hours to relieve internal mechanical stresses induced during the rapid cooling process. After the annealing period, the furnace was allowed to cool slowly to room temperature at a controlled rate of approximately 10°C per hour to ensure the complete relaxation of the glass network. The as-prepared glass specimens were subsequently cut using a precision low-speed diamond saw and polished on both sides to obtain optically flat surfaces with a final thickness of approximately 2.1 mm, which was measured using a digital micrometer with an accuracy of ± 0.01 mm. The polished samples were then cleaned ultrasonically in acetone followed by distilled water to remove any surface contaminants and stored in a desiccator prior to further characterization.

2.2. Structural and Physical Characterization

The amorphous nature of the synthesized glass specimens was confirmed by X-ray diffraction analysis using a Philips

PW 1140 diffractometer operating with Cu-K α radiation having a wavelength of $1.54 \text{ \AA}$. The diffraction patterns were recorded over a 2θ range of 10° to 70° at a scanning speed of 2° per minute, with the generator operating at 40 kV and 30 mA. The absence of sharp crystalline peaks in the obtained diffraction patterns confirmed the non-crystalline, amorphous structure of all prepared glass samples. The density of each glass specimen was determined at room temperature using an AccuPyc 1330 helium pycnometer, which employs the gas displacement method to accurately measure the volume of solid samples.

Density measurements were performed using helium gas due to its inert nature and ability to penetrate even the smallest pores, ensuring highly precise volume determination with an instrumental error margin of $\pm 0.0001 \text{ g/cm}^3$. For each composition, at least five density measurements were taken and the average values were recorded to ensure statistical reliability. The molar volume V_m for each glass sample was subsequently calculated using the relationship $V_m = M/\rho$, where M represents the average molecular weight of the glass composition calculated from its molar fractions and ρ denotes the experimentally determined density. The obtained density and molar volume values are presented in Table 1, which also summarizes the complete compositional details of all four glass samples.

2.3. Gamma-Ray Attenuation Measurements

The gamma-ray shielding characteristics of the prepared glass specimens were experimentally determined using a high-performance SPECTECH NaI(Tl) detector system coupled to a computer-controlled multichannel analyzer for data acquisition and spectral analysis. The detector system was carefully calibrated using standard gamma-ray sources to ensure accurate energy and efficiency calibration across the entire measurement range. Collimated and well-focused gamma-ray beams were obtained using three standard radioactive point sources, namely Am-241 emitting photons at 59.5 keV, Cs-137 emitting photons at 662 keV, and Co-60 emitting photons at 1170 and 1330 keV, all of which were procured from a certified supplier with well-known activity and purity. The glass specimens were positioned precisely between the radioactive source and the detector, maintaining a fixed source-to-detector distance of 15 cm to ensure consistent geometry for all measurements.

Table 1. Composition and physical properties of the prepared glasses.

Sample	TeO_2 (mol%)	K_2TeO_3 (mol%)	ZnO (mol%)	Nb_2O_5 (mol%)	PbF_2 (mol%)	Er_2O_3 (mol%)	Density (g/cm^3)	Molar volume (cm^3/mol)
A	62	5	20	10	3	0.0	5.5713	29.05
B	62	5	20	10	3	2.0	5.5816	29.77
C	62	5	20	10	3	3.0	5.5901	30.10
D	62	5	20	10	3	4.5	5.6214	30.48

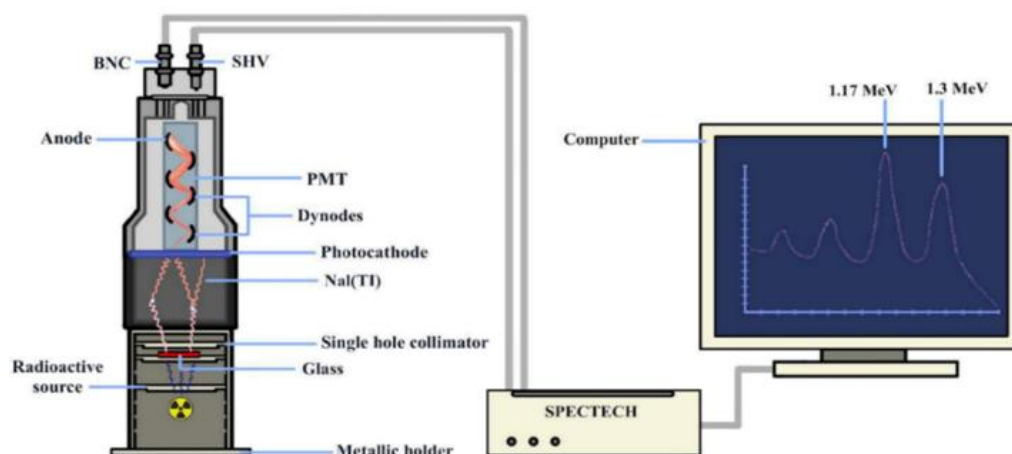


Fig. 1. Setup for measurement radiation parameters of produced glasses.

The collimator setup, featuring lead shielding blocks with a 5 mm diameter aperture, was employed to produce a narrow-beam geometry condition, thereby minimizing the contribution of scattered photons to the measured transmission intensities. The experimental arrangement for measuring the incident and transmitted radiation intensities through the glass samples is schematically illustrated in Figure 1.

For each measurement, the spectrum was accumulated for a sufficient counting time to achieve low statistical uncertainty, typically less than 1%, and each measurement was repeated at least three times to ensure reproducibility. The background counts were recorded for the same duration in the absence of the radioactive source and subsequently subtracted from the measured spectra to obtain net counts. The linear attenuation coefficient μ was calculated from the recorded incident and transmitted intensities using the fundamental Beer-Lambert attenuation equation:

$$I = I_0 \exp(-\mu d) \quad (1)$$

Where I_0 is the incident intensity, I is the transmitted intensity, and d is the sample thickness [12, 13]. The mass attenuation coefficient μ_m was subsequently derived by normalizing the linear attenuation coefficient to the measured density of each glass sample according to $\mu_m = \mu/\rho$. The half-value layer, which represents the thickness required to reduce the incident gamma-ray intensity by half, was computed using the expression $HVL = \ln(2)/\mu$, while the mean free path, representing the average distance a photon travels between successive interactions, was obtained from $MFP = 1/\mu$ [12,13]. The radiation protection efficiency, defined as the percentage of incident photons attenuated by the glass material, was evaluated for each sample at a fixed thickness of 0.7 cm using the equation:

$$RPE(\%) = [1 - \exp(-\mu d)] \times 100 \quad (2)$$

Where μ is the linear attenuation coefficient and d is the sample thickness [12, 13]. This comprehensive experimental

approach allowed for the systematic evaluation of all essential shielding parameters and enabled a thorough assessment of the influence of erbium oxide concentration on the gamma-ray attenuation performance of the investigated tellurite glass system.

3. RESULTS AND DISCUSSION

3.1. Density and Molar Volume

The experimentally determined density values for the prepared glass samples are presented in Table 1, revealing a systematic increase from 5.5713 g/cm³ for the undoped specimen (sample A) to 5.6214 g/cm³ for the glass containing 4.5 mol% Er₂O₃ (sample D). This progressive enhancement in density with increasing erbium oxide content can be attributed to several interrelated factors. First, erbium possesses a significantly higher atomic mass (167.26 g/mol) compared to tellurium (127.60 g/mol), which is the primary constituent being replaced in the glass network. The substitution of lighter tellurium atoms by heavier erbium atoms naturally leads to an overall increase in the average molecular weight of the glass composition, thereby contributing to higher density values [7].

Second, the incorporation of erbium ions into the tellurite glass network induces structural modifications that promote a more compact atomic arrangement. The presence of erbium ions, with their relatively high ionic field strength, tends to create stronger bonding interactions with the surrounding oxygen atoms, leading to a densification of the glass matrix [8]. Interestingly, the molar volume also exhibited an increasing trend with erbium doping, rising from 29.05 cm³/mol for the undoped sample to 30.48 cm³/mol for the 4.5 mol% Er₂O₃-doped glass. This simultaneous increase in both density and molar volume may appear counterintuitive at first glance, as these parameters are typically inversely related. However, this behavior can be explained by considering the structural rearrangements occurring within the glass network upon erbium

incorporation. The introduction of Er_2O_3 leads to the conversion of TeO_4 trigonal bipyramids into TeO_3 trigonal pyramids through the creation of non-bridging oxygen atoms, which expands the overall network volume while simultaneously allowing for closer packing of heavier erbium ions [9]. This dual effect results in the observed increase in both density and molar volume, indicating that the structural changes induced by erbium doping are complex and involve modifications to both the short-range and intermediate-range order of the glass network.

3.2. Linear and Mass Attenuation Coefficients

The measured linear attenuation coefficients and mass attenuation coefficients for all glass samples across the investigated photon energy range of 59.5 to 1330 keV are presented in Figure 2.

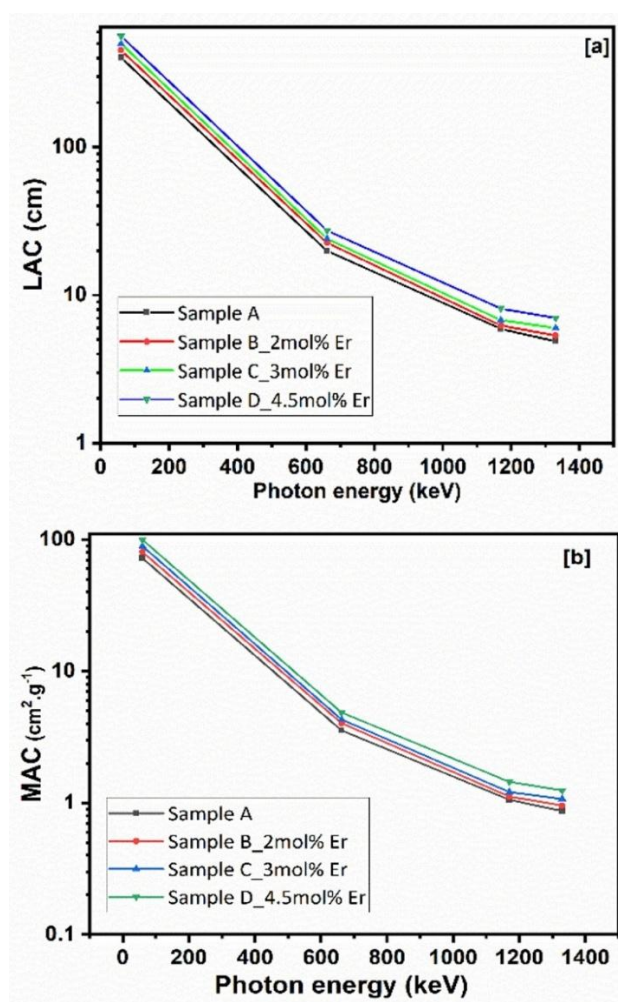


Fig. 2. (a) Measured LAC and (b) MAC values of the prepared glass samples at 59.5, 662, 1170, and 1330 keV.

The results clearly demonstrate that both the LAC and MAC values exhibit a pronounced dependence on both the erbium

oxide concentration and the incident photon energy. At the lowest photon energy of 59.5 keV, the LAC values for samples A through D were determined to be 58.723, 63.894, 68.147, and 72.558 cm^{-1} , respectively, while the corresponding MAC values were 10.540, 11.448, 12.190, and 12.905 $\text{cm}^2\cdot\text{g}^{-1}$. These values progressively decreased with increasing photon energy, as expected from the energy-dependent nature of photon interaction mechanisms. At 662 keV, for instance, the LAC escalated from 19.892 cm^{-1} for the undoped specimen to 27.321 cm^{-1} for the glass containing 4.5 mol% Er_2O_3 , representing an enhancement of approximately 37%. Similarly, the MAC increased from 3.5638 to 4.8602 $\text{cm}^2\cdot\text{g}^{-1}$ across the same compositional range, reflecting a relative improvement of about 36%. This systematic enhancement in attenuation coefficients with increasing erbium content can be attributed to the elevated effective atomic number and increased electron density of the glass system resulting from the incorporation of high-Z erbium ions [10, 11]. The effective atomic number of the glass matrix increases as erbium, which has an atomic number of 68, replaces tellurium, which has an atomic number of 52. This substitution enhances the probability of photoelectric absorption at low photon energies and Compton scattering at intermediate energies, both of which are fundamental mechanisms contributing to photon attenuation. Furthermore, the addition of erbium ions increases the total number of electrons available for interaction with incident photons, thereby improving the overall attenuation capability of the glass [11].

The energy dependence of the attenuation coefficients reveals the dominance of different interaction mechanisms across the investigated energy range. At low photon energies around 59.5 keV, the photoelectric effect is the predominant interaction mechanism, and its probability scales approximately with Z^4/E^3 , which explains the strong enhancement observed with erbium doping. At intermediate energies such as 662 keV, Compton scattering becomes the dominant process, and the attenuation coefficients depend primarily on electron density, which is also favorably influenced by erbium incorporation. At higher energies around 1170 and 1330 keV, pair production begins to contribute, though its contribution remains relatively small within the energy range investigated. The measured MAC values for the present glass system were compared with those reported for other rare-earth-doped glass systems in the literature, including europium-doped, samarium-doped, and dysprosium-doped tellurite and borate glasses [14-16]. The comparison reveals that the present erbium-doped niobium-potassium tellurite-zinc-lead fluoride glasses exhibit superior attenuation characteristics, particularly at low and intermediate photon energies, which can be attributed to the optimized combination of heavy metal oxides and the specific structural features of the present glass composition.

3.3. Half-Value Layer and Mean Free Path

The calculated half-value layer and mean free path values for

all glass samples are presented in Figure 3 as functions of photon energy and erbium oxide concentration. The HVL represents the thickness of a given material required to attenuate incident gamma radiation by fifty percent, while the MFP denotes the average distance a photon travels between successive interactions within the material. Both parameters are inversely related to the linear attenuation coefficient and serve as practical indicators of shielding effectiveness, with lower values indicating superior attenuation performance. The results demonstrate that both the HVL and MFP exhibit a clear decreasing trend with increasing Er_2O_3 concentration across all investigated photon energies.

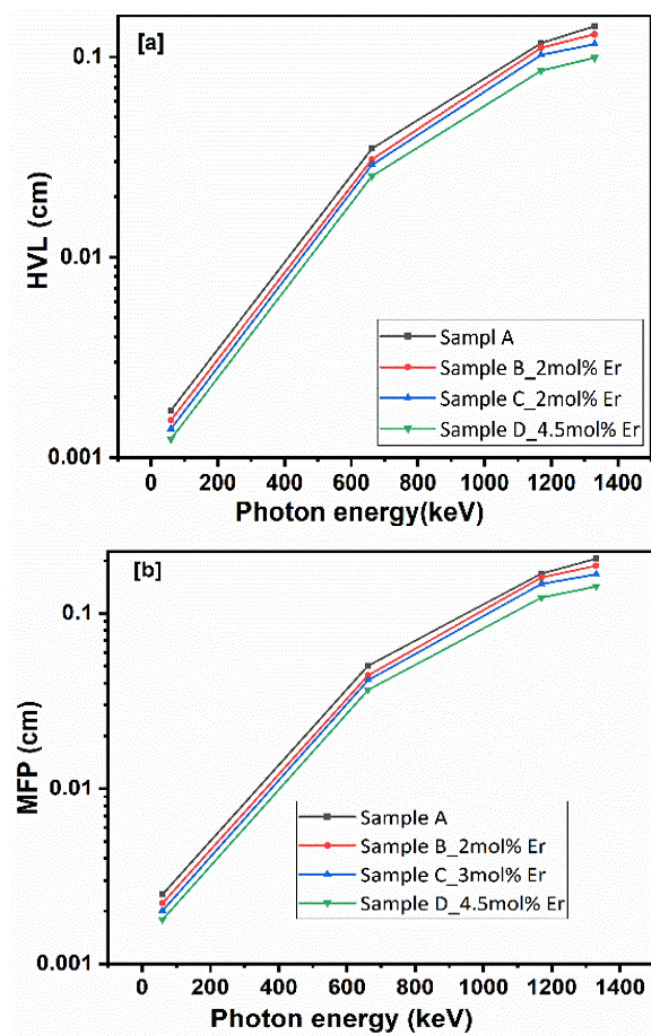


Fig. 3. Measured HVL and MFP values of the prepared glass samples at 59.5, 662, 1170, and 1330 keV.

At 662 keV, for example, the HVL decreased from 0.0348 cm for the undoped sample to 0.02537 cm for the 4.5 mol% Er_2O_3 -doped glass, representing a reduction of approximately 27%. Similarly, the MFP at the same energy was reduced from 0.0503 to 0.0366 cm across the same compositional range, reflecting a decrease of about 27%. These reductions are a direct consequence of the enhanced linear attenuation

coefficients achieved through erbium doping, which increase the probability of photon interaction per unit thickness of the glass material [12, 13]. The photon energy dependence of HVL and MFP reveals that both parameters increase with increasing energy, which reflects the reduced interaction probability of higher-energy photons with the glass matrix. At 59.5 keV, the HVL values were extremely small, ranging from 0.0118 cm for the undoped sample to 0.0095 cm for the 4.5 mol% Er_2O_3 -doped glass, indicating that exceptionally thin layers of the material are sufficient to provide substantial attenuation at low photon energies. At the highest investigated energy of 1330 keV, the HVL values increased to approximately 0.095 to 0.118 cm, reflecting the greater penetrating power of high-energy photons.

The remarkably low HVL and MFP values obtained for the present glass system, particularly for the erbium-doped compositions, are highly advantageous for practical shielding applications as they indicate that only modest thicknesses of the glass material are required to achieve effective radiation attenuation. This is especially important in applications where space constraints or weight limitations are critical considerations [17]. The specimen with 4.5 mol% Er_2O_3 exhibited the superior shielding efficacy, with the lowest HVL and MFP values among all analyzed compositions, which is consistent with its highest density and attenuation coefficients. The observed trends in HVL and MFP align well with the structural modifications induced by erbium incorporation, as the presence of Er^{3+} ions within the tellurite host matrix promotes a more compact and dense glass network with enhanced photon interaction probabilities [18].

3.4. Radiation Protection Efficiency

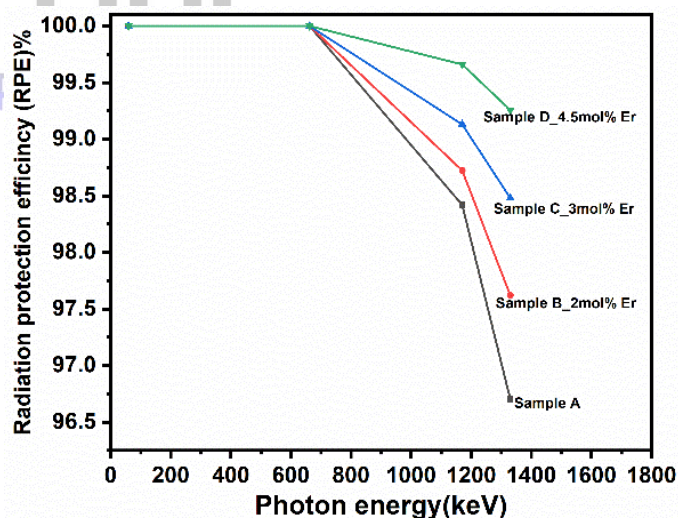


Fig. 4. Radiation protection efficiency (RPE) of the prepared glass samples at 59.5, 662, 1170, and 1330 keV.

The radiation protection efficiency, which quantifies the percentage of incident photons attenuated by a given

thickness of shielding material, was evaluated for all glass samples at a fixed thickness of 0.7 cm across the photon energy range of 59.5 to 1330 keV, and the results are presented in Figure 4. The RPE values demonstrate a strong dependence on both photon energy and erbium oxide concentration, with the highest values observed at low photon energies and the lowest at high photon energies. At 59.5 keV, the RPE values for samples A through D were determined to be 97.23%, 98.41%, 98.72%, and 99.06%, respectively, indicating that even the undoped glass provides excellent attenuation at this energy, while the 4.5 mol% Er_2O_3 -doped glass achieves nearly complete attenuation of incident photons.

The incremental improvement in RPE with erbium doping is more modest at this low energy due to the already high attenuation achieved by the base glass composition, but the enhancement remains significant. As the photon energy increases to 662 keV, the RPE values decrease substantially to 75.21%, 79.38%, 81.67%, and 84.85% for samples A through D, respectively. This reduction is expected due to the decreased interaction probability of higher-energy photons, which penetrate the glass material more readily. Nevertheless, the erbium-doped samples still maintain a clear advantage over the undoped glass, with the 4.5 mol% Er_2O_3 composition providing approximately 10% higher protection efficiency at this energy. At the highest investigated energies of 1170 and 1330 keV, the RPE values further decline to approximately 55-65%, reflecting the greater penetrating power of high-energy gamma radiation. Despite this reduction, the erbium-doped formulations continue to exhibit superior shielding efficacy compared to the undoped specimen across all energies, confirming the beneficial effect of erbium incorporation on the radiation attenuation performance [12].

The observed energy dependence of RPE is consistent with the fundamental physics of photon interactions, where the photoelectric effect dominates at low energies and decreases rapidly with increasing energy, while Compton scattering becomes the primary interaction mechanism at intermediate energies and pair production begins to contribute at higher energies. The significant enhancement in RPE achieved through erbium doping at all photon energies underscores the effectiveness of this approach for improving the shielding performance of tellurite glasses. For practical applications requiring radiation protection, the 0.7 cm thickness employed in this study is relatively modest, and even thicker samples would provide even higher protection efficiencies. However, the results demonstrate that the present glass system, particularly the 4.5 mol% Er_2O_3 -doped composition, can provide excellent shielding performance with minimal material thickness, making it highly suitable for applications where weight, space, or transparency are important considerations [19,20]. The superior RPE values achieved by the erbium-doped glasses compared to other rare-earth-doped systems reported in the literature further validate the effectiveness of the present composition and the beneficial role of erbium ions in enhancing the photon attenuation capability of the tellurite glass network.

4. CONCLUSION

The present investigation systematically evaluated the gamma-ray shielding performance of erbium-doped niobium-potassium tellurite-zinc-lead fluoride glasses across a wide photon energy range from 59.5 to 1330 keV. The experimental results clearly demonstrated that the incorporation of erbium oxide into the tellurite glass matrix significantly enhanced the radiation attenuation capabilities of the prepared samples. As the Er_2O_3 concentration increased from 0 to 4.5 mol%, the density rose from 5.5713 to 5.6214 g/cm³, while the molar volume increased from 29.05 to 30.48 cm³/mol, reflecting the structural modifications induced by the introduction of erbium ions into the glass network. The linear attenuation coefficient and mass attenuation coefficient both exhibited substantial enhancement with increasing erbium content across all investigated photon energies. At 662 keV, for instance, the linear attenuation coefficient increased from 19.892 to 27.321 cm⁻¹, while the mass attenuation coefficient improved from 3.5638 to 4.8602 cm²·g⁻¹. Concurrently, the half-value layer decreased from 0.0348 to 0.02537 cm, and the mean free path reduced from 0.0503 to 0.0366 cm, indicating that thinner layers of the erbium-doped glasses are required to achieve equivalent attenuation compared to the undoped glass. The radiation protection efficiency at 0.7 cm thickness reached approximately 99% at low photon energies for the 4.5 mol% Er_2O_3 -doped sample, demonstrating exceptional shielding performance. Among all compositions, the glass containing 4.5 mol% Er_2O_3 consistently exhibited the most superior shielding efficacy, with the highest attenuation coefficients, lowest HVL and MFP values, and greatest radiation protection effectiveness across the entire energy spectrum. These findings unequivocally establish that erbium-doped tellurite glasses are highly promising candidates for gamma-ray shielding applications, particularly in scenarios where transparent, lightweight, and moldable shielding materials are desired [18,19]. The optimized composition offers a viable alternative to conventional lead-based shields, providing comparable or superior attenuation performance while avoiding the toxicity and mechanical limitations associated with lead. Future work could explore the incorporation of additional rare-earth elements or the optimization of processing conditions to further enhance the shielding properties of these glasses for specific applications in medical, industrial, and nuclear radiation environments.

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

Hanan H. Alshahrani: Formal Analysis, Data Curation, interpretation of results and Original draft preparation; Reman M. Alqahtani: Sample preparation, Experimental Work, Data collection, and interpretation of results. Manar A. Alshafei: Data Curation, Fawzia E. M. Elbashir: Data Curation, Aliyu Adamu: Data Curation,

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