

RESEARCH ARTICLE

Study and Analysis of Novel Nanomaterial for Radiation Shielding Applications

Hend Abd-Allah ^{1,2*}, Atef El-Taher ¹

ABSTRACT: This study investigates the gamma-ray shielding performance of cadmium tungstate (CdWO_4) nanoparticles through computational simulations using the EpiXS program. The selected nanomaterial represents an economically viable, lightweight, and readily processable alternative for radiation protection applications. Simulation results revealed significant attenuation properties, with the linear attenuation coefficient reaching a maximum value of 38.6 cm^{-1} at the energy of 80 keV. The mass attenuation coefficients were also determined, and the results demonstrated a strong energy dependence consistent with the dominance of photoelectric absorption at lower photon energies. Half-value layer analysis indicated that the shielding effectiveness is directly influenced by incident photon energy, with higher energies requiring greater material thickness to achieve equivalent attenuation. The tenth-value layer and mean free path parameters further confirmed the material's efficiency in attenuating radiation across a broad energy spectrum. The effective atomic number and electron density values were calculated to provide insight into the interaction mechanisms governing the shielding behaviour, with results showing highest values in the low-energy region where photoelectric absorption predominates. Additionally, exposure and energy absorption buildup factors were evaluated using geometric progression fitting parameters to account for scattered photon contributions. The combination of favourable shielding characteristics together with the material's lightweight nature, low production cost, and processing flexibility positions CdWO_4 nanoparticles as promising candidates for X-ray and gamma-ray shielding applications requiring thin shielding layers to enhance economic feasibility.

Keywords: CdWO_4 Nanoparticles; Radiation Shielding; Linear Attenuation Coefficient; EpiXS Program; Half-Value Layer; Mass Attenuation Coefficient

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1. INTRODUCTION

The protection of personnel and the public from harmful ionizing radiation remains a fundamental concern across numerous sectors, including nuclear power generation, medical diagnostics and therapy, space exploration, and industrial radiography. X-rays and gamma rays, being highly

penetrating electromagnetic radiation, pose particular challenges for effective shielding due to their ability to traverse substantial thicknesses of ordinary materials. The development of efficient shielding materials requires a comprehensive understanding of the physical mechanisms by which photons interact with matter, specifically the photoelectric effect, Compton scattering, and pair production, each of which dominates in different energy regimes [1]. The photoelectric effect is most significant at low photon energies and depends strongly on the atomic number of the absorbing material, typically scaling as Z^4 to Z^5 . Compton scattering prevails at intermediate energies and is primarily governed by electron density rather than atomic number. Pair production becomes relevant at energies exceeding 1.022 MeV and exhibits a Z^2 dependence. These fundamental

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interaction processes dictate the attenuation behaviour of any candidate shielding material and must be carefully considered during the selection and design phases [2].

Conventional shielding materials have historically included lead, concrete, steel, and various alloys. Lead, despite its excellent attenuation properties arising from its high density and atomic number, suffers from significant drawbacks including toxicity, high weight, and limited mechanical strength [3]. Concrete, while inexpensive and readily available, requires considerable thickness to provide adequate shielding and offers limited flexibility in application. These limitations have motivated extensive research into alternative materials that can provide comparable or superior shielding performance while addressing the practical constraints of weight, cost, toxicity, and processability [4]. Polymer-based composites incorporating high-Z fillers have emerged as promising candidates, offering the advantages of light weight, flexibility, and ease of fabrication, though careful optimization of filler loading and dispersion is essential to achieve satisfactory shielding efficiency [5]. Iron-based materials have also been employed, though they present challenges such as low mechanical strength and considerable heaviness, which limit their practical applicability in certain contexts [6].

The advent of nanotechnology has opened new avenues for radiation shielding research, with nanomaterials offering unique advantages over their bulk counterparts [7]. The reduced dimensions of nanoparticles result in increased surface area to volume ratios, enhanced dispersion characteristics, and the potential for superior interaction cross-sections due to quantum confinement effects. Numerous studies have investigated various nanomaterials including metal oxides such as bismuth oxide, lead oxide, tungsten oxide, and cadmium oxide, often incorporated into polymeric matrices or formed into composite structures [8]. These nanocomposites have demonstrated enhanced shielding properties while maintaining desirable attributes including flexibility, comfortability, reduced weight, and cost-effectiveness compared to conventional shielding materials [9, 10]. The ability to tailor the composition, size, and morphology of nanoparticles provides additional degrees of freedom for optimizing shielding performance across different energy ranges. Furthermore, nanomaterials are considered environmentally friendly alternatives to traditional shielding materials, as they can be manufactured using relatively simple and low-cost techniques [11]. Recent investigations have shown that various nanocomposites made of metal or metal oxide particles in the nano-dimension can significantly improve the radiation shielding characteristics while simultaneously offering enhanced mechanical and thermal properties [12].

Among the various heavy metal oxides that have attracted attention for radiation shielding applications, cadmium tungstate (CdWO_4) presents particularly interesting characteristics. Cadmium tungstate is a well-known scintillator material with excellent luminescent properties, high density, and favourable X-ray absorption characteristics due to the presence of both cadmium and tungsten atoms,

which possess relatively high atomic numbers (48 and 74 respectively) [13]. The combination of these two heavy elements within a single compound offers the potential for enhanced photoelectric absorption at low energies while maintaining reasonable stability and processability. Recent studies have demonstrated that CdWO_4 nanoparticles can be synthesized through various methods including co-precipitation, hydrothermal treatment, solvothermal routes, and molten salt methods, yielding controlled particle sizes and morphologies [14, 15, 16, 17]. These synthesis approaches are relatively straightforward and cost-effective, making CdWO_4 nanomaterials economically viable for large-scale applications. Moreover, cadmium-based materials have been found to exhibit radiation shielding qualities comparable to lead while being less hazardous, which addresses one of the primary concerns associated with conventional lead-based shielding materials [18]. The versatility of CdWO_4 nanoparticles, combined with their favourable physical and chemical properties, makes them attractive candidates for incorporation into protective clothing, shielding containers for radioactive source transport, and isolation materials for radioactive waste management facilities [19]. Additionally, materials with high atomic numbers such as tungsten, bismuth, and cadmium find extensive applications in radiography, radiotherapy, academic research, food industry processing, gas detectors, and security devices [20].

The novelty of the present investigation lies in the comprehensive evaluation of CdWO_4 nanoparticles specifically for their gamma-ray shielding capabilities, an aspect that has received limited attention in the existing literature. While significant research has been conducted on the photocatalytic properties and luminescent behaviour of cadmium tungstate nanostructures, systematic studies of their radiation attenuation parameters including linear and mass attenuation coefficients, half-value layers, effective atomic numbers, and buildup factors are scarce. The unique combination of cadmium and tungsten within a single nanostructured material offers synergistic shielding effects that have not been thoroughly explored. Furthermore, the use of advanced simulation tools such as the EpiXS program, which is based on the most recent evaluated nuclear data libraries including EPICS2017 of ENDF/B-VIII and EPDL97 of ENDF/B-VI, enables accurate prediction of shielding parameters without the need for extensive experimental measurements [21]. This computational approach facilitates rapid screening of potential shielding materials and provides valuable data for the rational design of optimized shielding composites. The present work extends beyond previous investigations by providing a detailed energy-dependent analysis of all relevant shielding parameters, thereby establishing a comprehensive benchmark for the radiation protection performance of this particular nanomaterial across a wide energy range from 15 keV to 15 MeV.

The application of nanomaterials in radiation shielding extends beyond mere replacement of toxic or heavy materials to enable new functionalities and improved performance

characteristics. In medical applications, lightweight and flexible shielding materials can significantly reduce operator fatigue during prolonged procedures while maintaining the required level of protection [22]. In nuclear waste management, shielding materials that can be easily moulded or applied as coatings offer advantages in complex geometries and remote handling scenarios. The space industry similarly demands shielding materials with exceptional weight efficiency to minimize launch costs while providing adequate protection against cosmic radiation. Nanoparticle-based composites can be engineered to meet these diverse requirements, with the nanosized fillers providing superior dispersion and interaction with incoming radiation compared to conventional micron-sized particles [23].

Studies have shown that nanomaterials outperform traditional lead and concrete in several aspects, including being transparent in some cases, additive manufacturing compatibility, cost-effectiveness, light weight, ease of processing, and importantly, having minimal negative effects on living organisms [24]. These attributes make nanomaterials particularly attractive for applications involving direct human contact, such as protective clothing for radiation workers. The growing body of research on gamma-ray shielding properties of various nanomaterials, including those based on zinc oxide, copper oxide, nickel oxide, and bismuth oxide, has demonstrated the potential of these materials to address the limitations of conventional shielding approaches [25]. However, systematic investigations of the shielding performance of CdWO₄ nanoparticles, particularly regarding their energy-dependent attenuation characteristics and buildup factors, remain limited in the current literature [26, 27].

Concerns about the amount of radiation to which workers are exposed, as well as the management of radioactive waste, must be addressed in addition to the benefits of nuclear energy. The protection of humans from radiation is a critical and fascinating research topic that continues to drive innovation in materials science and engineering. As radiation shielding alternatives, steel, polymeric materials, lead-based materials, and lead-free materials can all be employed depending on the specific application requirements. However, nanomaterials have risen to prominence as a new alternative material that overcomes many of the disadvantages associated with lead and concrete materials used in traditional radiation shielding, and research in this area has grown significantly in recent years. Numerous studies on the gamma-ray shielding of nanomaterials have been conducted, though investigations on the gamma as well as neutron shielding of glass materials remain relatively uncommon. Studies of the various properties and parameters of nanomaterials have recently attracted the attention of researchers and technologists, leading to continuous advancements in the field.

In this paper, we report on the systematic evaluation of the gamma-ray shielding properties of CdWO₄ nanoparticles using the EpiXS computational program, which is based on the EPICS2017 and EPDL97 evaluated nuclear data libraries.

The shielding parameters investigated include the linear attenuation coefficient, mass attenuation coefficient, half-value layer, tenth-value layer, mean free path, effective atomic number, electron density, atomic and electronic cross-sections, as well as energy absorption and exposure buildup factors. The energy range considered spans from 15 keV to 15 MeV, covering the typical photon energies encountered in medical, industrial, and nuclear applications. The results are analysed in terms of the underlying photon interaction mechanisms and compared with established shielding materials to assess the potential of CdWO₄ nanoparticles as viable candidates for lightweight and cost-effective radiation protection applications. This investigation aims to contribute to the growing body of knowledge on nanomaterial-based radiation shielding and to provide a foundation for future experimental studies and practical applications of CdWO₄ nanoparticles in this important field.

2. EXPERIMENTAL DETAILS

The CdWO₄ nanoparticles investigated in this study were synthesized using a co-precipitation method, with the detailed synthesis procedure and characterization results having been reported in our earlier work [4]. The synthesis involved the controlled precipitation of cadmium and tungstate ions under specific conditions to yield nanoparticles with uniform size distribution and desired crystalline structure. The resulting nanoparticles were characterized using various techniques including X-ray diffraction, transmission electron microscopy, and UV-visible spectroscopy to confirm their phase purity, morphology, and optical properties, all of which have been previously documented.

For the determination of gamma-ray shielding parameters of the synthesized CdWO₄ nanoparticles, the EpiXS computational program was employed. EpiXS is a Windows-based application program specifically developed for photon attenuation, dosimetry, and shielding calculations. The program is built upon two major evaluated nuclear data libraries, namely EPICS2017 of ENDF/B-VIII and EPDL97 of ENDF/B-VI.8, which provide comprehensive and reliable photon interaction data across a broad energy spectrum. This computational tool has been widely validated and utilized in the radiation shielding research community for its accuracy and versatility in predicting various shielding parameters for user-defined materials.

The EpiXS program is capable of computing a comprehensive set of shielding parameters essential for evaluating the radiation protection performance of materials. These parameters include partial and total cross sections (σ), which describe the probability of photon interaction with the material atoms, and mass attenuation coefficients (μ/ρ) and linear attenuation coefficients (μ), which quantify the reduction in photon intensity per unit mass or length of the shielding material, respectively. Additionally, the program calculates mean free paths (MFP), half-value layers (HVL), and tenth-value layers (TVL), all of which are practical

parameters indicating the material thickness required to reduce the photon intensity to specific fractions of its original value. The effective atomic number (Z_{eff}) and electron density (N_{eff}) are also computed, providing insight into the effective shielding characteristics of the composite material based on its elemental composition. Furthermore, the program determines auxiliary parameters and buildup factors for both energy absorption (EABF) and exposure (EBF) through the Geometric-Progression (G-P) fitting method. These buildup factors account for the contribution of scattered photons to the total dose, which is particularly important for accurately assessing shielding effectiveness at larger penetration depths where multiple scattering events become significant. The computational capability of EpiXS extends over an extensive energy range from 1 keV to 100 GeV, thereby covering all photon energies relevant to medical, industrial, and nuclear applications.

The input to the EpiXS program consisted of the elemental composition and density of the CdWO_4 nanoparticles. The elemental composition was determined from the stoichiometric formula of CdWO_4 , with the weight fractions of cadmium, tungsten, and oxygen being calculated accordingly. The density of the synthesized nanoparticles was experimentally determined using standard pycnometry methods. All shielding parameters were computed across the energy range of interest, specifically from 15 keV to 15 MeV, which encompasses the typical photon energies encountered in diagnostic radiology, radiotherapy, industrial radiography, and nuclear power applications. The results obtained from the EpiXS calculations were systematically analysed to evaluate the energy-dependent shielding performance of the CdWO_4 nanoparticles, with particular attention paid to the underlying photon interaction mechanisms governing the attenuation behaviour in different energy regions. The computational approach adopted in this study offers significant advantages in terms of speed, cost-effectiveness, and reproducibility compared to experimental measurements, while still providing reliable and physically meaningful results based on well-established nuclear data libraries.

3. RESULTS AND DISCUSSION

3.1. Radiation-absorbing parameter calculation procedure

There is a relationship between the radiation intensity (I) with absorbent material, thickness t , and the radiation intensity before having encountered the material, as shown in the following equation (I_0). [25–31].

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

Where μ is the linear radiation attenuation coefficient (LAC). The LAC (cm^{-1}) value, which is independent of material density and represents attenuation per unit length, is the first gamma-ray absorption parameter obtained. It is an important parameter to determine the values required to reduce primary

radiation by half (HVL; $X_{1/2}$; cm) or one-tenth (TVL; $X_{1/10}$; cm) [32–35]. Figure 1 shows energy-dependent changes in LAC that illustrate the contributions of different photon interaction mechanisms to the attenuation of gamma and X-ray radiation through CdWO_4 nanoparticles. The total LAC curve represents the combined effects of key processes such as photoelectric absorption, coherent scattering, incoherent (Compton) scattering, and pair production. Photoelectric absorption dominates at low photon energies (up to approximately 100 keV) and is strongly dependent on the atomic number (Z) of the shielding material, exhibiting a dependence roughly proportional to Z^4 to Z^5 . This results in high attenuation values at lower energies.

Coherent (Rayleigh) scattering occurs without energy loss and is significant mainly at low energies but contributes much less to the overall attenuation compared to photoelectric absorption. In contrast, incoherent or Compton scattering predominates in the medium energy range (approximately 100 keV to several MeV), where photons interact with electrons causing energy loss through inelastic scattering; this mechanism depends more on electron density rather than Z . Pair production becomes relevant at higher photon energies above 1.022 MeV, where photon interaction with nuclear or electron fields produces electron-positron pairs; its cross-section increases with energy and approximately scales with Z^2 . The LAC generally decreases with increasing photon energy due to the reduction in interaction probability, although the interplay between these mechanisms introduces complexity in the attenuation behavior across energy ranges. Consequently, the gamma shielding effectiveness of CdWO_4 nanoparticles fundamentally depends on the photon energy spectrum, rendering them highly effective over broad energy ranges due to their diverse photon interaction properties [36–39].

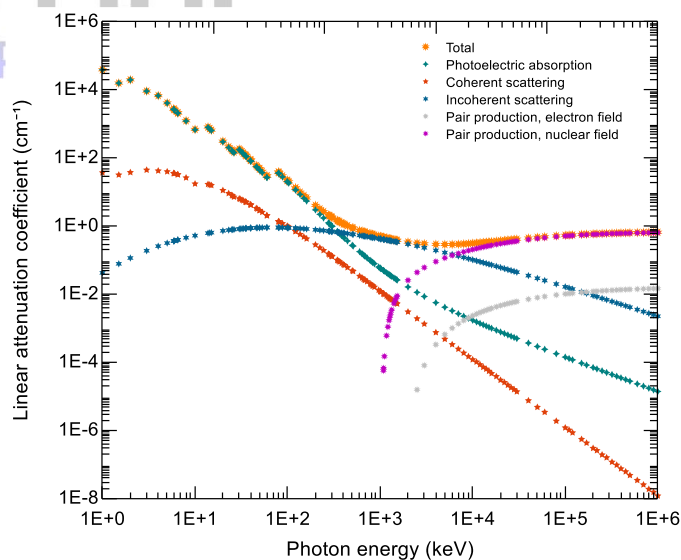


Fig. 1. Linear attenuation coefficient (LAC).

By dividing the linear attenuation coefficient (LAC) by the

material's specific gravity, one can obtain fundamental information about the shielding material's capacity to lower the amount of gamma-ray radiation. The EpiXS method was used to determine the samples' MAC values [11–17]:

$$MAC = \sum_i w_i (MAC)_i \quad (2)$$

W_i denotes the weight fraction of the i th constituent element. Figure 1 depicts the change in MAC values as a function of energy for the MAC values of sample were determined using the EpiXS program [17], and the changes were discovered to be related to photon energy, as shown in Figure 2. Figure 2 depicts how three different interaction processes influenced the MAC values.

In the medium and low energies, MAC values tend to decrease rapidly with energy. The change in the cross-section of the photoelectric interaction caused by the $Z^4/E^{3.5}$ relationship explains this trend. There are abrupt increases in the energy range of 30 KeV to 200 KeV in Figure 1. This sharp peak corresponds to the K absorption edge of the element. It corresponds to the energy of the absorbed photon. Because of the linear change in Compton scattering with Z in medium energies, the pair production interaction mechanism (which varies with Z^2) caused MAC values to rise again at higher energies [7].

The sample had high MAC values due to W, as shown in Figure 1. The photoelectric effect is very strong in this region ($E_{\text{Photon}} < 100 \text{ keV}$), and the absorption cross-section is directly proportional to the fourth or fifth order of the atomic numbers (Z^4 -5) of the atoms in a material in this case [40].

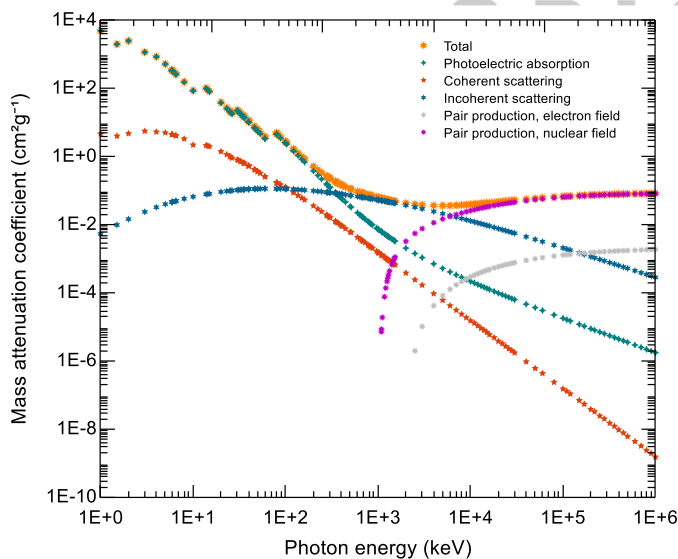


Fig. 2. Mass attenuation coefficient (MAC).

The thickness of a homogeneous material that reduces the photon beam's intensity to a tenth of its original intensity is referred to as TVL and is determined using the following [41–

43]:

$$TVL = \frac{\ln(10)}{\mu} \quad (3)$$

Figure 3(a) demonstrates that at low photon energies, the TVL is low, meaning less material thickness is needed to attenuate the radiation. As photon energy increases, TVL increases sharply at first and then tends to flatten at very high energies, indicating that higher-energy photons penetrate deeper, requiring thicker shielding.

The half-value layer (HVL), also known as half-value thickness, is a useful parameter for use in some radiation applications because it indicates the thickness of the material required to halve a certain photon flux [42].

$$HVL = \frac{\ln(2)}{\mu} \quad (4)$$

As shown in Figure 3(b), HVL decreases at very low photon energies, reflecting effective attenuation due primarily to the photoelectric effect. It then increases with energy because higher-energy photons interact less frequently, thus penetrating further. Beyond a certain point, the HVL curve shows a minimum, likely corresponding to the K absorption edge of heavy elements (such as tungsten in CdWO_4), where photon absorption sharply increases. At very high energies, HVL rises again as pair production and Compton scattering dominate and photons penetrate more deeply.

The MFP (cm) represents the average distance travelled by a photon during the photon-matter interaction and is the reciprocal of the LAC, so it mirrors energy-dependent interaction probabilities. Furthermore, the MFP is the distance at which the function $1/e$ reduces the intensity of the radiation. HVL is a useful parameter in some radiation applications. At low energies, MFP is small, indicating photons are quickly absorbed or scattered. MFP peaks at intermediate to high energies where photon interactions (especially the photoelectric effect) decline and photons can travel further between interactions, as shown in Figure 3 (c). A gradual decline at very high energies might reflect increasing pair production or other interaction mechanisms [41].

$$MFP = 1/\mu \quad (5)$$

The HVL, TVL, and MFP are critical parameters for determining the material's gamma shielding ability and the level of gamma radiation penetrating the environment. Figures 3 (a-c) show energy-dependent variations of MFP, TVL, and HVL curves, respectively. The elemental composition of the sample influences HVL, TVL, and MFP values. The MFP, TVL, and HVL values of the samples studied are quite small, up to 0.1 MeV in energy. The MFP, TVL, and HVL values were low in the CdWO_4 sample due to Cd concentration. These parameters were enhanced with photon energies ranging from 100 to 5000 MeV. Lower-energy photons are absorbed more effectively, demanding thinner shielding (low TVL, HVL, MFP), while higher-

energy photons require increased thickness due to their greater penetration capability and predominant scattering or pair production interactions [44, 45].

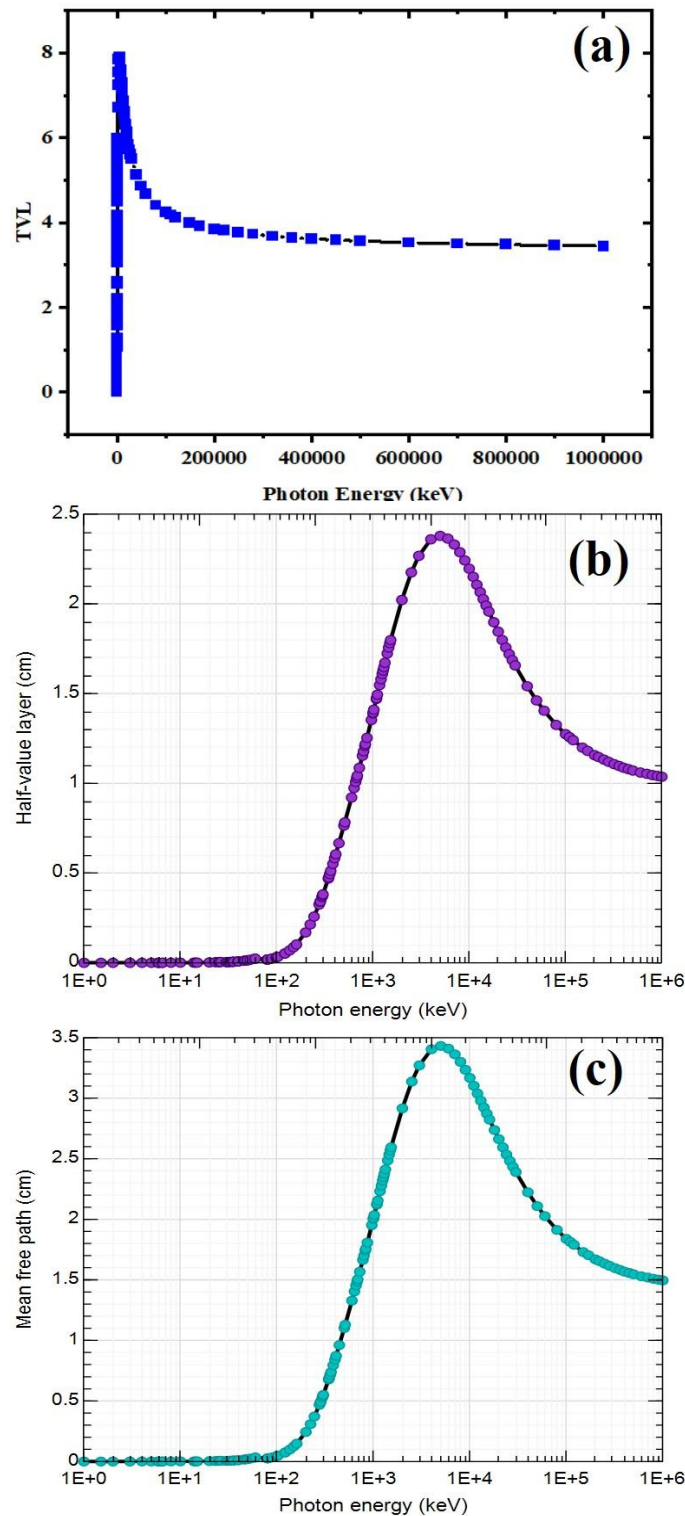


Fig. 3. (a) the tenth value layer (TVL) values, (b) the half value layer (HVL) values, and (c) mean free path (MFP), versus the incident photon energy of the sample.

An effective atomic number (Z_{eff}) varies with the material and certain parameters of the interacting radiation and provides information about the material. The Z_{eff} values of the samples were calculated in this study using [32, 33]:

$$Z_{eff} = \left(\frac{\sum_i f_i A_i (MAC)_i}{\sum_j f_j A_j Z_j (MAC)_j} \right)^{1/3} \quad (6)$$

Where f_j denotes the ratio of the i^{th} element's atomic number to the total number of atoms in the absorber, and A_i and Z_i denote the atomic weight and atomic number of the i^{th} element in the absorber material, and so on. The effective atomic number is also referred to as a virtual atomic number because it represents the totality of any complex material composed of more than one atom and indicates which shielding material possesses this material's property. Furthermore, this number characterizes materials in a set of material classes based on their shielding capacities and can be used to select the best-shielding material. This parameter is proportional to incident photon energy and is directly impacted by the kinds of constituent element atoms in materials. It is influenced by Compton scattering interactions. Figure 4 depicts the attitude of the obtained effective atomic numbers (Z_{eff}) for photon-energy-varying samples. A sample's ability to absorb radiation is indicated by the magnitude of its Z_{eff} value. The Z_{eff} values were influenced by three photon substance interaction processes [44, 45], as shown in Figure 4.

Z_{eff} values in the low-energy region have the highest values for the sample when compared to other energy regions, and the highest values are found at the element's K absorption edges. Z_{eff} 's energy dependence decreased in the middle and high energy zones, with the lowest values found in high energies where pair production (change with $\log E$) was dominant. Because this parameter is directly proportional to the atomic and electronic cross-sections (ACS and ECS) of the target material. To demonstrate that the Z_{eff} values calculated for any material depend on both the photon-matter interaction mechanism and the primary photon energy, the Z_{eff} values would be independent of photon-matter interactions if the Z_{eff} values were only dependent on the type and molar fraction of the atoms forming the material. Considering this result, it is possible to conclude that the Z_{eff} values of complex materials, like Z_{eff} , cannot be stated as a single number as in pure element atoms at different photon energies for complex materials, and are obtained by dividing the MAC values by the ECS values.

The obtained results show that the decreasing order of N_{eff} values up to approximately 1 MeV energy value. This result differs significantly from the rankings obtained for MAC and Z_{eff} values. This result can be attributed to the mole fraction as well as the atomic mass of the elements that make up the material. Because the N_{eff} value can be computed:

$$N_{eff} = NA \frac{n Z_{eff}}{\sum_i n_i A_i} \quad (7)$$

Where, NA is Avogadro's number, and n_i is the total number of elements in the composite. The less N_{eff} value is. It is not

possible to claim that the material has a higher shielding capacity regardless of whether its N_{eff} value is greater or lesser. As a result, if a material contains elements with a high atomic mass, the N_{eff} values of the material will be small at any photon energy.

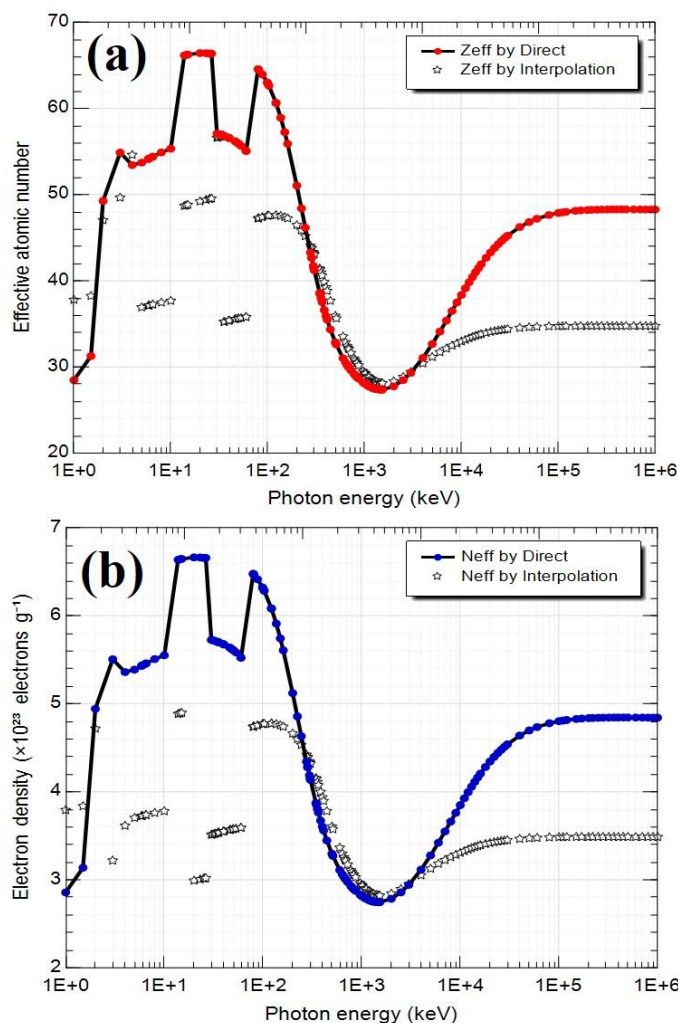


Fig. 4. (a) the effective atomic number (Z_{eff}), and (b) N_{eff} values versus the incident photon energy of the samples.

3.2. Atomic Cross Section (ACS) and Electron Cross Section (ECS)

As photon energy increases, ACS values decrease due to reduced photon-atom interactions. This trend is consistent with the mass attenuation coefficient (MAC) results, where the highest MAC values correspond to the highest atomic cross sections. Similarly, the probability of photon-electron interaction, described by ECS values, also decreases with increasing photon energy. The changes in ACS and ECS values as a function of photon energy are depicted in Figure 5.

Photon build-up factors, which demonstrate the possibility of photon scattering, are another important

parameter in radiation protection applications. The first step in the calculation is to determine how much of the total number of photons that hit the material is scattered. This is a purely theoretical process that involves G-P fitting coefficients (a , b , c , d , and XK), R , and Z_{eq} values are provided to calculate the build-up factors.

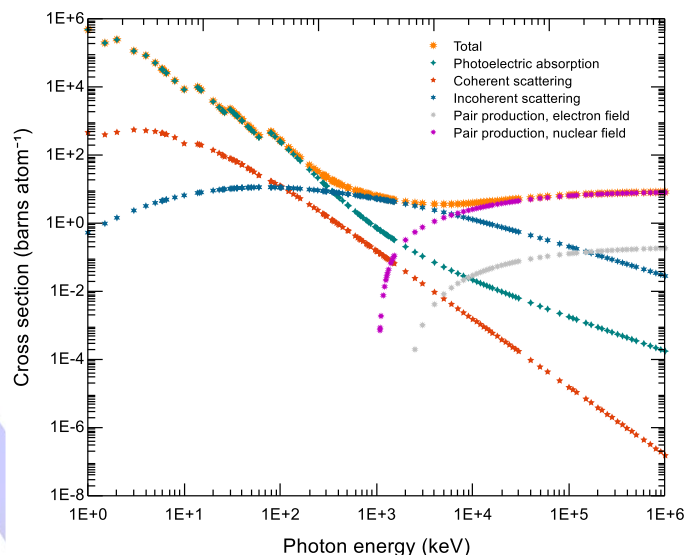


Fig. 5. Cross-section values versus the incident photon energy of the samples.

Photon Scattering Parameter (R), defined as the ratio of incoherent scattering cross-section to total cross-section, helps quantify the fraction of total photons scattered. R values, depicted across photon energies 0.015 to 15 MeV, reveal Compton scattering dominance in the middle energy range. As energy increases beyond this range, pair production becomes more dominant, reducing R values as shown in Figure 6. Compton scattering, or inelastic scattering, is dominant in the middle energy region. The inelastic scattering cross-section reaches its maximum within the selected limits and becomes almost independent of the material composition when given a constant total cross-section. Furthermore, as energy increases, pair production becomes more dominant, and Compton scattering becomes less likely. As a result, R values tend to decrease after a certain maximum. When photons are taken up in materials [33-35]. The virtual atomic number that identifies the complex material is Z_{eff} , whereas when scattering occurs, this value is Z_{eq} . The changes in the Z_{eq} values of the sample studied are depicted in Figure 6.

Figure 7 displays the G-P (Geometric Progression) fitting parameters (a , b , c , d , and XK) plotted against photon energy (in keV), which are used to calculate the Energy Absorption Buildup Factor (EABF) and Exposure Buildup Factor (EBF) for CdWO_4 nanomaterials. G-P fitting parameters (a , b , c , d , XK): These parameters are empirical constants used in the geometric progression fitting formula to model the buildup factors (EBF and EABF) in shielding

materials. The buildup factor accounts for scattered radiation that contributes to the total dose inside the shielding material, beyond the primary uncollided photons. These are intermediate coefficients that describe the shape and behavior of the buildup factor curve as a function of photon energy and penetration depth (mean free path, MFP). XK: This parameter represents the "cross-over" or "breakpoint" energy that separates regions of different buildup behavior in the energy spectrum. The parameters 'a' and 'XK' show significantly higher values at low photon energies (around a few keV to a few thousand keV) then gradually level off or become constant at higher energies up to 15 MeV. This suggests that these parameters dominate the buildup factor behavior in the lower energy region where photoelectric absorption and initial scatterings are prevalent. Parameters b, c, and d are much lower in value and show relatively minor changes across the energy range, indicating more subtle contributions to the complex photon scattering and buildup phenomena in the material [11-13].

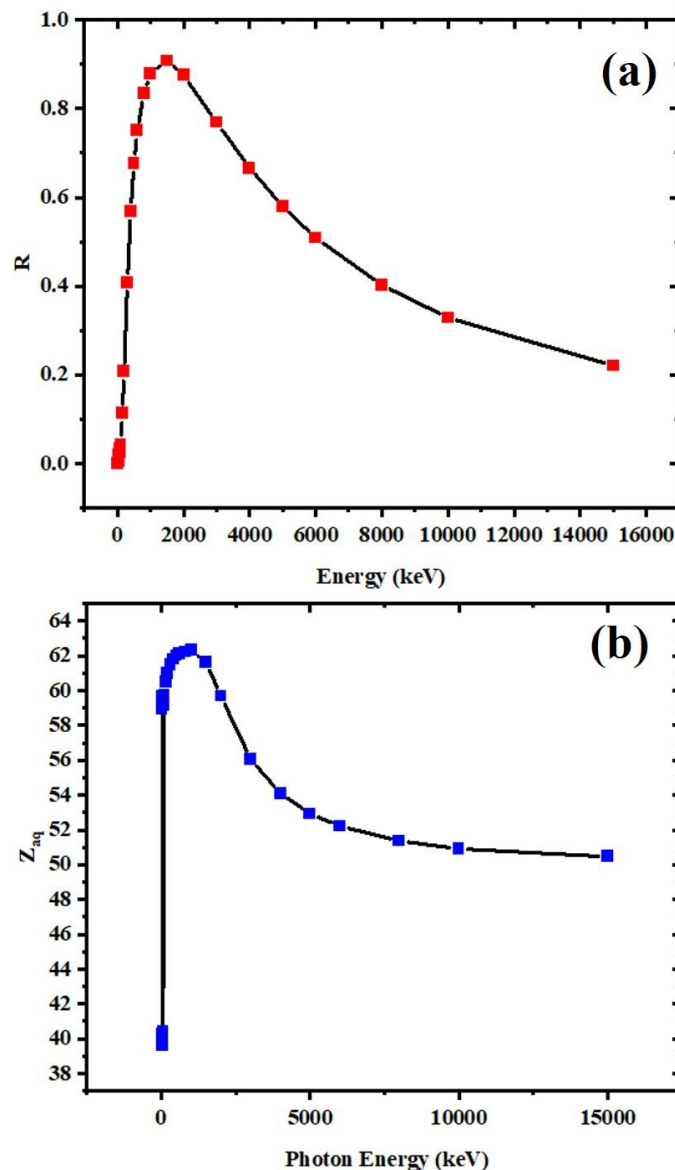


Fig. 6. (a) R and (b) Za values versus the incident photon energy of the sample.

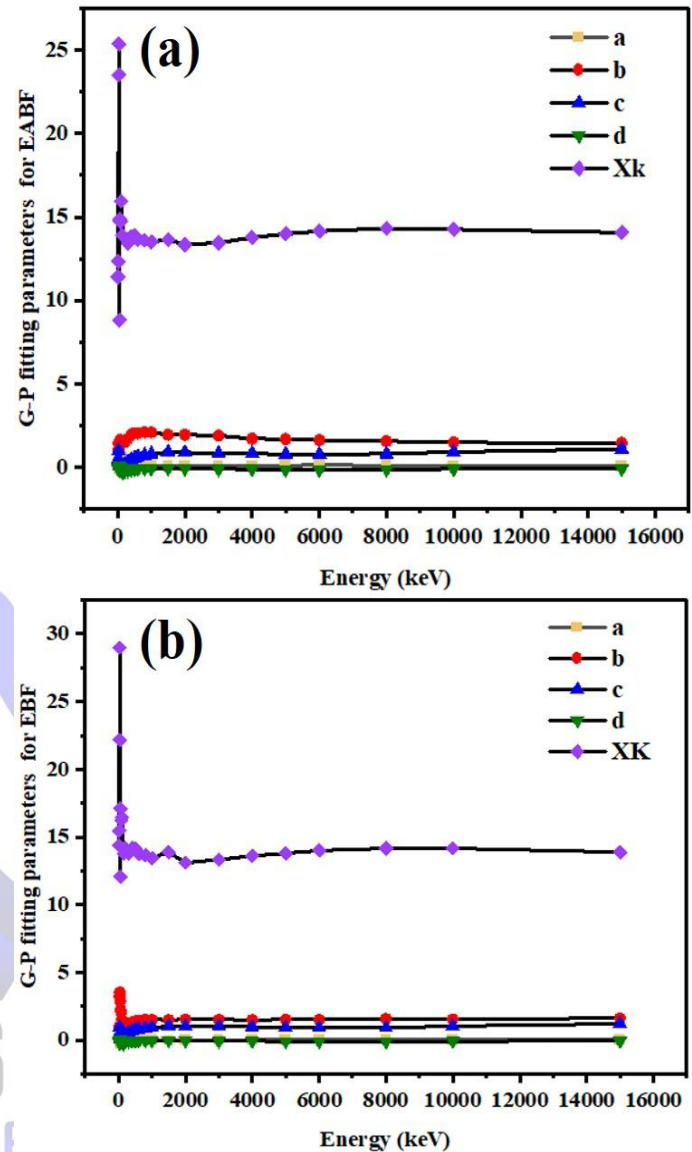


Fig. 7. G-P fitting parameters for (a, b, c, d, and XK) for (a) EABF and (b) EBF

When designing gamma radiation shielding and medical physics applications, buildup factors are critical. EBF and EABF [18]. To evaluate buildup factors, various parameters such as photon energy absorption and dose were used (i.e., exposure). EBF and EABF are affected by energy values and penetration. Depths (1, 2, 5, 10, 20, 30, and 40 mfp) of the investigated samples are shown in Figure 8. As shown in Figure 8, EBF and EABF values gradually increase between 0.1 and 3 MeV; they accelerate after the 6 MeV energy value (especially for high penetration depths). From Figure 8 clear that at medium energies where Compton scattering occurs, the EBF and EABF values of the samples change proportionally to Z_{eq} values. The EBF and EABF values of the investigated samples increased more rapidly at 6-15 MeV, which is due to Z_2 . Figure 8 shows that the EBF and EABF

values increased with the depth of penetration (1-40 MFP). This implies that the quantity of secondary photons increases with sample thickness. For example, the EBF values for the 1 and 40 MFP are in the order of 101 and 108, respectively. The positron is quickly destroyed, resulting in the production of another pair of 511 keV photons. Some of the original Photon loss is compensated for by these secondary gamma photons. As the pair production Process continues to dominate at energies greater than 3 MeV, the accumulation factors increase with increasing Z_{eq} for deeper penetration depths (>15mfp). At shallow penetration depths (15mfp), these particles may escape or collide multiple times within the material after coming to rest, annihilating them further. Secondary gamma rays contribute to the strength of primary gamma rays [45].

As a result, high specific heat, high melting point, high density, high mechanical strength, high radiation shielding parameters such as MAC, LAC, ACS, ECS, and Z_{eff} , low half-value layer (HVL), and low mean free path (MFP) values are the most important properties of an alternative shielding material.

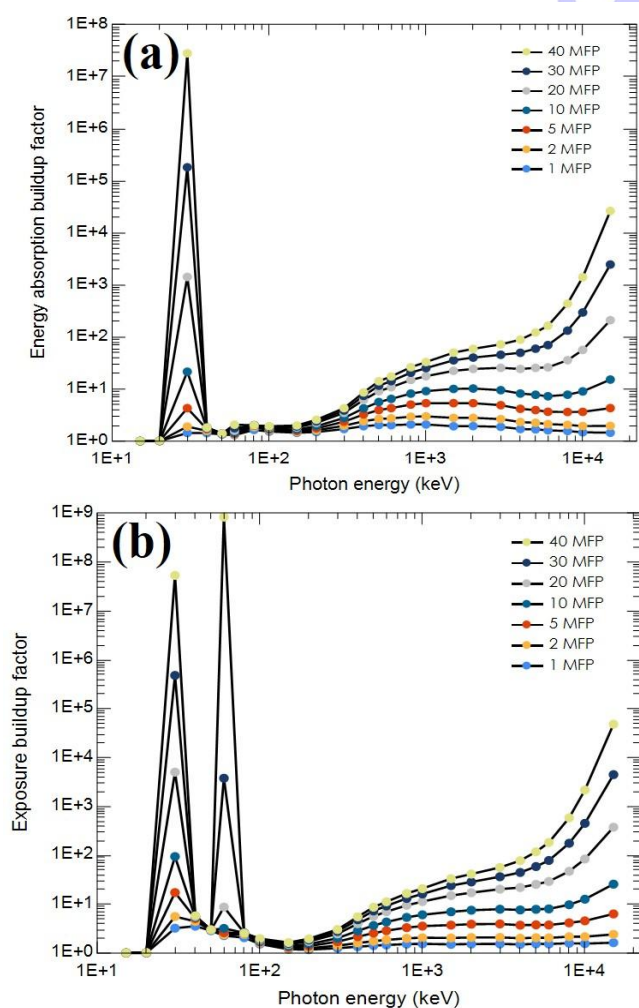


Fig. 8. (a) The energy absorption buildup factors and (b) The exposure buildup factors in the energy region 15–15000 KeV at 1, 2, 5, 10, 20, 30, 40 mfp.

4. CONCLUSION

The present investigation has demonstrated that CdWO₄ nanoparticles exhibit significant gamma-ray shielding capabilities across a broad energy range based on the comprehensive computational analysis performed using the EpiXS program. The linear attenuation coefficient reached its maximum value of 38.6 cm⁻¹ at 0.08 MeV, while the mass attenuation coefficient attained a value of 4.88 cm²g⁻¹ at the same energy, indicating exceptional attenuation efficiency at low photon energies where photoelectric absorption predominates. The half-value layer results clearly established that the penetrating ability of the material is strongly dependent on photon energy, with higher energies requiring substantially greater material thickness to achieve equivalent attenuation. This energy-dependent behaviour underscores the importance of considering the specific radiation spectrum when designing shielding applications. The evaluation of buildup factors through geometric progression fitting parameters revealed that scattered photon contributions become increasingly significant at higher energies and greater penetration depths, emphasizing that effective shield design must account for both direct attenuation and secondary radiation. The relatively high values of the G-P fitting parameters at low energies confirmed the dominance of photoelectric absorption, while the stable values observed at high energies were consistent with the prevalence of Compton scattering and pair production mechanisms. The combination of favourable shielding characteristics with the material's lightweight nature, low production cost, ease of processing, good dispersion properties, and flexibility positions CdWO₄ nanoparticles as promising candidates for X-ray and gamma-ray shielding applications requiring thin shielding layers to enhance economic feasibility. The potential applications extend from stationary uses such as radioactive source shielding and waste management facility isolation to mobile applications including protective clothing for radiation workers. Future research directions may focus on the incorporation of these nanoparticles into various polymeric matrices to develop flexible and comfortable shielding materials for diverse radiation protection scenarios.

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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Not applicable

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

Hend Abd-Allah: Formal Analysis, Data Curation, interpretation of results and Original draft preparation; Atef El-Taher: Data Curation, Write and Review.

REFERENCES

- [1] Güngör, A.H.M.E.T., Akbay, İ.K., Yaşar, D.O.Ğ.A.N. and Özdemir, T., **2018**. Flexible X/Gamma ray shielding composite material of EPDM rubber with bismuth trioxide: Mechanical, thermal investigations and attenuation tests. *Progress in nuclear energy*, 106, pp.262-269. <https://doi.org/10.1016/j.pnucene.2018.03.021>
- [2] Negm, H.H., Allam, E.A., Abdeltwab, E., Mostafa, M., Mahmoud, M.E. and El-Taher, A., **2024**. A new nanocomposite of copper oxide and magnetite intercalated into Attapulgit clay to enhance the radiation shielding. *Radiation Physics and Chemistry*, 216, p.111398. <https://doi.org/10.1016/j.radphyschem.2023.111398>
- [3] Abdelhamid, M., Fouad, D., Alian, A., Nasr, A.A., Abd-Allah, H., Farouk, M., Abd Elmaleck, B.S., Alexiou, A., Papadakis, M., Batiha, G.E.S. and Anwar, F.A., **2025**. Evaluating the In Vitro Anthelmintic Activity of Zinc Oxide Nanoparticles (ZnO-NPs) Against the Adult Stages of *Fasciola hepatica*. *Veterinary Medicine and Science*, 11(1), p.e70170. <https://doi.org/10.1002/vms3.70170>
- [4] Negm, H., Abd-Allah, H., Shaalan, N.M., Abdel-Latief, A.Y., Abd-Elnaiem, A.M., Moustafa, S. and Abdel-Rahim, M.A., **2026**. Co-precipitation synthesis and Calcination-Tuned properties of CdWO₄ nanoparticles for efficient photocatalytic degradation of methylene blue. *Journal of Inorganic and Organometallic Polymers and Materials*, 36(1), pp.663-680. <https://doi.org/10.1007/s10904-025-03966-3>
- [5] Rilwan, U., Edeh, S.A., Idris, M.M., Fatima, I.I., Olukotun, S.F., Arinseh, G.Z., Bonat, P.Z., El-Taher, A., Mahmoud, K.A., Hanafy, T.A. and Sayyed, M.I., **2025**. Influence of waste glass on the gamma-ray shielding performance of concrete. *Annals of Nuclear Energy*, 210, p.110876. <https://doi.org/10.1016/j.anucene.2024.110876>
- [6] Singh, C., Singh, T., Kumar, A. and Mudahar, G.S., **2004**. Energy and chemical composition dependence of mass attenuation coefficients of building materials. *Annals of nuclear Energy*, 31(10), pp.1199-1205. <https://doi.org/10.1016/j.anucene.2004.02.002>
- [7] Negm, H., Abd-Allah, H., Abdel-Latief, A.Y., Abdel-Rahim, M.A., El-Taher, A. and Shaalan, N.M., **2024**. Fabrication and characterization of structured Zn1-xCd_xWO₄ (0 ≤ x ≤ 1) with tunable photoluminescent and promising applicable heterometallic nanocomposites in shielding properties. *Radiation Physics and Chemistry*, 215, p.111335. <https://doi.org/10.1016/j.radphyschem.2023.111335>
- [8] Shirkhanloo, H., Safari, M., Amini, S.M. and Rashidi, M., **2017**. Novel semisolid design based on bismuth oxide (Bi₂O₃) nanoparticles for radiation protection. *Nanomedicine Research Journal*, 2(4), pp.230-238. <https://doi.org/10.22034/nmrj.2017.04.004>
- [9] Negm, H.H., Allam, E.A., Nabil, I.M., Abdeltwab, E., Mostafa, M. and El-Taher, A., **2024**. Exploring the potential of attapulgit clay composites containing intercalated nano-cadmium oxide and nano-nickel oxide for efficient radiation shielding applications. *Radiation Physics and Chemistry*, 225, p.112149. <https://doi.org/10.1016/j.radphyschem.2024.112149>
- [10] Kaur, P., Singh, K.J., Kurudirek, M. and Thakur, S., **2019**. Study of environment friendly bismuth incorporated lithium borate glass system for structural, gamma-ray and fast neutron shielding properties. *Spectrochimica acta part A: molecular and biomolecular spectroscopy*, 223, p.117309. <https://doi.org/10.1016/j.saa.2019.117309>
- [11] Abd-Allah, H. and El-Taher, A. **2025**. Evaluation of CuO Nanoparticles as Potential Gamma-Ray Shielding Materials Using EpiXS Calculations. *Science of Alloys and Glasses* 1(4), pp. 179-190; <https://doi.org/10.69626/sag.2025.0179>.

- [12] Abd-Allah, H. and El-Taher, A., **2025**. Fabrication and Characterization of Structured ZnO with Promising Applicable Nanomaterials in Shielding Properties. *Science*, 1(3), pp.122-134. <https://doi.org/10.69626/sag.2025.0122>
- [13] Singh, N., Singh, K.J., Singh, K. and Singh, H., **2004**. Comparative study of lead borate and bismuth lead borate glass systems as gamma-radiation shielding materials. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 225(3), pp.305-309. <https://doi.org/10.1016/j.nimb.2004.05.016>
- [14] Mahmoud, M.E., El-Sharkawy, R.M., Allam, E.A., Elsaman, R. and El-Taher, A., **2019**. Fabrication and characterization of phosphotungstic acid-Copper oxide nanoparticles-Plastic waste nanocomposites for enhanced radiation-shielding. *Journal of Alloys and Compounds*, 803, pp.768-777. <https://doi.org/10.1016/j.jallcom.2019.06.290>
- [15] El-Taher, A., Zakaly, H.M., Pyshkina, M., Allam, E.A., El-Sharkawy, R.M., Mahmoud, M.E. and Abdel-Rahman, M.A., **2021**. A comparative study between fluka and microshield modeling calculations to study the radiation-shielding of nanoparticles and plastic waste composites. *Zeitschrift für anorganische und allgemeine Chemie*, 647(10), pp.1083-1090. <https://doi.org/10.1002/zaac.202100062>
- [16] El-Sharkawy, R.M., Allam, E.A., El-Taher, A., Elsaman, R., Massoud, E.E.S. and Mahmoud, M.E., **2022**. Synergistic effects on gamma-ray shielding by novel light-weight nanocomposite materials of bentonite containing nano Bi₂O₃ additive. *Ceramics International*, 48(5), pp.7291-7303. <https://doi.org/10.1016/j.ceramint.2021.11.290>
- [17] Hila, F.C., Asuncion-Astronomo, A., Dingle, C.A.M., Jeong, J.F.M., Javier-Hila, A.M.V., Gili, M.B.Z., Balderas, C.V., Lopez, G.E.P., Guillermo, N.R.D. and Amorsolo Jr, A.V., **2021**. EpiXS: A Windows-based program for photon attenuation, dosimetry and shielding based on EPICS2017 (ENDF/B-VIII) and EPDL97 (ENDF/B-VI. 8). *Radiation Physics and Chemistry*, 182, p.109331. <https://doi.org/10.1016/j.radphyschem.2020.109331>
- [18] Zakaly, H.M., Ashry, A., El-Taher, A., Abbadly, A.G., Allam, E.A., El-Sharkawy, R.M. and Mahmoud, M.E., **2021**. Role of novel ternary nanocomposites polypropylene in nuclear radiation attenuation properties: In-depth simulation study. *Radiation Physics and Chemistry*, 188, p.109667. <https://doi.org/10.1016/j.radphyschem.2021.109667>
- [19] García-Pérez, U.M., Martínez-de La Cruz, A. and Peral, J., **2012**. Transition metal tungstates synthesized by co-precipitation method: Basic photocatalytic properties. *Electrochimica Acta*, 81, pp.227-232. <https://doi.org/10.1016/j.electacta.2012.07.045>
- [20] Sagadevan, S., Podder, J. and Das, I., **2016**. Hydrothermal synthesis of zirconium oxide nanoparticles and its characterization. *Journal of Materials Science: Materials in Electronics*, 27(6), pp.5622-5627. <https://doi.org/10.1007/s10854-016-4469-6>
- [21] Huang, G., Zhang, S., Xu, T. and Zhu, Y., **2008**. Fluorination of ZnWO₄ photocatalyst and influence on the degradation mechanism for 4-chlorophenol. *Environmental science & technology*, 42(22), pp.8516-8521. <https://doi.org/10.1021/es801672a>
- [22] Mancheva, M., Iordanova, R. and Dimitriev, Y., **2011**. Mechanochemical synthesis of nanocrystalline ZnWO₄ at room temperature. *Journal of alloys and compounds*, 509(1), pp.15-20. <https://doi.org/10.1016/j.jallcom.2010.08.033>
- [23] Wang, Y., Ma, J., Tao, J., Zhu, X., Zhou, J., Zhao, Z., Xie, L. and Tian, H., **2006**. Morphology-controlled synthesis of CdWO₄ nanorods and nanoparticles via a molten salt method. *Materials Science and Engineering: B*, 130(1-3), pp.277-281. <https://doi.org/10.1016/j.mseb.2006.02.012>
- [24] Travaglini, D.H., Pawel, M.D., Mahurin, S.M. and Dai, S., **2007**. Metastable Tetragonal CdWO₄ Nanoparticles Synthesized with a Solvothermal Method. *Journal of Colloid and Interface Science*, 306(2). <https://doi.org/10.1016/j.jcis.2006.10.064>
- [25] Allam, E.A., El-Sharkawy, R.M., Shaaban, K.S., El-Taher, A., Mahmoud, M.E. and El Sayed, Y., **2022**. Structural and thermal properties of nickel oxide nanoparticles doped cadmium zinc borate glasses: preparation and characterization. *Digest Journal of Nanomaterials & Biostructures (DJNB)*, 17(1), p.161. <https://doi.org/10.15251/DJNB.2022.171.161>
- [26] Yue, K., Luo, W., Dong, X., Wang, C., Wu, G., Jiang, M. and Zha, Y., **2009**. A new lead-free radiation shielding material for radiotherapy. *Radiation protection dosimetry*, 133(4), pp.256-260. <https://doi.org/10.1093/rpd/ncp053>
- [27] Ivanova, T., Bliznakova, K. and Pallikarakis, N., **2006**. Simulation studies of field shaping in rotational

- radiation therapy. *Medical physics*, 33(11), pp.4289-4298. <https://doi.org/10.1118/1.2358200>
- [28] Allam, E.A., El-Sharkawy, R.M., El-Taher, A., Shaaban, E.R., Massoud, E.E.S. and Mahmoud, M.E., **2022**. Enhancement and optimization of gamma radiation shielding by doped nano HgO into nanoscale bentonite. *Nuclear Engineering and Technology*, 54(6), pp.2253-2261. <https://doi.org/10.1016/j.net.2021.12.026>
- [29] El-Taher, A., Zakaly, H.M., El-Sharkawy, R., Allam, E.A., Al Meshari, M. and Mahmoud, M.E., **2023**. Effect of bismuth oxide nanoparticles on the radiation shielding of bentonite clay using Fluka modeling calculations and simulation studying. *Progress in Nuclear Energy*, 155, p.104494. <https://doi.org/10.1016/j.pnucene.2022.104494>
- [30] El-Sharkawy, R.M., Allam, E.A., El-Taher, A., Shaaban, E.R. and Mahmoud, M.E., **2021**. Synergistic effect of nano-bentonite and nanocadmium oxide doping concentrations on assembly, characterization, and enhanced gamma-rays shielding properties of polypropylene ternary nanocomposites. *International Journal of Energy Research*, 45(6), pp.8942-8959. <https://doi.org/10.1002/er.6427>
- [31] El-Sharkawy, R.M., Shaaban, K.S., Elsaman, R., Allam, E.A., El-Taher, A. and Mahmoud, M.E., **2020**. Investigation of mechanical and radiation shielding characteristics of novel glass systems with the composition $x\text{NiO}-20\text{ZnO}-60\text{B}_2\text{O}_3-(20-x)\text{CdO}$ based on nanometal oxides. *Journal of Non-Crystalline Solids*, 528, p.119754. <https://doi.org/10.1016/j.jnoncrysol.2019.119754>
- [32] El-Taher, A., Ali, A.M., Saddeek, Y.B., Elsaman, R., Algarni, H., Shaaban, K. and Amer, T.Z., **2019**. Gamma ray shielding and structural properties of iron alkali alumino-phosphate glasses modified by PbO. *Radiation Physics and Chemistry*, 165, p.108403. <https://doi.org/10.1016/j.radphyschem.2019.108403>
- [33] Mahmoud, M.E., El-Khatib, A.M., Badawi, M.S., Rashad, A.R., El-Sharkawy, R.M. and Thabet, A.A., **2018**. Recycled high-density polyethylene plastics added with lead oxide nanoparticles as sustainable radiation shielding materials. *Journal of cleaner production*, 176, pp.276-287. <https://doi.org/10.1016/j.jclepro.2017.12.100>
- [34] Saddeek, Y.B., Shaaban, K.H.S., Elsaman, R., El-Taher, A. and Amer, T.Z., **2018**. Attenuation-density anomalous relationship of lead alkali borosilicate glasses. *Radiation Physics and Chemistry*, 150, pp.182-188. <https://doi.org/10.1016/j.radphyschem.2018.04.028>
- [35] El-Taher, A., Mahmoud, H.M. and Abbady, A.G., **2007**. Comparative study of attenuation and scattering of gamma-rays through two intermediate rocks. *Indian Journal of Pure and Applied Physics*, 45(3), pp.198-203.
- [36] Lu, X., Zheng, Y., Yang, J. and Qu, J., **2020**. Multifunctional paraffin wax/carbon nanotube sponge composites with simultaneous high-efficient thermal management and electromagnetic interference shielding efficiencies for electronic devices. *Composites Part B: Engineering*, 199, p.108308. <https://doi.org/10.1016/j.compositesb.2020.108308>
- [37] Wang, W.Y., Ma, X., Shao, Y.W., Qi, X.D., Yang, J.H. and Wang, Y., **2021**. Flexible, multifunctional, and thermally conductive nylon/graphene nanoplatelet composite papers with excellent EMI shielding performance, improved hydrophobicity and flame resistance. *Journal of Materials Chemistry A*, 9(8), pp.5033-5044. <https://doi.org/10.1039/d0ta11040j>
- [38] Davies, U., Kunchev, T., Cosgrove, P., Read, N., Kowalski, M.A. and Shwageraus, E., **2019**. Nuclear energy: Between global electricity demand, worldwide decarbonisation imperativeness, and planetary environmental implications. *Journal of Environmental Management*, 249, pp.109208-109208. <https://doi.org/10.1016/j.jenvman.2019.06.109>
- [39] Almeshari, M., Sallam, F.H., Tharwat, M., Alzamil, Y., Salih, M., Alshoumr, B., Alyahyawi, A. and El-Taher, A., **2024**. Preparation and structure investigation of polyethylene terephthalate polyester reinforced $\text{Ni}_0.5\text{Zn}_0.5\text{Fe}_2\text{O}_4$ nanoparticles for gamma ray shielding performance. *Physica Scripta*, 99(5), p.055311. <https://doi.org/10.1088/1402-4896/ad3486>
- [40] Negm, H.H., El-Sharkawy, R.M., Abdeltwab, E., Mostafa, M., Mahmoud, M.E. and El-Taher, A., **2024**. Evaluation of shielding properties of a developed nanocomposite from intercalated attapulgite clay by Cd/Pb oxides nanoparticles. *Physica Scripta*, 99(5), p.055956. <https://doi.org/10.1088/1402-4896/ad3b48>
- [41] Khalil, A., Bondouk, I.I., Allam, E.A., Nabil, I.M., Al-Abyad, M., Saudi, H., El-Taher, A., Mahmoud, M.E. and Amar, A., **2024**. A binary composite material of nano polyaniline intercalated with Nano- Fe_2O_3 for enhancing gamma-radiation-shielding properties: experimental and simulation study. *Progress in Nuclear Energy*, 169, p.105067. <https://doi.org/10.1016/j.pnucene.2024.105067>

- [42] Tekin, H.O., ALMisned, G., Rammah, Y.S., Ahmed, E.M., Ali, F.T., Baykal, D.S., Elshami, W., Zakaly, H.M., Issa, S.A., Kilic, G.Ö.K.H.A.N. and Ene, A., **2022**. Transmission factors, mechanical, and gamma ray attenuation properties of barium-phosphate-tungsten glasses: Incorporation impact of WO₃. *Optik*, 267, p.169643. <https://doi.org/10.1016/j.ijleo.2022.169643>
- [43] Alafer, F., Sallam, F.H., Al Meshari, M., Alzamil, Y., Abanomy, A., Alhujaili, S. and El-Taher, A., **2024**. The influence of thermal treatment on the structural properties and gamma rays shielding of bentonite clay ceramic. *Radiation Physics and Chemistry*, 217, p.111531. <https://doi.org/10.1016/j.radphyschem.2024.111531>
- [44] Rilwan, U., Aliyu, G.M., Olukotun, S.F., Idris, M.M., Mundi, A.A., Bello, S., Umar, I., El-Taher, A. and Mahmoud, K.A., **2024**. Recycling and characterization of bone incorporated with concrete for gamma-radiation shielding applications. *Nuclear Engineering and Technology*, 56(7), pp.2828-2834. <https://doi.org/10.1016/j.net.2024.02.045>
- [45] Abbas, M.I., El-Khatib, A.M., Elsafi, M., El-Shimy, S.N., Dib, M.F., Abdellatif, H.M., Baharoon, R. and Gouda, M.M., **2023**. Investigation of gamma-ray shielding properties of bismuth oxide nanoparticles with a bentonite–gypsum matrix. *Materials*, 16(5), p.2056. <https://doi.org/10.3390/ma16052056>

