



Theoretical and Experimental Investigation of Gamma Radiation Induced Modifications in Sustainable Biopolymeric Materials.

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Abstract

The current study takes a theoretical and experimental approach to evaluate the interaction of gamma radiation with sustainable biopolymeric materials. The biopolymeric materials' sensitivity to gamma radiation was studied over a variety of radiation doses in order to better understand their behavior and prospective application in radiation-related situations. The effects of gamma radiation were investigated experimentally, and key photon interaction parameters such as the mass attenuation coefficient, linear attenuation coefficient, half-value layer, tenth value layer, and mean free path were calculated theoretically.

The findings demonstrated that gamma radiation has a considerable impact on the performance of the studied biopolymeric materials, with the magnitude of the effects varying depending on the radiation dose used. Theoretical evaluations suggested that these materials had good gamma-ray attenuation properties, and practical findings validated their prospective usage in radiation conditions. The consistency between theoretical and experimental data supports the validity of the approaches used to examine radiation interaction properties.

Overall, this study sheds light on the effects of gamma radiation on sustainable biopolymeric materials, highlighting their potential applications in radiation shielding, sterilization processes, biomedical technologies, and other advanced functional materials. The combined theoretical and experimental approaches help to develop environmentally friendly materials for radiation-related applications.

Keywords: Mass Attenuation Coefficient, Half-Value Layer, Tenth Value Layer

1. Introduction

The growing demand for environmentally friendly materials has prompted substantial study into biopolymeric materials made from renewable biological resources. Biopolymers, unlike traditional synthetic polymers, are biodegradable, biocompatible, and environmentally friendly, making them appealing for a variety of applications such as biomedical engineering, packaging, tissue engineering, environmental remediation, and radiation protection technologies [1-5]. Their distinct molecular

architectures and abundance of functional groups allow for the customization of material qualities while retaining sustainability and ecological compatibility [6, 7].

Gamma radiation is a high-energy electromagnetic radiation that can penetrate matter deeply. Gamma photons interact predominantly with materials via photoelectric absorption, Compton scattering, and pair creation, depending on photon energy and material composition [8-10]. These interactions cause energy to be transferred to the substance, resulting in the formation of free radicals and a variety of physiochemical changes. Such alterations can have a considerable impact on the performance and functionality of polymeric systems, making the study of radiation-material interactions an essential area of research [11-13].

Radiation processing has evolved as a viable and environmentally acceptable method of altering material properties that does not require chemical additions or high-temperature treatments. Polymeric materials exposed to gamma radiation can affect their intermolecular interactions and molecular organization, resulting in changes in material behavior. As a result, gamma radiation has found broad use in sterilization, food preservation, medical device fabrication, waste treatment, and advanced material processing [14-16]. Understanding how sustainable biopolymeric materials respond to gamma radiation is critical for developing their technological uses.

Biopolymeric materials have structural properties that make them particularly susceptible to ionizing radiation. The presence of amino, hydroxyl, carboxyl, and other functional groups promotes interactions with radiation-induced reactive species, potentially affecting the material's stability and performance [17-19]. Previous studies have shown that gamma radiation can alter the physicochemical properties of natural biopolymers, affecting their appropriateness for biomedical, industrial, and environmental applications [20-22]. Such research have emphasized the need of assessing radiation effects in order to maximize material performance in irradiation conditions.

In addition to experimental studies, theoretical evaluation of photon interaction parameters provides useful insights into the radiation attenuation behavior of materials. The mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP) are all often used parameters to examine the interaction of gamma rays with matter [23-25]. These criteria are especially significant in determining the possible suitability of materials for radiation shielding and protection.

Recent advancements in computational methodologies and radiation transport databases have allowed for precise theoretical predictions of gamma-ray attenuation properties over a wide energy range. The combination of theoretical calculations and experimental observations provides a complete method to studying radiation-material interactions and confirming shielding efficacy [26-28]. Such collaborative investigations are critical for generating dependable and long-lasting materials capable of performing efficiently in radiation conditions.

Despite significant development in biopolymer research, there are still very few thorough studies evaluating gamma radiation impacts using both theoretical and experimental methodologies. Furthermore, there is a rising demand to develop environmentally sustainable materials with good radiation interaction properties that can be used as alternatives to traditional shielding materials [29-31]. Sustainable biopolymeric materials have various advantages, including renewability, minimal environmental impact, ease of processing, and the possibility of functional modification, making them intriguing candidates for radiation-related applications [32-34].

As a result, the current work seeks to conduct a comparative theoretical and experimental evaluation of the impacts of gamma radiation on sustainable biopolymers. The study focuses on determining radiation interaction parameters and understanding the materials' sensitivity to gamma radiation. The results of this research are intended to provide useful information for the creation of eco-friendly materials suited for radiation protection, biomedical technologies, sterilization processes, and other advanced functional applications.

2. Experimental Details

2.1 Materials

Gelatin, collagen, silk fibroin, and keratin were chosen as representative sustainable protein-based biopolymeric materials due to their biodegradability, biocompatibility, and diverse biomedical and industrial applications. The materials were sourced commercially and used without additional purification. The elemental compositions and densities of the examined biopolymers were used in theoretical estimates of photon interaction parameters.

2.2 Gamma Ray Attenuation Measurements

The gamma-ray attenuation properties of the biopolymeric materials under investigation were experimentally evaluated utilizing a narrow-beam transmission system. To record the gamma-ray spectra, a NaI(Tl) scintillation detector and a multichannel analyzer (MCA) were used. Before conducting measurements, the detector's energy was calibrated using conventional radioactive sources.

Gamma-ray photons generated by radioactive sources of varying energy were allowed to pass through the biopolymer samples, and their intensities were measured using the NaI(Tl) detector. The experimental setup was intended to reduce dispersed radiation while maintaining a narrow-beam geometry. Spectra for each measurement were gathered to provide appropriate counting statistics, and background radiation was removed from the recorded counts. The Beer-Lambert law [35, 36] was used to determine the linear attenuation coefficient (μ).

$$I = I_0 e^{-\mu t} \quad (1)$$

where I_0 and I denote the initial and final intensities of the photons during the interaction. The material's thickness is also given in centimeters. The sample's linear attenuation coefficient, μ (cm^{-1}), reflects the decreasing likelihood of an incident gamma photon interacting with the target material per unit length [37]. The linear attenuation coefficient (μ) can be expressed as [37]

$$\mu = \frac{1}{t} \ln \frac{I_0}{I} \quad (2)$$

where the absorbance is determined by the density, sample thickness, and Z , and is expressed as $\ln(I_0/I)$. For a sample, the mass attenuation coefficients are obtained by inserting the material's density in equation (2) [37].

$$\mu_m = \frac{1}{\rho} \ln \frac{I_0}{I} \quad (3)$$

in which the density (ρ) is given in terms of g/cm^3 . The mass of each atom in the compound represents the mass attenuation coefficient (μ_m) of that type of compound. The mass attenuation coefficient (μ_m) for the chosen molecule can therefore be expressed as follows: [38]

$$\mu_m = \sum W_i (\mu_m)_i \quad (4)$$

Where, W_i and $(\mu_m)_i$ are the weight fraction and mass attenuation coefficient for the i^{th} constituent element, respectively. W_i for the chemical molecule can be computed using the following formula: [38]

$$W_i = \frac{n_i A_i}{\sum_i n_i A_i} \quad (5)$$

where n_i and A_i stand for the number of formula units and the atomic weight of the i^{th} constituent element, respectively.

2.3 Theoretical Calculations

The theoretical mass attenuation coefficients of the investigated biopolymeric materials were computed using the National Institute of Standards and Technology's (NIST) X-COM photon cross-section database [26]. The calculations were based on the elemental compositions of the materials.

Several gamma-ray shielding parameters were calculated using the MAC values obtained, including: Linear attenuation coefficient (LAC), Half-value layer (HVL), Tenth-value layer (TVL), Mean free path (MFP). The half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP) were computed using the following relationships [39-41].

The HVL and TVL parameters characterize the thickness needed to decrease the photon intensity to 50% and 10% of its initial value, respectively. The bulk thickness of the nanomaterial and the fractional weight of the j th included element are denoted by the quantities w_i and μ_m (in g/cm^2), respectively. The values HVL and TVL describe the thickness needed to decrease the photon intensity to 50% and 10% of its initial value, respectively [42-43].

$$\text{HVL} = \frac{\ln(2)}{\mu} \quad (6)$$

$$\text{TVL} = \frac{\ln(10)}{\mu} \quad (7)$$

Mean free path is a significant quantity that characterizes the average distance a photon travels between two successive collisions with a particle (such as an atom, molecule, or photon). This formula can be used to compute it [44].

$$\text{MFP} = \frac{1}{\mu} \quad (8)$$

The theoretical results were compared to experimental attenuation data from the NaI(Tl) scintillation detector to assess the photon interaction behavior and shielding performance of the examined sustainable biopolymeric materials.

3. Results and discussions

The gamma-ray shielding performance of the investigated biopolymeric materials was assessed using several standard photon attenuation parameters, including the mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP). These characteristics are commonly used to evaluate the interaction of gamma photons with matter and to calculate the radiation shielding capability of materials [45-48].

3.1 Linear Attenuation Coefficient (LAC)

The linear attenuation coefficient (LAC) is a measure of gamma photon attenuation per unit thickness of a material that is directly connected to shielding performance [49-50]. For all samples, LAC values declined steadily as photon energy increased. LAC values at 122 keV were between 0.10983 cm^{-1} for S1 and 0.28241 cm^{-1} for S2. At 1330 keV, LAC values for S1 and S2 fell to 0.04265 cm^{-1} and 0.10974 cm^{-1} respectively. Among the examined samples, S2 had the highest LAC values, suggesting the most gamma photon attenuation per unit thickness, whereas S1 had the lowest. The attenuation order was: $S2 > S4 > S3 > S1$. As a result, S2 had the best shielding performance in terms of photon attenuation.

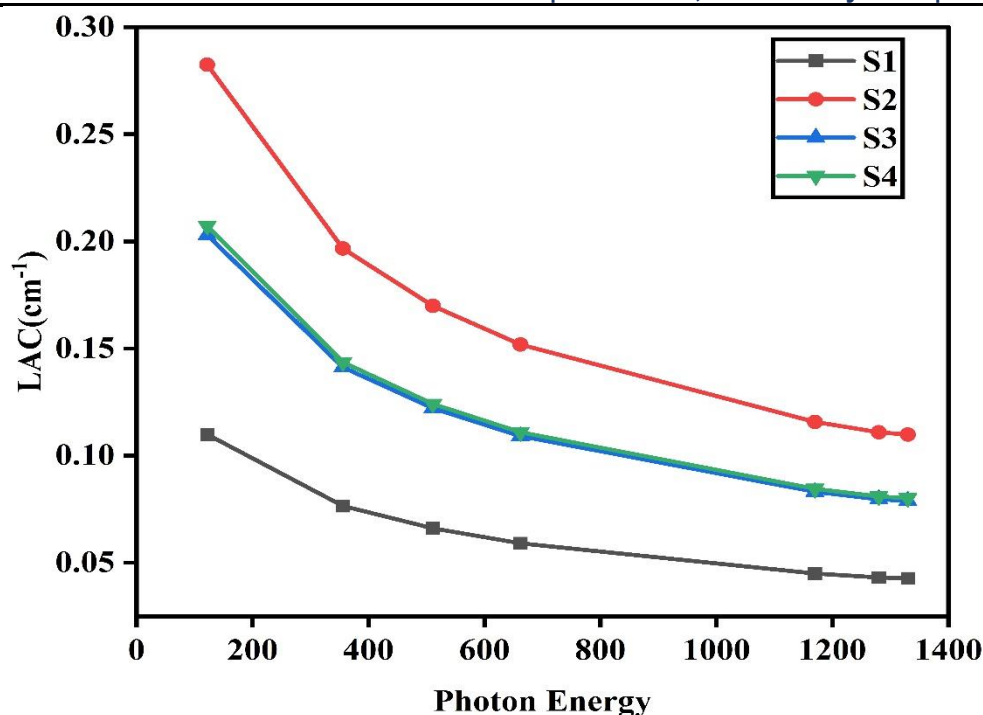


Figure 5 Linear Attenuation Coefficient (LAC) of the Biopolymeric Materials.

3.2 Mass Attenuation Coefficient (MAC)

Table. 2 shows the Biopolymeric Materials mass attenuation coefficient ($\text{cm}^2/\text{g}^{-1}$).

Energy	S1	Exp	S2	Exp	S3	Exp	S4	Exp
122	0.166	0.138	0.149	0.122	0.148	0.119	0.155	0.128
356	0.119	0.086	0.107	0.079	0.106	0.074	0.107	0.064
511	0.099	0.073	0.092	0.066	0.090	0.062	0.093	0.059
662	0.090	0.067	0.083	0.058	0.080	0.051	0.083	0.048
1170	0.067	0.049	0.063	0.044	0.062	0.038	0.063	0.037
1280	0.061	0.038	0.060	0.035	0.058	0.031	0.060	0.035
1330	0.059	0.033	0.060	0.029	0.056	0.023	0.059	0.026

The mass attenuation coefficient (MAC, μm) is a radiation shielding characteristic that measures the probability of gamma-ray contact per unit mass of a material. It is extensively used to assess the attenuation capability of shielding materials because it is independent of the sample's physical dimensions and is primarily determined by photon energy and elemental makeup [51-53]. Higher MAC values correspond to larger photon absorption and scattering probabilities.

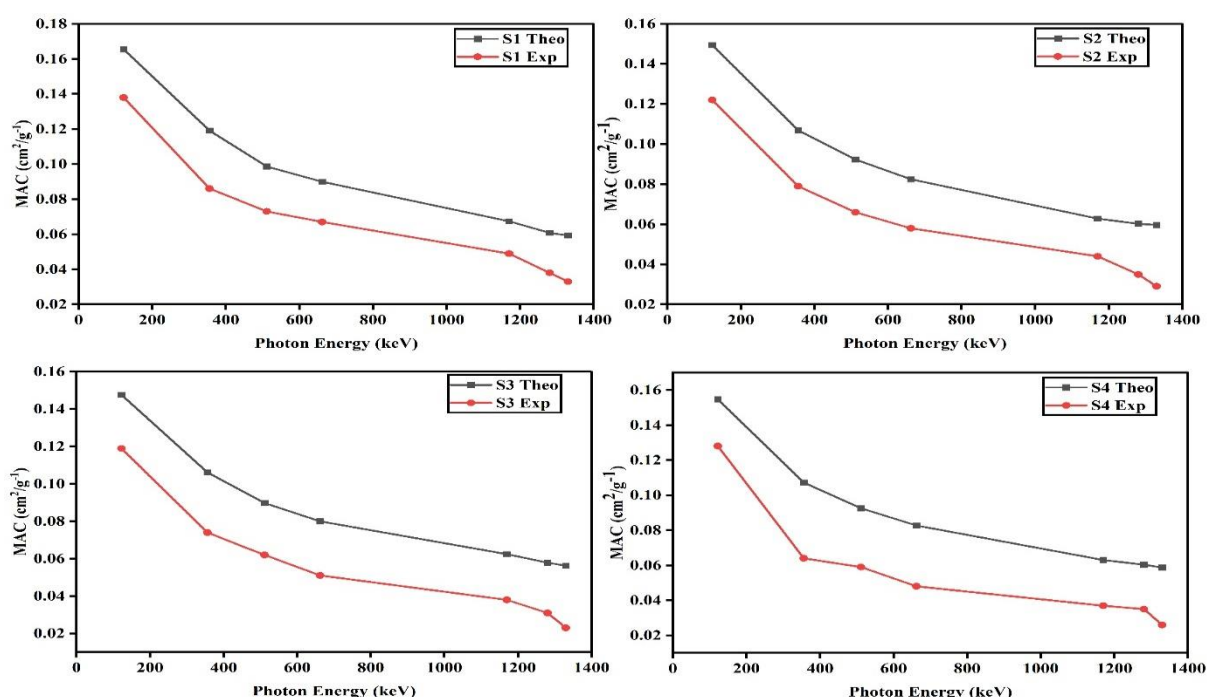
The MAC values of the researched sustainable biopolymeric materials (gelatin, collagen, silk fibroin, and keratin, denoted as S1-S4) were assessed both theoretically and practically over the photon energy range of 122-1330 keV in the current work. The theoretical MAC values were calculated using the National Institute of Standards and Technology's (NIST) XCOM photon cross-section database, which uses the mixture rule and elemental cross-section data to accurately predict photon attenuation coefficients over a wide energy range [55-58]. The MAC values were found experimentally utilizing a narrow-beam transmission setup made up of a NaI(Tl) scintillation detector and a multichannel analyzer (MCA). The Beer-Lambert law was used to determine attenuation by recording the incident and transmitted gamma-ray intensity through each sample [58, 59].

The figure 6 reported theoretical and practical MAC values followed a similar trend, falling steadily with increasing photon energy for all studied substances. This pattern is due to the energy dependency of photon interaction processes. At lower energies (122-356 keV), photoelectric absorption dominates, resulting in very high attenuation coefficients. Photoelectric cross-section is strongly dependent on photon energy and atomic number [61]. As photon energy increases, the photoelectric effect's contribution drops dramatically, and Compton scattering emerges as the major interaction mechanism, resulting in decreased attenuation probabilities and MAC values. At energies greater than 1 MeV, the attenuation coefficients decline even more because high-energy photons have better penetrating capability and lower interaction probability inside the material matrix [61]. Throughout the energy range studied, the experimental results were consistent with the theoretical XCOM computations. Minor differences in theoretical and experimental results can be attributable to factors such as detector resolution, counting statistics, sample thickness fluctuations, geometrical alignment uncertainties, and the contribution of scattered radiation during measurements [62,63]. Nonetheless, the consistency of both datasets demonstrates the dependability of the experimental approach used and justifies the theoretical predictions.

Among the biopolymeric materials tested, sample S4 had the highest theoretical MAC values over the whole energy range, indicating the largest photon interaction probability per unit mass. At 122 keV, S4 had a predicted MAC value of $0.155 \text{ cm}^2 \text{ g}^{-1}$, whereas the actual value was $0.128 \text{ cm}^2 \text{ g}^{-1}$. At 1330 keV, S4 showed the strongest attenuation capabilities, with theoretical and actual MAC values of 0.059 and $0.026 \text{ cm}^2 \text{ g}^{-1}$, respectively. S1 had the lowest attenuation coefficients of any of the energies examined. According to the theoretical MAC results, the total attenuation performance is as follows: $S4 > S2 > S3 > S1$. The higher MAC values reported for S4 indicate improved gamma-ray interaction properties and shielding effectiveness when compared to the other biopolymers studied. The close match between theoretical and actual data confirms that XCOM-based calculations may reliably predict the gamma-ray attenuation behavior of sustainable biopolymeric materials. As a result, these materials have enormous potential for use in radiation shielding systems, biomedical technologies, sterilization processes, and ecologically friendly radiation-protection materials.

Figure 6 Theoretical and experimental results of Biopolymeric Materials for MAC.

3.3 Half-Value Layer (HVL):



The half-value layer (HVL) is the thickness needed to lower incident photon intensity by 50% [64]. Lower HVL values indicate better shielding performance since less material thickness is required. The HVL values for all samples increased as photon energy increased, indicating that high-energy photons have a larger penetrating ability. S2 had the lowest HVL values across all energies, whereas S1 had the greatest. For instance, at 122 keV, the HVL values were 2.454 cm (S2), 3.344 cm (S4), 3.415 cm (S3), and 6.311 cm (S1). At 1330 keV, the readings jumped to 6.316 cm (S2), 8.653 cm (S4), 8.795 cm (S3), and 16.251 cm (S1). The HVL based shielding performance is as follows: $S2 > S4 > S3 > S1$. Because lower HVL values are preferable, S2 requires the least radiation protective thickness.

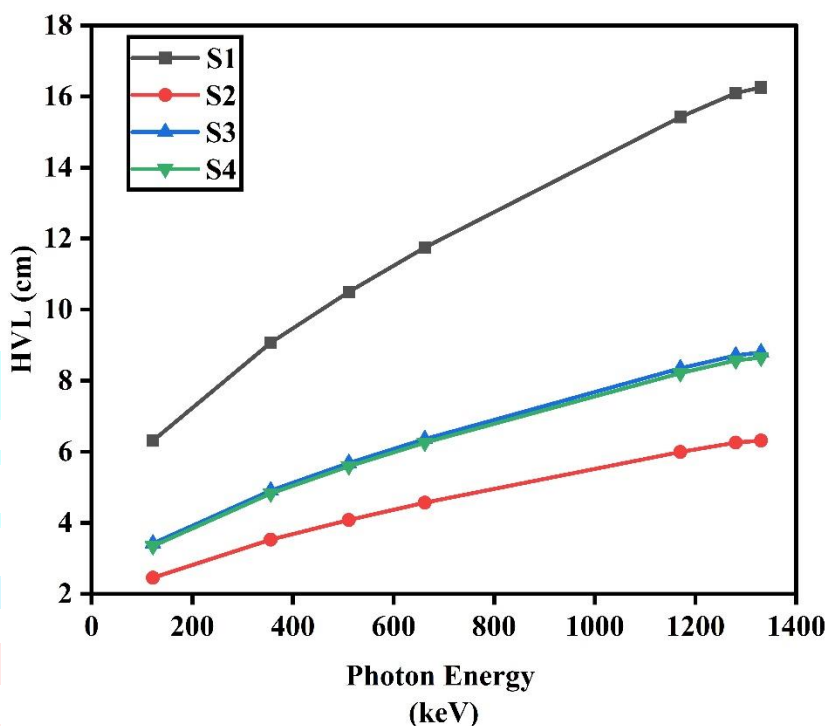


Figure 8 Half Value Layer (HVL) of the Biopolymeric Materials.

3.4 Tenth-Value Layer (TVL):

The TVL denotes the thickness required to lower photon intensity to one-tenth of its original value [65]. Lower TVL values, like with HVL, imply superior shielding capability. Because high-energy photons have a lower contact probability, TVL values increase with increasing photon energy. S2 had the lowest TVL values on average, whereas S1 had the highest. TVL values at 122 keV were 8.153 cm (S2), 11.110 cm (S4), 11.345 cm (S3), and 20.965 cm (S1). They rose to 20.982 cm, 28.743 cm, 29.217 cm, and 53.984 cm at 1330 keV. The TVL rankings were $S2 > S4 > S3 > S1$. As a result, among the materials examined, S2 had the most efficient photon attenuation.

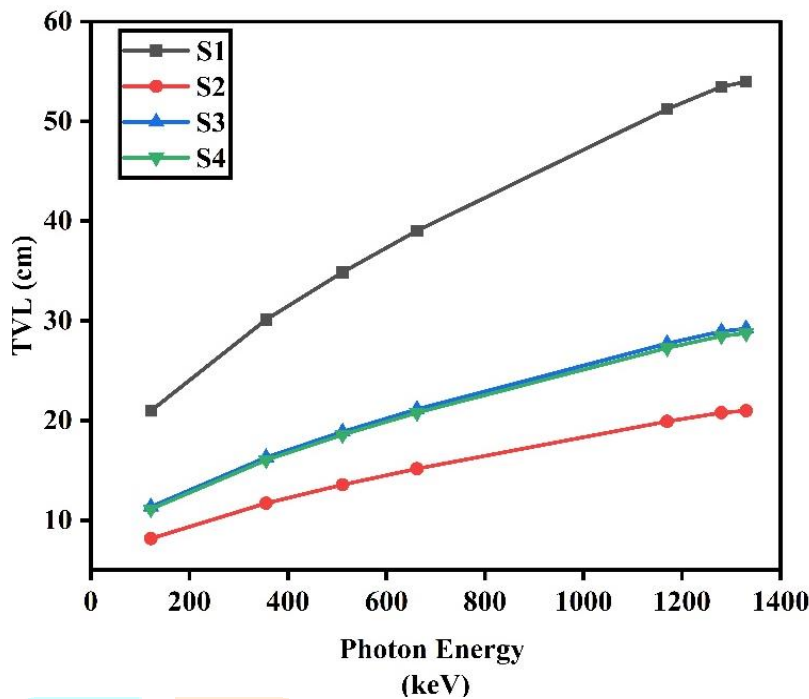


Figure 9 Tenth Value Layer (TVL) of the Biopolymeric Materials.

3.5 Mean Free Path (MFP):

The mean free path (MFP) is the average distance a photon travels between successive interactions in a material [66-67]. Lower MFP values indicate increased contact probabilities and superior shielding efficiency. MFP increased with increasing photon energy in all samples because high-energy photons travel further before interacting with matter. S2 showed the lowest MFP values, whereas S1 had the highest. At 122 keV, MFP values ranged from 3.541 cm (S2) to 9.105 cm (S1). At 1330 keV, the readings rose to 9.112 cm, 12.483 cm, 12.689 cm, and 23.445 cm, respectively. The MFP trend was as follows: $S2 < S4 < S3 < S1$. Because lower MFP values suggest better shielding performance, S2 had the best gamma-ray interaction properties.

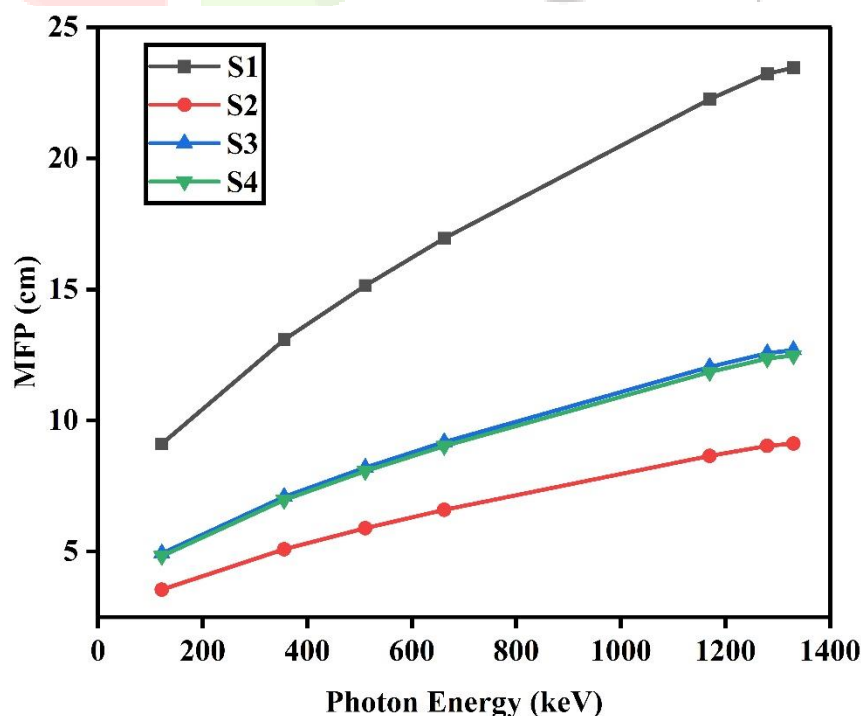


Figure 7 The mean free path (MFP) of the Biopolymeric Materials.

Conclusion

The present research is a complete theoretical and experimental investigation of the interaction of gamma radiation with sustainable biopolymeric materials, specifically gelatin, collagen, silk fibroin, and keratin. Important shielding measures such as mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP) were used to analyze gamma-ray attenuation qualities over a wide photon energy range. The findings demonstrated that attenuation behavior is strongly dependent on both photon energy and material composition. MAC and LAC values declined with increasing photon energy for all examined materials, indicating a shift from photoelectric absorption dominance at low energies to Compton scattering at intermediate and high energies. In contrast, HVL, TVL, and MFP values rose with photon energy, indicating that high-energy gamma photons have greater penetrating capability.

Among the tested biopolymeric materials, sample S2 had the best gamma-ray shielding performance, with the greatest LAC values and the lowest HVL, TVL, and MFP values across the energy range. Sample S4 had the highest MAC values, indicating a larger chance of photon contact per unit mass. The strong agreement between theoretical calculations produced from the XCOM database and actual measurements performed with the NaI(Tl) scintillation detector justifies the reliability of the methodology used and confirms the accuracy of the photon interaction parameters assessed.

Overall, the results show that sustainable biopolymeric materials have significant gamma-ray attenuation capabilities while maintaining biodegradability, biocompatibility, and environmental friendliness. These properties make them potential candidates for use in radiation shielding, biomedical devices, sterilization technologies, packaging systems, and other sophisticated functional materials. The current study adds vital information to the development of environmentally friendly radiation protection materials and demonstrates the potential of natural biopolymers as long-term alternatives for future radiation-related applications.

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