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Assessment of linear, mass attenuation coefficients, and effective atomic numbers in some polymers for use as gamma-ray shields

S. A. Abd El Azeem[1,2]

[(1)] *Physics Department, Faculty of Women for Arts, Science and Education, Ain Shams University, Cairo 11757, Egypt*

[(2)] *Physics Department, College of Sciences and Humanities, Prince Sattam Bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia*

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ABSTRACT

In this study, a Geiger-Muller counter was used as a detector to measure the linear and mass attenuation coefficients (μ_m) for several polymers, including polypropylene (PP), polyethylene terephthalate (PET), high density polyethylene (HDPE), and polystyrene (PS). It was found that the linear attenuation coefficients were 8.6136, 35.1, 9.1169, 4.496 cm^{-1} for PP, PET, HDPE, and PS, respectively. Also, the mass attenuation coefficients (μ_m) were 10.074, 36.5, 9.698, 4.68 cm^2/g for PP, PET, HDPE, and PS, respectively. Theoretically, the total atomic, electric cross sections, the effective atomic numbers (Zeff), HVL and TVL were computed using the values of mass attenuation coefficients (μ_m) that were obtained for the samples under study. The chosen polymers' theoretical values were found to be in perfect agreement with the earlier literature. The current study concluded that Polyethylene Terephthalate (PET) is the best shielding polymer material because it has higher μ_m values than the other polymer materials.

INTRODUCTION

It is a significant task to protect living organisms and other systems from the harmful effects of ionizing radiations such as gamma rays, which is why radiation protection has become one of the most important topics in recent decades due to the variety of applications for radioactive materials. So, to prevent these negative effects, proper shielding must be applied. It is common knowledge that materials with high atomic number elements (like Ba, Pb, and Bi) are used to attenuate gamma rays. Low atomic number materials, like polymers and plastics, are frequently used in medical applications as tissue equivalents and phantom materials [1-6]. In both primary and secondary defense against gamma radiation, polymers are crucial. Due to their numerous beneficial characteristics, including softness, insulation, elasticity, and low weight, polymers are widely used in a variety of industries. Low-Z polymer materials such as C-, H-, and O-based, are not flammable, have a low weight, are less expensive, are more stable at high temperatures, and can be used on a large scale [7].

The two most important and crucial parameters used in the study of gamma rays are the linear and mass attenuation coefficients. The physical state and composition of the material affect these parameters. The energy of the incident gamma radiation, the atomic number, the density of the elements in the shielding material, and the thickness of the shielding all affect how well a material blocks gamma rays [8-10]. The goal of the current study is to investigate some polymers' effective atomic numbers and mass attenuation coefficients. The calculated results and those found in the literature were compared for the purpose of the system validation.

Theoretical background

Gamma-ray shielding parameters

Linear and mass attenuation coefficient

Gamma radiation is primarily absorbed by Compton, photoelectric, and pair production interactions when it travels through matter. Thus, as the thickness of the absorbing material increases, the radiation's intensity decreases. The intensity will be I as the radiation is

Corresponding author: samah.zy2@gmail.com

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absorbed by the material $I(x)$. The Beer-law Lambert's provides the formula for intensity $I(x)$ as follows:

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

where I_0 is the beam's initial intensity, $I(x)$ is the intensity transmission to thickness x through an absorber and the absorbing material's linear attenuation coefficient is μ.

Rearranging equation (1) and taking the logarithm of both sides results in the expression

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

By dividing the linear absorption coefficient by the material density (g/cm^2), which is known as the mass absorption coefficient (μ_m), the relationship between radiation and material density is made clear [11].

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

The following rule of mixture equation is used to produce polymers:

$$(\mu_m)_{\text{Polymer}} = \sum_i w_i (\mu_m)_i \quad \textbf{(4)}$$

where is$(\mu_m)_i$ the mass attenuation coefficient for each individual element in the polymer and w_i is the fractional atomic mass of the elements which is given by:

$$W_i = \frac{ni\ Ai}{\sum_j nj\ Aj} \quad \textbf{(5)}$$

Where n_i is the number of formula units and A_i is the *i*th element's atomic weight. The table in reference [12] includes the μ_m values for elements (Z=1-92) and a few other substances over a wide energy range of 1 keV–20 MeV.

Effective atomic number

The effective atomic number Z_{eff} of a material composed of different elements can be calculated using the following relation [13]:

$$Z_{eff} = \frac{\sigma t}{\sigma e} \quad \textbf{(6)}$$

Where σ_t and σ_e stand for the total atomic and electric cross sections, respectively. The total atomic cross-sections(σ_t) can be calculated using the relation given below [14]:

$$\sigma_t = \frac{1}{N_A}\frac{(\mu_m)polymer}{\sum_i Wi/Ai} \quad \textbf{(7)}$$

The letter N_A stands for Avogadro's number. The total electric cross-section (σ_e) is given by the formula below [11]:

$$\sigma_e = \frac{1}{N_A}\sum_i \frac{fi\ Ai}{Zi}(\mu_m)i \quad \textbf{(8)}$$

where Z_i is the i_{th} element's atomic number, and f_i is the number of atoms that belong to element *i* in the mixture or compound.

Half-value layer (HVL) and tenth value layer (TVL)

HVL and TVL are effective radiation-shielding parameters that reduce radiation intensity by factors of 0.5 and 0.1 of the initial intensity level, respectively [15].

$$HVL = \frac{\ln 2}{\mu} \quad \textbf{(9)}$$

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

MATERIALS AND METHODS

In the current study, 20 circular samples of polymers (Polypropylene, Polyethylene Terephthalate, High Density Polyethylene, and Polystyrene) with increasing thickness were prepared for each element, figure 1. Three measurements with a micrometer screw gauge were taken to determine the average thickness of each circular sample.

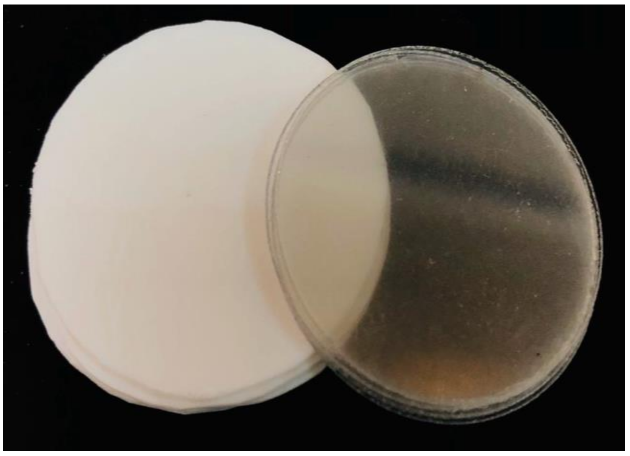

Fig. (1): Some types of samples

Geiger Muller counters were used to measure the count rate of radiation for all samples. High voltage (900–1000 V) was applied to the counters through preamplifiers, which were then connected to amplifiers and discriminator-based ADCs (analogue to digital converter), figure 2.

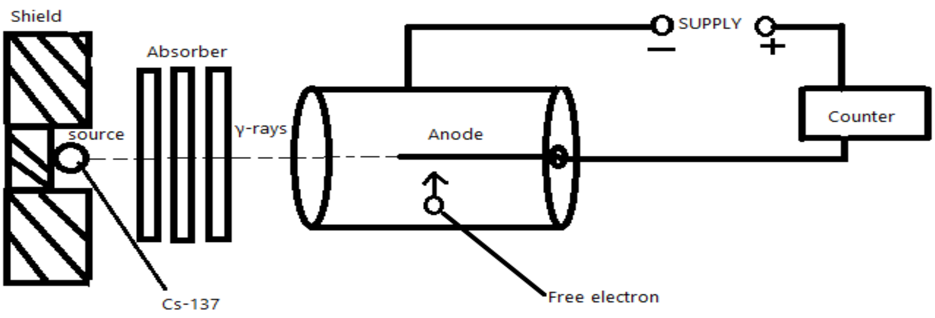

Fig. (2) Schematic view of the experimental set-up

RESULTS AND DISCUSSION

One of the most crucial areas of basic physics is the investigation of gamma radiation interactions with various polymer types. Applied nuclear radiation fields like nuclear radiation therapy, radiation health physics, shielding for nuclear reactors, storing radioactive materials, etc. also place a premium on nuclear gamma radiation shielding materials. As a result, using a Cs-137 gamma source, the linear mass absorption coefficients of gamma radiation for polypropylene, polyethylene terephthalate, high density polyethylene, and polystyrene were measured.

Table 1 displays the molar mass values for polymers based on their chemical formulas. The molar mass of these samples changes along with their chemical composition, it can be inferred.

Table (1): The densities and chemical composition of polymer materials.

Polymer materials	Chemical formula	Density g/cm^3	Molar mass (gmol^{-1})
Polypropylene (PP)	C_3H_6	0.855	42
Polyethylene terephthalate (PET)	$C_{10}H_8O_4$	1.389	192
Polyethylene (HDPE)	C_2H_4	0.94	28
Polystyrene (PS)	C_2H_3	0.96	27

By using a Geiger counter to measure the incident photon intensity ($\boldsymbol{I_0}$)and the photon intensity ($\boldsymbol{I}$) after they have passed through samples with a thickness ($\boldsymbol{x}$), one can calculate the linear attenuation coefficient quantity (μ). Table 2 shows the results of the calculations for the mass absorption coefficient (μ_m) and linear absorption coefficient (μ) for the Polypropylene (PP) sample at various thicknesses. It was obvious that there is a significant variation in the values of mass absorption coefficient and linear absorption coefficient due to the existence of impurities in the samples. The relationship between $\mathbf{ln}\,(\frac{I_0}{I})$ and the various levels of polypropylene sample thickness is depicted in Figure 3. The results show that gamma ray intensity decreases as shield thickness increases; this behavior is perfectly consistent with the equation's theoretical assumptions (1). In general, the findings broadly concur with those of earlier studies, [16].

Table (2): Calculations of the linear and mass absorption coefficient for samples made of polypropylene

X (cm)	μ ($\mathrm{cm^{-1}}$)	$\mu_m = \frac{\mu}{\rho}$ (cm^2/g)
0.015	128.60 $\pm$ 25.72	150.40 $\pm$ 30.08
0.030	78.30 $\pm$ 15.66	91.50 $\pm$ 18.3
0.045	50.80 $\pm$ 10.16	59.40 $\pm$ 11.88
0.060	39.50 $\pm$ 7.90	46.10 $\pm$ 9.22
0.075	33.40 $\pm$ 6.68	39.06 $\pm$ 7.81

For the various thicknesses of the Polyethylene Terephthalate samples, the calculations for the linear absorption coefficient (μ) and mass absorption coefficient (μ_m) are shown in Table 3. Figure 4 shows a plot of $\mathbf{ln}\left(\frac{I_0}{I}\right)$ against various absorber material thicknesses for polyethylene terephthalate samples. The outcomes were contrasted with those reported in the literature using other techniques [17].

Table (3): Calculations for the polyethylene terephthalate samples' linear and mass absorption coefficients

X (cm)	μ ($\mathrm{cm^{-1}}$)	$\mu_m = \frac{\mu}{\rho}$ (cm^2/g)
0.009	107.80 $\pm$ 21.56	77.61 $\pm$ 15.52
0.018	105.56 $\pm$ 21.11	75.95 $\pm$ 15.19
0.027	85.62 $\pm$ 17.12	61.64 $\pm$ 12.33
0.036	66.70 $\pm$ 13.34	48.02 $\pm$ 9.60
0.045	51.80 $\pm$ 10.36	37.29 $\pm$ 7.46

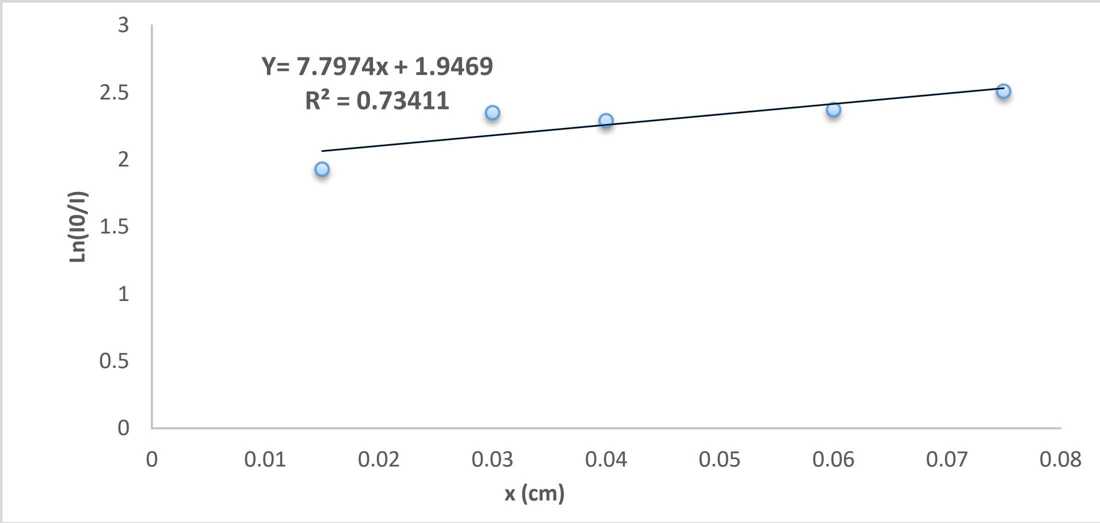

Fig. (3): Plot of ln(I_0/I) versus the thickness of the PP material

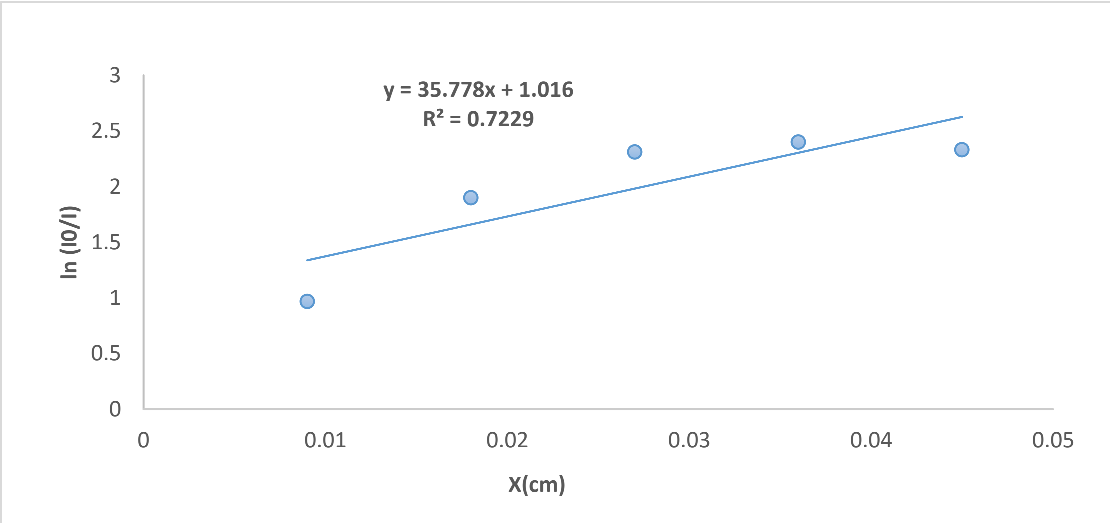

Fig. (4): Plot of ln(I_0/I) versus the PET material thickness

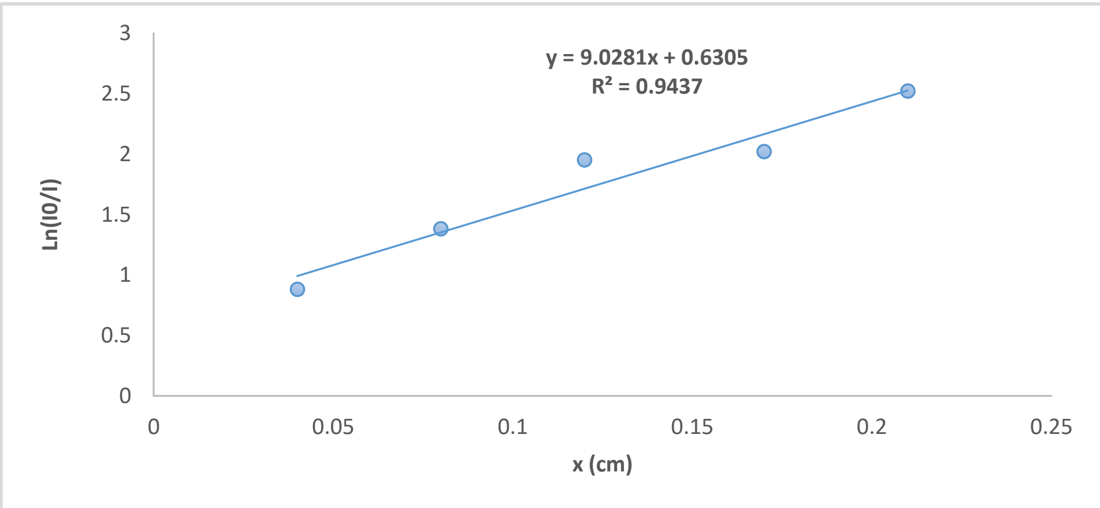

Fig. (5): Plot of ln(I_0/I) versus the thickness of the HDPE material

For the various thicknesses of the high-density polyethylene samples, the calculations for the linear absorption coefficient (μ) and mass absorption coefficient (μ_m) are shown in Table 4. The relationship between the various high density polyethylene sample thicknesses and $\ln\left(\frac{I_0}{I}\right)$ is shown in Figure 5.

Table (4): Calculations of the linear coefficient and mass absorption coefficient for high-density polyethylene samples

X (cm)	μ (cm^{-1})	$\mu_m = \frac{\mu}{\rho}$ (cm^2/g)
0.04	20.60 $\pm$ 4.00	21.98 $\pm$ 4.40
0.08	16.04 $\pm$ 3.21	17.04 $\pm$ 3.41
0.12	15.70 $\pm$ 3.14	16.68 $\pm$ 3.33
0.17	11.88 $\pm$ 2.38	12.62 $\pm$ 2.52
0.21	11.72 $\pm$ 2.34	12.45 $\pm$ 2.49

For samples of various polystyrene thickness, the calculations for the linear absorption coefficient (μ) and mass absorption coefficient (μ_m) are shown in Table 5. The relationship between the various polystyrene sample thicknesses and $\ln\left(\frac{I_0}{I}\right)$ is depicted in Figure 6.

Table (5): Calculations for the polystyrene samples' linear and mass absorption coefficient

X (cm)	μ (cm^{-1})	$\mu_m = \frac{\mu}{\rho}$ (cm^2/g)
0.03	19.30 $\pm$ 3.86	20.10 $\pm$ 4.02
0.06	18.60 $\pm$ 3.72	19.30 $\pm$ 3.86
0.09	17.40 $\pm$ 3.48	18.12 $\pm$ 3.62
0.12	11.10 $\pm$ 2.22	11.50 $\pm$ 2.30
0.12	7.00 $\pm$ 1.40	7.29 $\pm$ 1.46

The value of $\ln\left(\frac{I_0}{I}\right)$ which corresponds to each thickness of the sample and the straight line joining the plotted points are the parameters that best fit a least squares curve, as can be seen in all the Figures. The attenuation constants μ and μ_m are calculated using the values of the slope m and c as shown in Table 6. The equation to the fitting straight line is shown on the graphs, and the coefficient of x is the slope (m), while the equation's constant is the intercept on the y-axis (c) [18].

Table (6): Gamma ray attenuation coefficients for various absorbers

Samples	density(ρ) g/cm^3	Slope (m)	Y- intercept (c)	μ (cm^{-1})	$\mu_m = \mu/\rho$ (cm^2/g)
PP	0.85	7.80	1.95	8.61	10.07
PET	1.38	35.78	1.02	35.10	36.50
HDPE	0.94	9.03	0.63	9.12	9.70
PS	0.96	3.87	0.78	4.50	4.68

By using equations (6), (7), and (8), the calculated values of total atomic scattering cross-sections, electronic scattering cross-sections, and effective atomic numbers Z_{eff} for all the chosen polymers are displayed in Table 7. The selected polymers are made up of a variety of constituent elements in a range of weight fractions and Z_{eff} values. Additionally, it is evident that the μ_m values for Polystyrene and Polyethylene Terephthalate (PET) are significantly different (PS).

Figure 7 shows the plotted values of the effective atomic numbers Z_{eff} and the mass attenuation coefficient m. The polyethylene terephthalate (PET) material was found to have the highest values of m and Z_{eff}. Therefore, among the chosen polymer materials, it can be used as the best shielding polymer material.

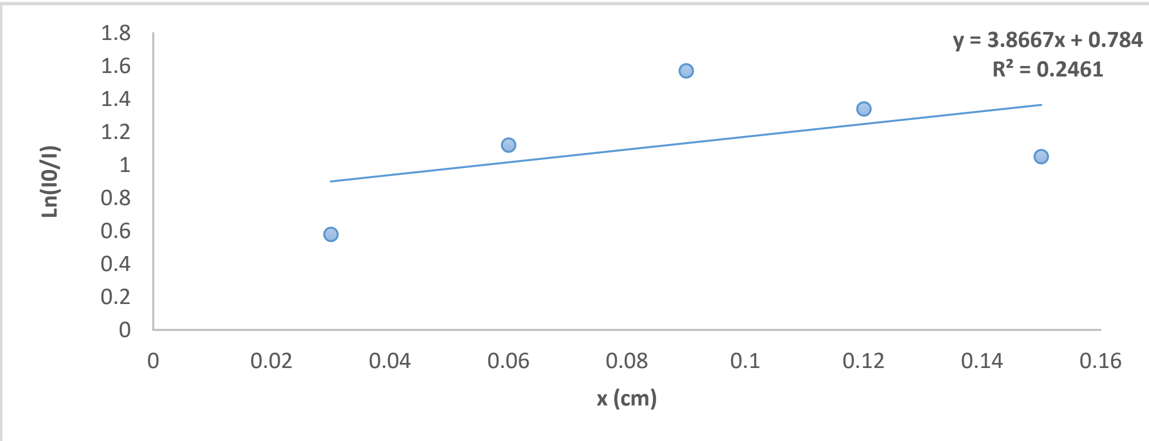

Fig. (6): Plot of the PS absorber material thickness versus ln (I_0/I)

Calculating the half-value layer and tenth value layer thicknesses is a different method of evaluating the shielding performance of the materials under investigation. Table 8 and Figure 8 both display the variation in HVL and TVL of the chosen materials. The material made of polyethylene terephthalate (PET) was found to have the lowest HVL and TVL values. As a result, it can be used as the best shielding polymer material among the ones that were chosen.

Table (7): The effective atomic numbers and mass attenuation coefficients for various polymer samples.

Name of material	Mass absorption coefficient μ_m cm^2/g	Total atomic cross-section σ_t (cm^{-2})	Total electric cross-section σ_e(cm^{-2})	Effective atomic number Z_{eff}
PP	10.07	$7.9\,0x\ 10^{-23}$	$9.04x\ 10^{-24}$	8.74
PET	36.50	$5.32\ x\ 10^{-22}$	$1.96\ x\ 10^{-23}$	16.56
HDPE	9.70	$7.55\ x\ 10^{-23}$	$8.47\ x\ 10^{-24}$	8.91
PS	4.68	$4.24\ x\ 10^{-23}$	$8.47\ x\ 10^{-24}$	5.00

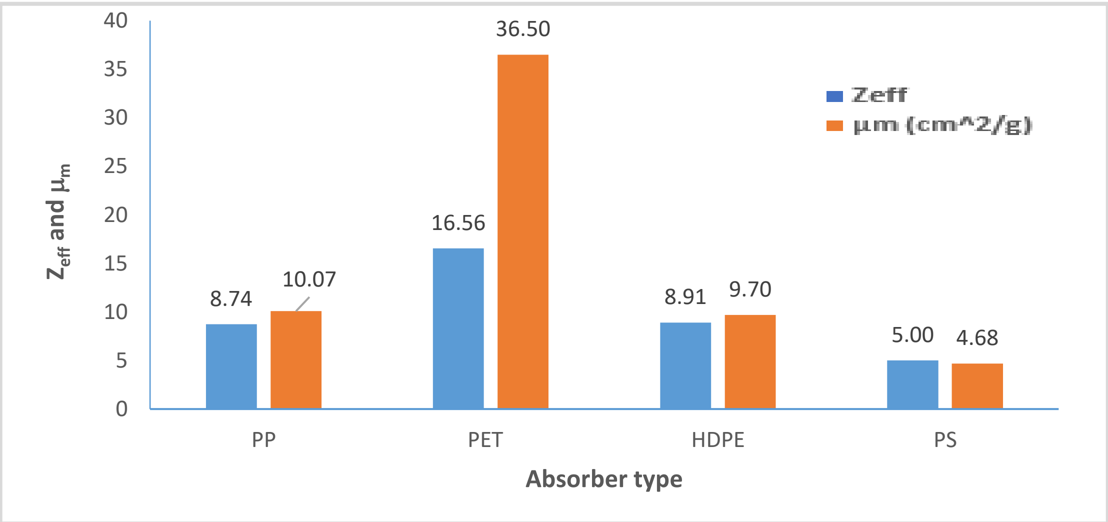

Fig. (7): Z_{eff} and μ_m are plotted against the type of absorber

Table (8): The HVL and TVL for various polymer samples.

Name of material	μ (cm^{-1})	HVL=ln2/μ (cm)	TVL=ln10/μ (cm)
PP	8.6136	0.08	0.267
PET	35.1	0.02	0.066
HDPE	9.1169	0.076	0.253
PS	4.496	0.1542	0.512

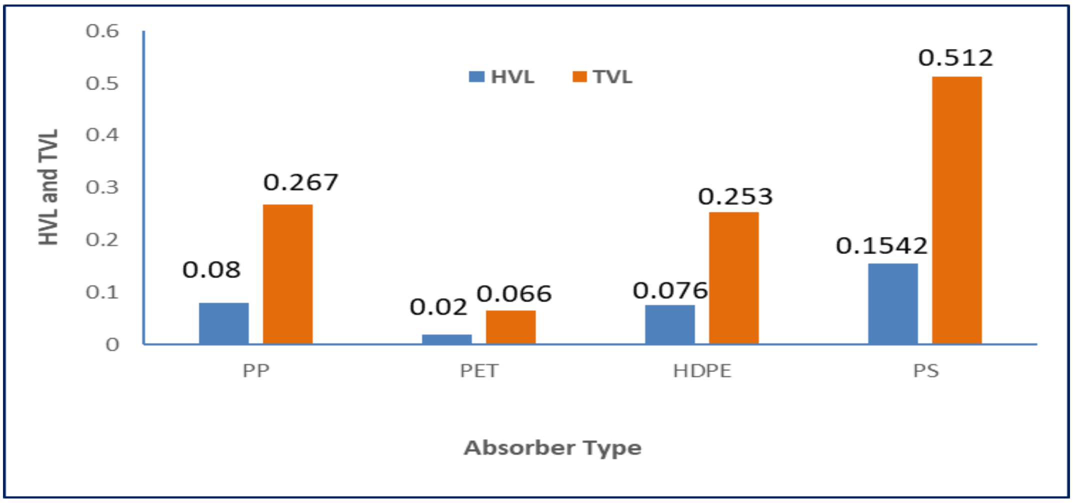

Fig. (8): HVL and TVL are plotted against the type of absorber

CONCLUSION

The fundamental variables in the investigation of gamma ray interaction are mass attenuation coefficient, effective atomic number, effective electron density, total atomic scattering cross-section, and electronic scattering cross-section. Ionizing radiation interacts with materials in a variety of ways, primarily depending on the type and amount of absorbing material. For some polymers, the effective atomic number Z_{eff} and the mass attenuation coefficient μ_m were calculated. According to the findings, Polystyrene (PS) has the lowest values of μ_m and Z_{eff}, while Polyethylene Terephthalate (PET) has the highest values. Given that polymers are made of C, H, and O constituent elements and can be used as tissue substitute materials, the obtained results may be appropriate for medical applications.

The current study concluded that because Polyethylene Terephthalate (PET) has more μ_m values than the other polymer materials, it can be used as the best shielding polymer material. Applications in dosimetry, radiation protection, and technology could all benefit from this information.

The findings of the current study compared to those published in the literature for the system validation for further investigations of other different materials.

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