Research Article

Ghada ALMisned, Elaf Rabaa, Duygu Sen Baykal, Erkan Ilik, Gokhan Kilic, Hesham M. H. Zakaly, Antoaneta Ene*, Huseyin Ozan Tekin*

The impact of chemical modifications on gamma-ray attenuation properties of some WO_3-reinforced tellurite glasses

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Abstract: We report the role of the chemical modifications on various gamma-ray attenuation properties of four different tellurite glasses reinforced through WO_3. The chemical compositions and glass densities are used in terms of determining some critical attenuation properties, such as linear and mass attenuation coefficients, half value layer, and effective atomic number values. Based on the rise in density, it was determined that the maximum concentration of WO_3 also resulted in a significant change in the overall gamma-ray absorption properties, when all of the study's findings were examined. It was observed that the glass sample, in which TeO_2 and WO_3 were 40 mol%, had the highest density. It was found that this glass with the highest density has the highest linear attenuation coefficient and mass attenuation coefficient and the lowest half value layer among the four samples specified. This demonstrates that WO_3 inclusion is a functional component that may be used in tellurium glasses and is a suitable material for situations requiring increased gamma-ray absorption properties.

Keywords: tellurite glasses, WO_3, glass shields, gamma-ray attenuation properties, GdF_3

1 Introduction

Radiation fields have expanded widely throughout the years, where people depend in daily bases on their beneficial services in different applications. Medical, nuclear power, and research fields are well known for their increased dependency on ionizing radiation for essential services, as well as they are aware of the hazard and risk posed by radiation [1–3]. Significant chromosomal abnormalities and carcinogenic effects may be caused by a high dosage of radiation. Radiation damage is dependent on the organ's sensitivity as well as the quantity of energy and the type of radiation received [4]. With the discovery of radiations' risk effects, researchers have focused their interest on minimizing the consequences by using suitable radiation shielding materials. Radiation-protection field works widely to protect people and the environment from wide range of radiation industries, by applying principles and guidelines in dealing with different types of radiation. Since various types of radiation, such as alpha, gamma, beta, neutrons, and X-ray radiation, have varied energy levels, the danger associated with them would also vary [5,6]. Consequently, various shielding materials have been provided to users in terms of minimizing the hazardous effects of ionizing radiation. The interaction of different types of radiation would vary

* **Corresponding author: Antoaneta Ene,** Department of Chemistry, Physics and Environment, Faculty of Sciences and Environment, INPOLDE Research Center, Dunarea de Jos University of Galati, 47 Domneasca Street, 800008 Galati, Romania, e-mail: Antoaneta.Ene@ugal.ro
* **Corresponding author: Huseyin Ozan Tekin,** Medical Diagnostic Imaging Department, College of Health Sciences, University of Sharjah, Sharjah, 27272, United Arab Emirates; Computer Engineering Department, Faculty of Engineering and Natural Sciences, Istinye University, Istanbul 34396, Türkiye, e-mail: tekin765@gmail.com
Ghada ALMisned: Department of Physics, College of Science, Princess Nourah Bint Abdulrahman University, P.O. Box 84428, Riyadh 11671, Saudi Arabia
Elaf Rabaa: Medical Diagnostic Imaging Department, College of Health Sciences, University of Sharjah, Sharjah, 27272, United Arab Emirates
Duygu Sen Baykal: Vocational School of Health Sciences, Medical Imaging Techniques, Istanbul Kent University, Istanbul 34433, Türkiye
Erkan Ilik, Gokhan Kilic: Department of Physics, Faculty of Science, Eskisehir Osmangazi University, Eskisehir, 26040, Türkiye
Hesham M. H. Zakaly: Institute of Physics and Technology, Ural Federal University, 620002 Ekaterinburg, Russia; Physics Department, Faculty of Science, Al-Azhar University, Assiut 800008, Egypt

depending on the material, for example, tungsten (W) and lead (Pb) would effectively block gamma radiation, but it is not effective when dealing with neutron radiation type, which needs for stronger, high-density material, such as concrete and borated polyethylene materials [7–9]. Many factors must be considered when selecting shielding materials, though shielding properties can change depending on the stress and heat they experience, causing damage to the material, and thus reducing its ability to protect. Lead shielding material has been commonly used for blocking gamma rays even in various advanced methods, for example, lead glass and clear leaded acrylic are options that create durable transparent shielding that is resistant to shattering [10]. However, the drawback of lead being toxic, having heavy nature, poor flexibility, and low chemical stability, alternative methods have been conducted to withstand those disadvantages [11,12]. Glass-based materials have raised the interest of researchers and radiation-protection technologies. Due to the potential properties of glass being homogenous, transparent, and easy to fabricate, and with the addition of heavy metal oxide, its radiation shielding properties would be enhanced [13–15]. TeO_2 is a glass-forming oxide with a low melting point and a lack of hygroscopic qualities; it is used in a variety of applications due to its non-crystalline structure and its high dielectric constant nature [16]. TeO_2 in particular has a higher density than most glass formers, and when combined with heavy metal oxides, high-density glasses are obtained. Due to this feature, it is frequently used in radiation shielding studies [13,14]. It has been selected in this study for its promising applications in lasers, fibers, non-linear optic devices in addition to its infrared transmission, and high gain density characteristics [17–19]. Due to their high suitability in implementing with different types of heavy metal oxide, a development in radiation shielding properties has been made with WO_3 as it is the second component in our study, which is a type of glass-forming agent; this would make it suitable for maintaining anti-crystallization, high density, and refractive index, as well as extending the glass transition temperature [20]. With the addition of GdF_3, the optical properties of the glass system would improve, and because it is usually used as fluorescent host material, a good performance in gaining high density and high transmittance and the ability of improving the glass stability are achieved [21]. The aim of this research is to investigate the gamma-ray attenuation properties of some tellurite glasses based on TeO_2-WO_3-GdF_3 composition with different elemental mass fractions [22]. We have selected four different glass samples with varying compositions in terms of calculating the radiation shielding parameters, such as linear attenuation coefficient (μ), mass attenuation coefficient (μ_m) and half value layer (HVL), tenth value layer (TVL), and build up factor as a function of the incorporated chemical changes in the glass structure. The findings would contribute to a better understanding of the link between tellurite glasses and their compositions and gamma-ray attenuation qualities.

2 Materials and methods

Some characteristics, particularly for gamma rays [23–28] and neutrons [29–32], allow for the investigation of materials that may be utilized in radiation fields. The quantitative values that would be obtained as a consequence of such a study may provide crucial information about the behavior of the examined material throughout operation. This research sets out to examine the gamma-ray attenuation characteristics of C1, C2, C3, and C4 samples using a glass-based TeO_2-WO_3-GdF_3 [22] system with varying composition. Py-MLBUF [33] was used to calculate the gamma-ray absorption features for energies between 0.015 and 15 MeV. The results of these analyses were then presented in a separate manner using ORIGIN. For each glass sample, we calculated its linear attenuation coefficient, mass attenuation coefficient, and Half value layer as a function of energy. For the energy range of 0.015–15 MeV, we also calculated the effective conductivity, atomic number, and mean free path.

3 Results and discussion

In this study, our purpose was to utilize the four glass samples to investigate radiation shielding abilities as a function of chemical composition and glass configuration to identify the sample with the most effective radiation shielding properties. Figure 1 depicts the variation in the glass densities. As seen in the figure, the elemental configurations listed in Table 1 have a noticeable impact on density. C4 glass has a density value of 6.0485 g/cm^3 when the amount of WO_3 is at its maximum and the amount of TeO_2 is at its minimum. Since density plays an essential role in gamma-ray absorption, the fact that a material having a large density has a high number of electrons in their orbits, where they tend to absorb through their inter interaction with the incoming photon more gamma rays [24]. C4 glass sample was designed by a composition of 40 mol% in TeO_2 and WO_3 and only 20 mol% of GdF_3 has proved to stand out with the highest density among all samples with a density value of

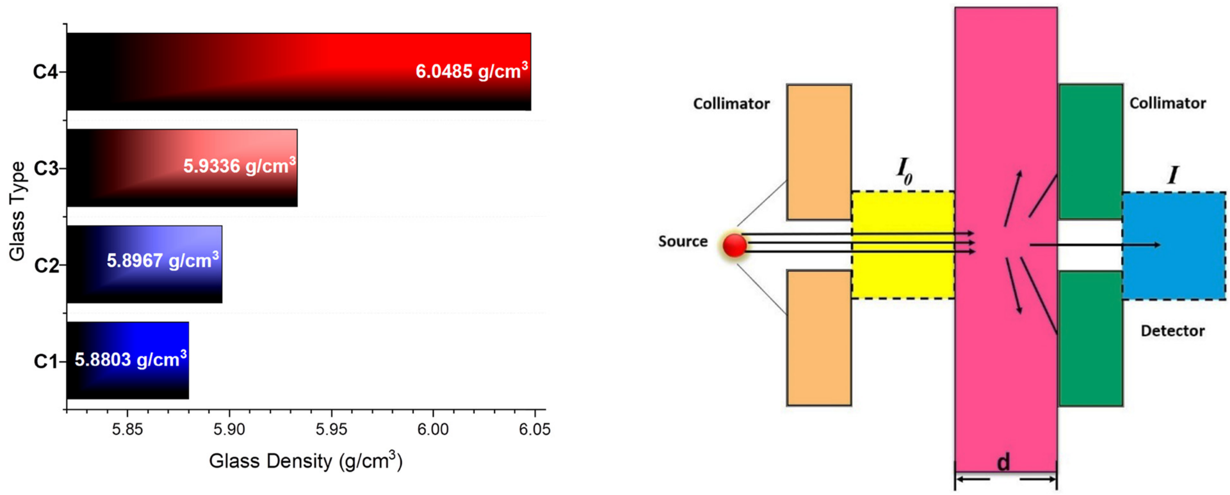

Figure 1: Variation of investigated glass densities and shematic diagram of theoretical setup.

Table 1: C1–C4 glass sample densities with glass compositions [22]

Sample	% mol fraction			Density (g/cm^3)
	TeO_2	WO_3	GdF_3	
C1	50	30	20	5.8803
C2	50	20	30	5.8967
C3	50	40	10	5.9336
C4	40	40	20	6.0485

6.0485 g/cm^3. The same addition of composition in TeO_2 and WO_3 in the tellurite glass system has enhanced the glass density since they share almost similar properties [34,35]. In this work, a calculation of linear attenuation coefficient and mass attenuation coefficient has been conducted. Linear attenuation coefficient is described to be one of the crucial investigation properties for gamma-ray absorption [36]. The attenuation coefficient, on the other hand, represents the penetration ability of a material when an incident photon passes through (see Figure 1). However, the linear attenuation coefficient describes in more detail the fraction of attenuated monoenergetic incoming photon with all the possible interactions including photoelectric effect, and Compton scattering, whether it was completely absorbed by the electrons on the atom's orbit, or half absorbed with the remainder being distributed [37]. Figure 2 depicts the variation in the linear attenuation coefficient with respect to energy. C4 sample was reported to have the highest (μ) value at 1 MeV with a value of 14.958/cm, whereas C3 sample placed second with no significant difference with a value of 14.169/cm. The highest values among the investigated glasses were reported in the C4 sample, which had the highest glass density (Figure 3). This can be explained by the direct relationship of μ value with the material density. Meanwhile, the term mass attenuation coefficient (μ_m) represents the fraction of removed gamma ray per unit mass. This parameter is density independent and can be linked to the elemental structure of the attenuator. Figure 4 depicts the variation in mass attenuation values as a function of responsible gamma-ray energy. The decreasing association between the four samples and energy increased due to the Compton scattering effect. Our findings indicated that the C4 sample had the highest m values among the examined samples. This may be explained by the high level of WO_3 integration into C4's chemical configuration, making it the sample with the highest level of heavy component. For example, C4 showed to have the greatest MAC at 0.4 MeV with a value of 0.14096 cm^2/g. In addition, HVL calculations were conducted to represent the materials' ability to decrease the intensity of the incoming photon to its half value with the minimum thickness possible. A material described as attenuating more effectively has the thinnest achievable thickness. HVL values have an inverse relationship with the attenuation coefficient, which explains the decreasing HVL values as the energy increases. As the photon's energy increases, the probability that a given material's thickness will absorb the energy decreases. Between all glass samples, Figure 4 demonstrates that C4 sample with the lowest value of HVL among all energy levels, with a value of 0.0463 cm at 0.1 MeV, while C3 sample reported to have a close value of 0.0489 cm. Furthermore, another fundamental factor for gamma-ray absorption properties that was investigated in this work is the mean free path. The mean free path values should be as low as possible since they indicate the average path taken by a moving particle between collisions with other particles inside the material, which might represent the attenuation ability of a material

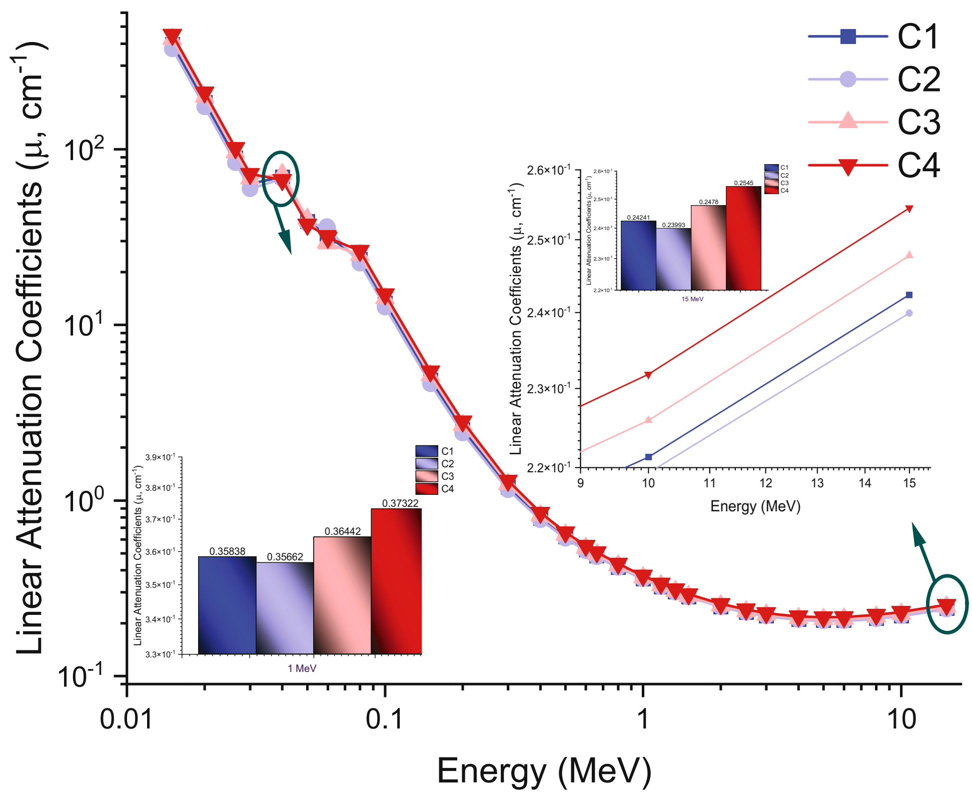

Figure 2: Variation of linear attenuation coefficient (1/cm) with photon energy (MeV) for all C1–C4 glasses.

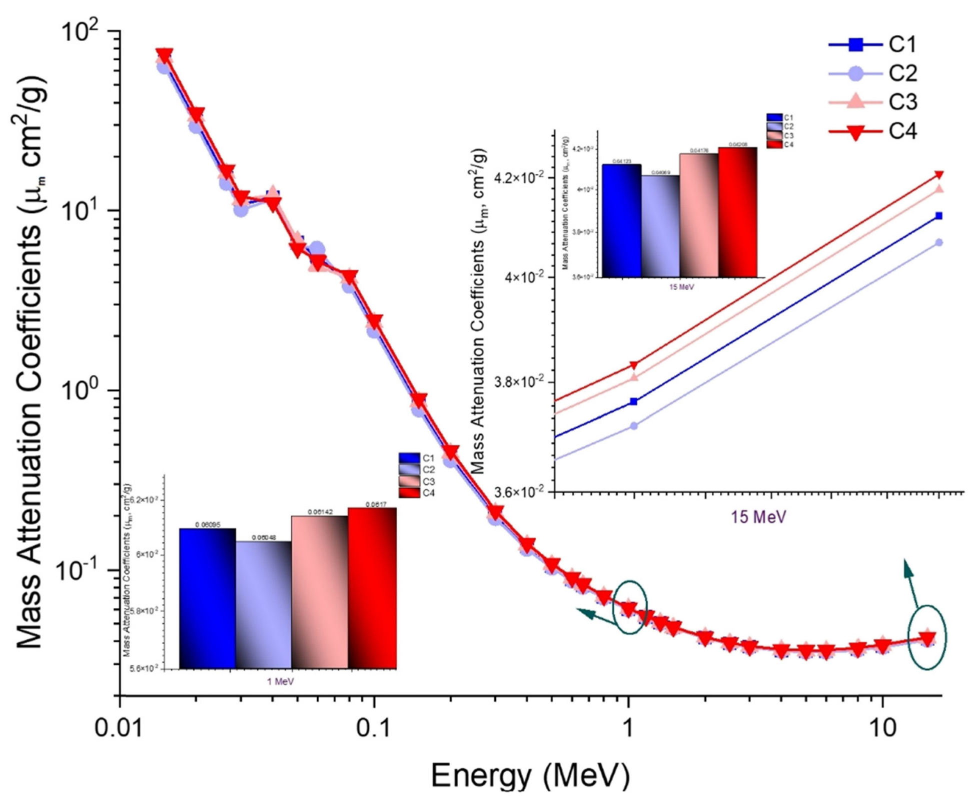

Figure 3: Variation of mass attenuation coefficients (cm^2/g) with photon energy (MeV) for all C1–C4 glasses.

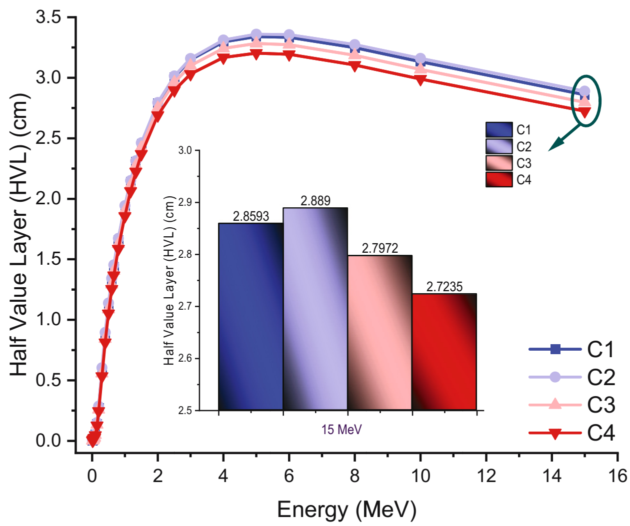

Figure 4: Variation of half value layer (cm) with photon energy (MeV) for all C1–C4 glasses.

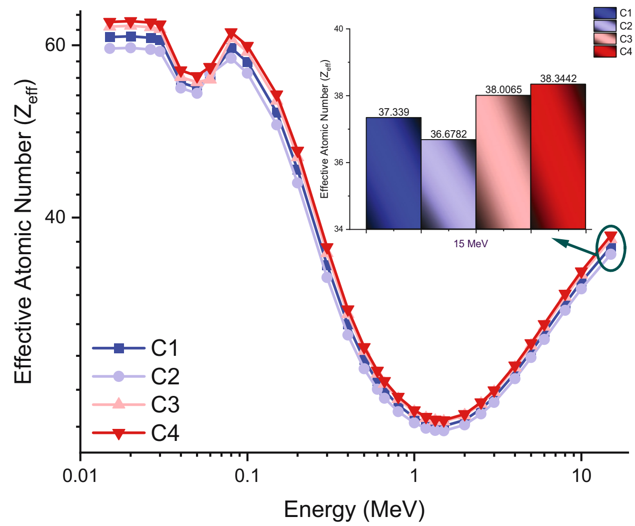

Figure 6: Variation of effective atomic number (Z_{eff}) with photon energy (MeV) for all C1–C4 glasses.

by altering its direction and energy level. Mean free path values change as a function of the photon energy entering the system, as seen in Figure 5. The average distance that a photon travels becomes longer as its energy level increases. Although the C4 sample's mfp value was the lowest of the group, the overall range was rather small. For situations when the MFP is small, this means that a photon is being absorbed by several close-range interactions. With 40 mol% TeO_2 and WO_3 in the tellurite glass system, the C4 sample provides significant advantages as a robust gamma-ray absorber. As an added feature, it is well known that the effective atomic number (Z_{eff}) plays a crucial part in studies of materials' gamma-ray absorption. There are a certain number of electrons in the material's atomic orbits, and this is represented by the Z number [38–40]. Because of the abundance of electrons, a high Z number would be able to interact with an incoming photon, reducing its energy via a collision that may excite or push an electron out of orbit. Figure 6 shows the variation in Z_{eff} values for four glass samples as a function of photon energy. High levels of effective atomic number may be seen in the low photon energy region of the graph, where absorption in the photoelectric effect is taking place. A decrease starts to occur at an energy of 0.1–1.5 MeV, where a clear incline starts to occur from 2 to 15 MeV for all glass samples. C4 sample among all samples proved to have the highest

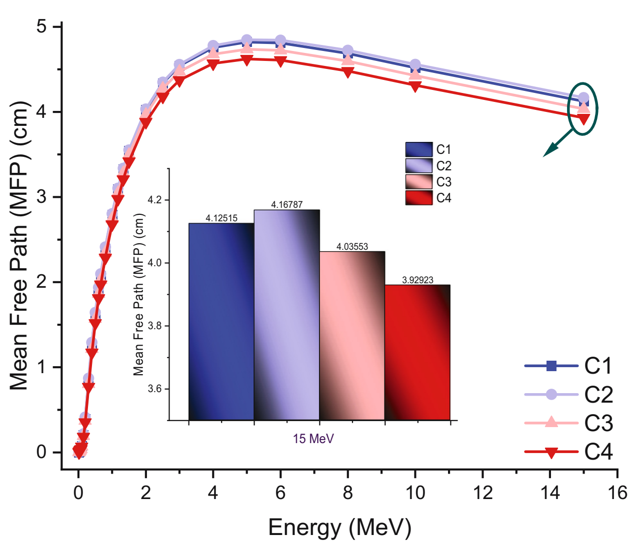

Figure 5: Variation of mean free path (cm) with photon energy (MeV) for all C1–C4 glasses.

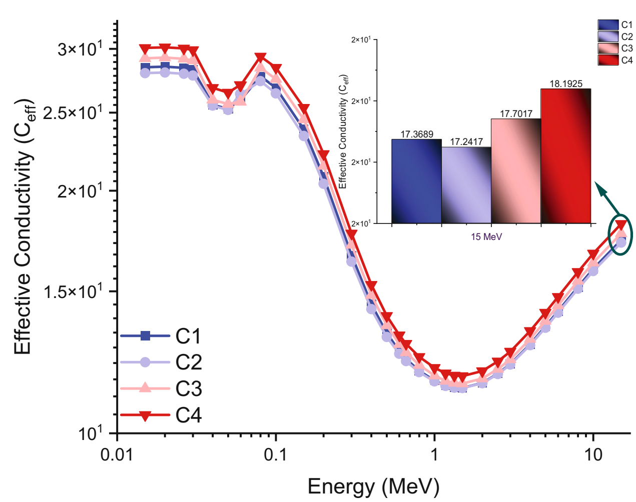

Figure 7: Variation of effective conductivity (C_{eff}) with photon energy (MeV) for all M1–M4 glasses.

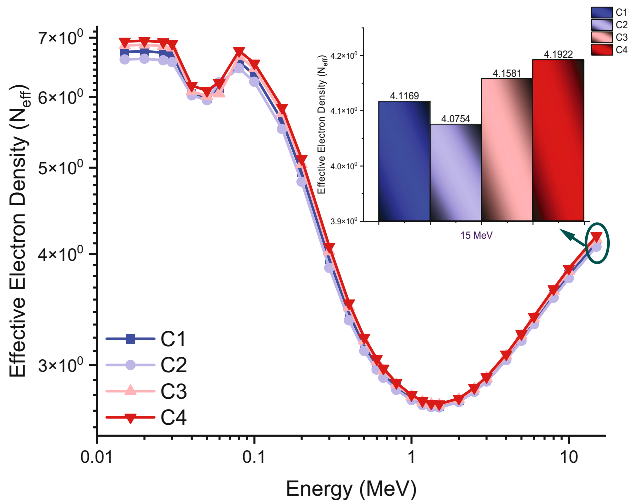

Figure 8: Variation of effective electron density (electrons/g) with photon energy (MeV) for all C1–C4 glasses.

(Z_{eff}) value of 25.1778 at 2 MeV energy level. Figure 7 depicts the variability in effective conductivity (C_{eff}) in all glass samples, where a noticeable and rapid decrease takes place as the photon energy rises, particularly in regions where the photoelectric effect is significant. In contrast, when energy levels increased, C_{eff} demonstrated a rise in high-level energies. Despite the variances, the C4 sample was found to have the highest C_{eff} values of all the samples examined. At 15 MeV, for instance, a value of 18.1925 S/m was obtained for a C4 sample, while a value of 17.3689 S/m was reported for a C1 sample. Due to the fact that effective conductivity and electron density are related, an increase in charge density also leads in an increase in conductivity. Figure 8 represents the effective electron density of the four glass samples in respect of photon energy. Based on the increase in density, it was observed that the highest quantity of WO_3 also produced a noteworthy change in the overall gamma-ray reduction qualities, when all the study's findings were included. This shows that WO_3 incorporation is a functional component that may be employed in tellurium glasses and is a suitable material for circumstances in which gamma-ray absorption qualities must be enhanced.

4 Conclusion

In recent years, the manufacturing of radiation-protection materials has become a significant area of study based on the strategy of increasing the density of glass materials, as shown by the literature. Although this condition may be caused by a variety of factors, the mechanical strength of glass materials, simplicity of manufacture, and spectral permeability in the visible region put these materials in a favorable position. By contributing significantly to radiation-based industrial, medicinal, and research investigations, such materials may drive process quality in an advantageous way. Transparency of the source transporter, for instance, permits the physical status of the resource during transportation and its prompt reaction in case of a suspected contamination, which is especially important in industries where resource carriage is necessary, such as nuclear medicine. On the other hand, after radioactive elements have been safely disposed of, the recycled products should keep their original mechanical properties and corrosion resistance. This avoids the scenarios that would lead to a rise in environmental radioactivity by preventing the contamination of the nucleic waste, which would be held for many years, and preventing it from interacting with the soil. This highlights the significance of developing denser glass structures that may simultaneously improve in other ways, such as in their optical, mechanical, thermal, and gamma-ray absorption capabilities. The aim of this study was to examine the changes caused by some chemical modifications in tellurite glasses, a popular glass group, from the perspective of gamma-ray absorption. Based on the increase in density, it was observed that the highest quantity of WO_3 also produced a noteworthy change in the overall gamma-ray reduction qualities, when all the study's findings were included. This shows that WO_3 incorporation is a functional component that may be employed in tellurium glasses and is a suitable material for circumstances in which gamma-ray absorption qualities must be enhanced.

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Conflict of interest: None.

Ethical approval: The conducted research is not related to either human or animals use.

Data availability statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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