



A benchmarking analysis on different rubber materials: towards customisation of lightweight and effective radiation protection solutions for aerospace and electronic applications

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Abstract

This study examines the efficacy of rubber, a non-toxic hydrocarbon polymer, as a shielding material against gamma rays and neutrons. We analyse four types of rubbers: Neoprene, Butyl, Natural, and Silicone, using computational methods and Monte Carlo simulations *via* MCNP (version 6.3) to evaluate their gamma ray and neutron shielding parameters. Notably, Neoprene, enhanced with chlorine, shows superior gamma ray attenuation capabilities with a mass attenuation coefficient (MAC) of 760.446 cm²/g at 0.015 MeV, indicating its potential as an effective material for gamma ray shielding applications. Conversely, Butyl rubber, with its high hydrogen content, exhibits exceptional neutron attenuation properties, with the highest Σ_R value of 11.861 1/cm, making it a preferred choice for neutron shielding. This investigation underscores the versatility and environmental benefits of rubber materials in radiation protection, highlighting their potential as lightweight, customisable and sustainable alternatives to conventional shielding substances like lead. Our findings reveal prominent advantages of Neoprene for gamma ray shielding and Butyl rubber for neutron protection, contributing to the development of safer, more effective radiation protection solutions.

Keywords Rubber · Radiation shielding · Gamma-ray · Neutrons

Introduction

Ionising radiation, which encompasses X-rays, gamma rays, alpha particles, beta particles and neutrons, has a significant impact on various aspects of modern society. It plays a crucial role in fields such as medical advancements, nuclear energy and scientific exploration. Unfortunately, the adverse

impacts of ionising radiation on human health have been widely recognized since the last century [1, 2]. The ionising radiation can eliminate an electron from an atom and induce changes in its composition. Moreover, the high dosage of this radiation type poses a significant risk to human health. Therefore, it is crucial to discover a method to mitigate its impact and safeguard the human body [2–4]. The principle of As Low as Reasonably Achievable (ALARA) emphasises the need to reduce radiation exposure to levels well below allowable limits. In this context, the most effective way to lower the risk is to apply a shield between the human body and the radiation source [5]. Lead (Pb) was used and regarded as an optimal shielding material against high-energy ionising radiation for a very long time. Nevertheless, Pb is known for its inherent weakness, high costs, and most significantly, its toxicity [6–8]. Researchers are currently carrying out studies to identify suitable shielding materials that possess superior capabilities and strength compared to Pb, in order to be selected as an alternative. Polymers, being part of a group of materials, possess numerous beneficial characteristics that make them highly suitable for use in radiation shielding

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applications. An outstanding attribute of these materials is their inherent lightweight [9, 10]. Polymers, in contrast to conventional heavy metals, possess a significantly lower weight, which enables convenient manipulation, transportation, and incorporation into diverse structures. Moreover, the molecular arrangement of polymers facilitates efficient interaction with ionising radiation. Polymers possess a lengthy molecular structure that enables them to effectively absorb and disperse radiation energy, rendering them highly efficient in reducing the intensity of neutron radiation [11, 12]. The addition of lightweight elements into their composition further improves their capacity to attenuate neutron radiation. These elements have a vital function in the polymer's ability to shield, by effectively reducing the speed and weakening the impact of neutrons through processes such as scattering and moderation [13]. Several polymers are recyclable, thereby aiding in the achievement of sustainability objectives and mitigating the environmental consequences linked to material consumption. This environmentally conscious aspect is in line with current efforts to embrace sustainable practices in diverse sectors, including industries that necessitate radiation shielding solutions. In addition, polymers can be customised and adjusted to fulfill precise criteria. Supplementing additives can be incorporated to improve their shielding abilities, enabling a flexible method to engage in a different levels and forms of radiation. The ability to modify materials in various ways offers a valuable level of adaptability when designing shielding materials for different purposes [14–16]. Rubbers are inexpensive hydrocarbon polymers that are recognised for their flexibility, significant elongation at the breaking point, tear resistance, and high impact strength. It exhibits high resilience, as it can be easily bent without experiencing any cracks or damage [17–19]. On the other hand, rubber materials, with their distinctive properties of flexibility and high impact strength, have garnered attention not only for general shielding applications but also for specialised sectors such as aerospace and electronics [20]. In aerospace applications, the protection against ionising radiation is critical, particularly in the outer space environment where gamma rays and neutrons present substantial risks to both equipment and astronauts. Rubber-based polymers, owing to their lightweight and effective radiation absorption capabilities, are ideal for such applications. They contribute to the safety and durability of spacecraft and satellites, allowing for more efficient design

and reduced costs in space missions [21, 22]. Furthermore, in the electronics industry, rubber materials are increasingly utilised to shield sensitive electronic components from harmful radiation, thereby enhancing device performance and longevity. The flexible nature of rubber makes it suitable for integration into various electronic devices, ensuring protection without compromising device design or functionality [22, 23]. The objective of this study is to investigate how various rubber types, characterised by different elemental compositions, provide protection against gamma ray and neutron radiation. In this specific context, the study seeks to investigate the enhancement of rubber materials for improved shielding against neutrons and gamma rays, focusing on the impact of their chemical composition. The initial phase will involve a thorough characterisation of various materials to identify those with optimal properties. Subsequent phases may be built upon the findings, specifically enhancing the chemical structure of the most promising sample to achieve superior protection levels.

Materials and methods

This study aims to analyse the gamma ray and neutron shielding parameters of four distinct types of rubber using the Phy-X/PSD software [24]. Table 1 displays the elemental composition of each type, including their weight fraction (wt%) and densities. The values were derived from the Compendium of Material Composition Data for Radiation Transport Modelling document [25]. The findings were interpreted and presented using statistical methods and graphical representations through ORIGIN2018.

Moreover, we performed Monte Carlo simulations using the Monte Carlo N-Particle (MCNP) version 6.3 [26–29] code to estimate the photon transmission factors (TF) for four different types of rubber materials: neoprene, butyl rubber, natural rubber (NR) and silicone rubber. The simulations aimed to determine the variation of TF values as a function of energy and thickness. The MCNP 6.3 simulation setup included an isotropic point source emitting photons at specific energies corresponding to commonly used radioisotopes: 0.662 MeV (Cs-137), 1.1732 MeV, and 1.3325 MeV (Co-60). The source was positioned centrally within a spherical vacuum chamber, ensuring an unobstructed path to the detector. Various thicknesses of the rubber materials,

Table 1 The elemental composition, weight fraction, densities of all rubber types

Sample code	Elemental weight fraction (Wt.%)					Density, ρ (g/cm ³)
	H	C	Cl	O	Si	
Neoprene	5.69	54.26	40.04	-	-	1.23
Butyl rubber	14.37	85.62	-	-	-	0.92
Natural rubber	11.83	88.16	-	-	-	0.92
Silicone rubber	8.07	32.11	-	22.35	37.47	1.01

serving as attenuators, were placed between the source and detector to measure their impact on the photon transmission. Figure 1 illustrates the schematic setup of the simulation. Panel (a) depicts a 2-dimensional representation, showing the relative positions of the source, attenuator, and detector, while panel (b) provides a 3-dimensional visualisation of the modelled environment within the spherical chamber. General inputs for the MCNP simulations included the definition of the geometry, materials, source information and tally specifications [30–31]. The geometry was constructed using MCNP's combinatorial geometry descriptions, ensuring precise representation of the isotropic point source, rubber material attenuators and the detector. The materials were defined with their respective elemental compositions and densities, as provided by the MCNP cross-section libraries. For each simulation, the source definition included energy-specific photon emission, modelled as an isotropic point source. The rubber materials were modeled with six different thicknesses, capturing the attenuation properties over a range of values. Each material's macroscopic cross-sections were inputted into MCNP to accurately simulate the interaction of photons with the materials. Post-processing of the MCNP output files involved extracting the tally results to calculate the TF for each material at the specified thicknesses and energies. The variation in TF as a function of energy and thickness was analysed to understand the shielding effectiveness of each rubber type.

Results and discussions

Comparison of material densities

Materials characterised by high atomic numbers (Z) and increased densities (g/cm^3) are acknowledged for their superior efficacy in absorbing gamma rays compared to substances with lower atomic numbers. This phenomenon is exemplified by the exceptional shielding capabilities of lead. In the scope of this study, the rubber materials under examination displayed a density range spanning from 0.9 to $1.25 \text{ g}/\text{cm}^3$, as illustrated in Fig. 2. Despite the relatively low density of rubber materials, their effectiveness in gamma-ray absorption was significantly augmented due to increasing density. This enhancement is attributed to the inherent flexibility, ease of manipulation and notable strength inherent in rubber [32]. Figure 2 underscores that Neoprene rubber exhibited the highest density values, particularly with the incorporation of chlorine (Cl). The addition of 40.04% of chlorine (Cl) resulted in a notable increase in density, reaching up to $1.23 \text{ g}/\text{cm}^3$ and therefore, improve the gamma ray absorption capabilities.

Mass attenuation coefficients (cm^2/g) of the examined rubbers

Figure 3 demonstrates the mass attenuation coefficient values for each type of rubber being examined, plotted against photon energy. MAC values indicate a material's

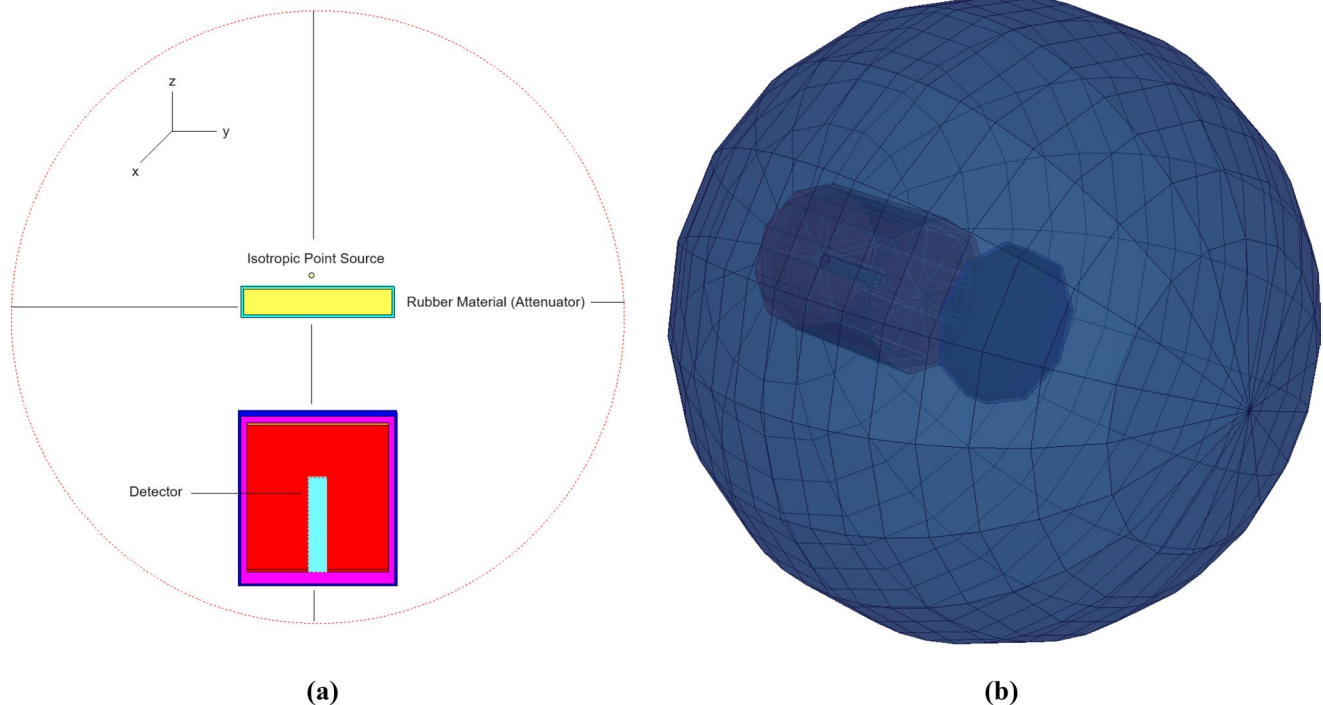


Fig. 1 (a-b) (a) 2-Dimensional and (b) 3-dimensional view of modelled MCNP 6.3 setup for Transmission Factor (TF) calculations

Fig. 2 Comparison of densities of the examined rubber types

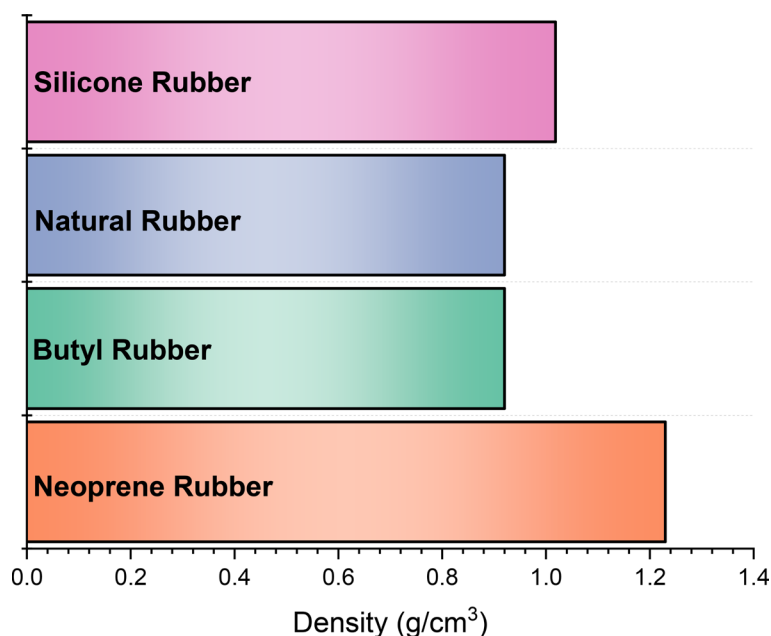
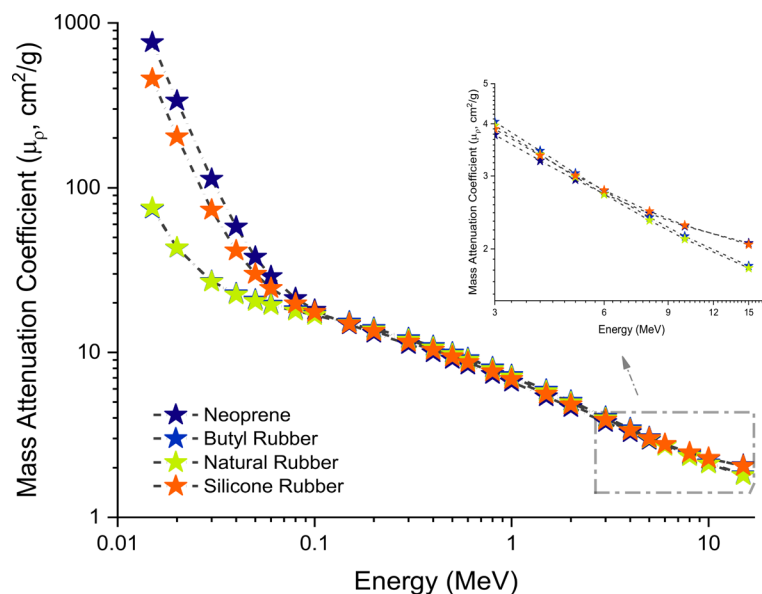


Fig. 3 Variation of mass attenuation coefficients (μ_m , cm^2/g) for different types of rubber as a function of photon energy



capacity to reduce the strength of a radiation beam as it passes through the material. In general, it is evident that there is an inverse relationship between energy and values, where higher energy levels correspond to lower values [33]. This phenomenon may arise from the substantial penetration and limited absorption of high-energy gamma rays. Neoprene rubber, with its increased density resulting from the inclusion of chlorine, displayed the highest values for all energy levels. This clearly indicates its exceptional ability to absorb gamma rays, making it highly effective in this regard. Moreover, the MAC values were measured at various energy levels, serving as a valuable technique for accurately assessing the radiation attenuation properties of the rubber materials under investigation. At a photon energy of

0.015 MeV, the mass attenuation coefficient (MAC) values for the rubber materials being studied exhibit distinct characteristics. Neoprene rubber has a significantly high MAC value of 760.446 g/cm^2 , which demonstrates its exceptional ability to reduce the intensity at this specific energy level. However, butyl rubber, NR and silicone rubber have respective MAC values of 74.549, 75.641, and 457.275 g/cm^2 . Furthermore, when the photon energy is 0.1 MeV, the MAC values for neoprene, butyl rubber, NR and silicone rubber were recorded as 18.098 g/cm^2 , 17.191 g/cm^2 , 16.829 g/cm^2 , and 17.581 g/cm^2 , respectively. Moreover, at a photon energy of 10 MeV, where pair production becomes the primary interaction mechanism [34], the MAC values for neoprene, butyl rubber, NR and silicone rubber were recorded

as 2.269 g/cm², 2.145 g/cm², 2.113 g/cm², and 2.281 g/cm², correspondingly. Overall, neoprene consistently exhibits positive MAC values, demonstrating its resilience and ability to efficiently attenuate gamma rays.

Linear attenuation coefficients (cm⁻¹) of the examined rubbers

The linear attenuation coefficient (LAC) is a gamma ray parameter that describes the ability of a shielding material to reduce the intensity of radiation as it passes through. It provides information about the interaction between gamma-rays and the material, giving valuable insights into the material's effectiveness in attenuating the radiation beam [35]. Figure 4 displays the rubber types that were analysed and utilised to calculate the LAC values across a spectrum of photon energy, ranging from 0.015 MeV to 15 MeV. The overall observation suggests that there is a decrease in LAC values as the photon energy increases and the effect of photoelectric absorption becomes less significant. Conversely, with increasing energy, the occurrence and influence of Compton Scattering and pair production become more prevalent and dominant, resulting in an increase in penetration [36]. Among the various rubber types examined, neoprene rubber demonstrates the highest performance across different energy levels, thus indicating its superior gamma ray shielding properties. Based on Fig. 4, we reported three distinct energy values that correspond to different energy regions where the mechanisms change, and the dominant interaction types arise. At an energy level of 0.015 MeV, which is in the low energy range known for the prevalence of absorption of low energy gamma rays and the predominance of the photoelectric absorption mechanisms, the measured values were recorded [37]. The values for neoprene, butyl rubber,

NR and silicone rubber were 935.349 cm⁻¹, 68.585 cm⁻¹, 69.590 cm⁻¹ and 465.734 cm⁻¹, respectively. At an energy of 0.1 MeV, the distribution became narrower, and the values are close to each other. The values are lower compared to the low-energy regions because the penetration increases, primarily due to the dominant mechanism of Compton Scattering [38]. The calculated results for neoprene, butyl rubber, NR and silicone rubber were 22.261 cm⁻¹, 15.816 cm⁻¹, 15.483 cm⁻¹, and 17.906 cm⁻¹, respectively. As the energy level rises, the values steadily decrease and the pair production mechanism becomes more prominent. At an energy of 10 MeV, the pair production mechanism dominates in high energy regions, resulting in significantly lower values compared to other regions, with only minor variations among them [39]. The values for the same sequence for neoprene, butyl rubber, NR and silicone rubber were 2.791 cm⁻¹, 1.974 cm⁻¹, 1.944 cm⁻¹, and 2.323 cm⁻¹, respectively. Notably, neoprene surpassed the other types of rubber examined in terms of highest LAC values across all energy regions with distinct characteristics.

Half value layer (HVL, cm) of the examined rubbers

As shown in Fig. 5, the study provides essential information about the Half-Value Layer (HVL) to determine how effectively different rubber types can shield against radiation across a wide range of photon energies, from 0.015 MeV to 15 MeV. It visually demonstrates the correlation between the thickness of a material and its capacity to attenuate ionising radiation intensity. The data presented in Fig. 5 demonstrates a steady rise in HVL values as photon energy increases. This observation is crucial in the field of radiation shielding, indicating that thicker shielding materials are necessary as the energy of incident photons increases to

Fig. 4 Variation of linear attenuation coefficients (μ , cm⁻¹) for different types of rubber as a function of photon energy

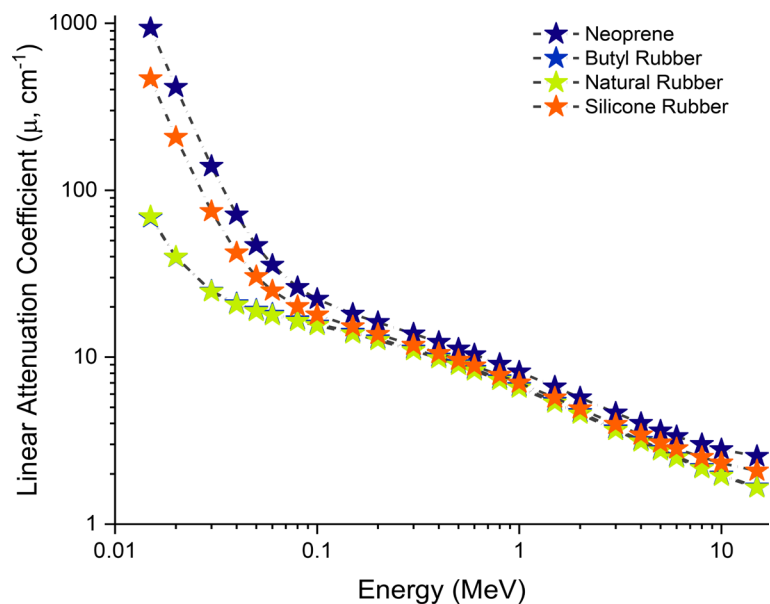
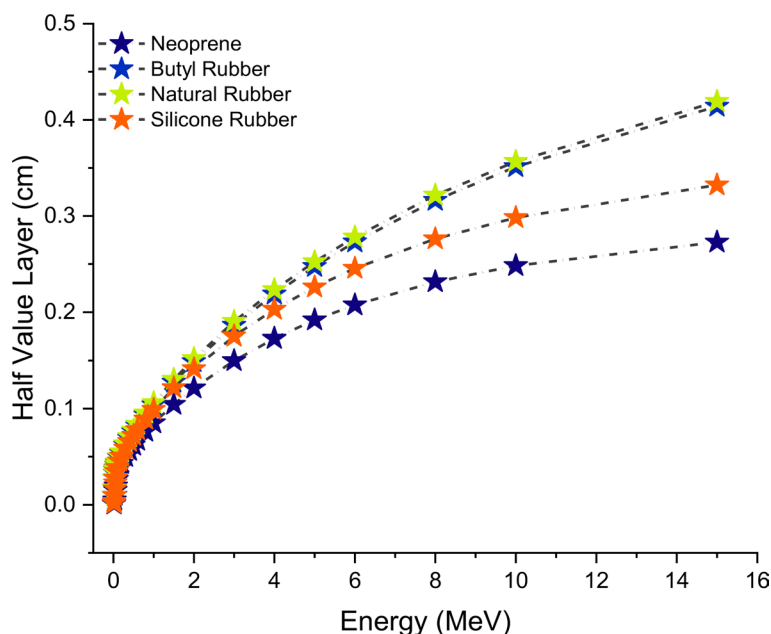


Fig. 5 Variation of half value layer (cm) for different types of rubber as a function of photon energy



effectively reduce radiation. Three separate energy regions were reported in this aspect, each distinguished by a dominant interaction mechanism. In the low-energy region, where photoelectric absorption is dominant, the values of the Half-Value Layer (HVL) remain consistently low and almost indistinguishable among different types of rubber. With an increase in photon energy, the effect of Compton scattering becomes more prominent, leading to a noticeable increase in Half-Value Layer (HVL) values. The variation depends on the density and elemental composition of each specific type of rubber [40]. At an energy level of 3 MeV, neoprene, butyl, natural, and silicone rubbers display different Half-Value Layer (HVL) values: 0.121 cm, 0.149 cm, 0.152 cm, and 0.141 cm, respectively. This indicates a transition point where both Compton scattering and photoelectric absorption have an impact. As the energy continues to increase, reaching 10 MeV, where pair production is the dominant process, Neoprene once again exhibits superior performance with a Half-Value Layer (HVL) of 0.248 cm. This means that Neoprene requires less thickness of material compared to Butyl rubber (0.351 cm), NR (0.357 cm) and Silicone rubber (0.298 cm) rubbers. Overall, neoprene rubber proves to be highly efficient in decreasing radiation intensity, demonstrating lower Half-Value Layer (HVL) values and necessitating less material thickness compared to other types of rubber. Neoprene's unique advantage makes it a promising option, particularly for applications that prioritise lightweight and efficient shielding solutions [41].

Mean free path (cm) of the examined rubbers

Figure 6 demonstrates the variation of mean free path (mfp) values of the examined rubber types as a function of photon energy. The mean free path (mfp) results introduce the average distance a photon can travel within a material before undergoing a scattering or absorption event [42]. The mfp parameter is used to assess the penetrative ability of different types of rubber, and thus, their effectiveness in providing radiation shielding [43]. The graph shows an increase in the MFP values as the energy increase. This indicates that at higher energy levels, photons have a greater probability of traveling longer distances within the material before experiencing interaction events [44]. Neoprene rubber, with the highest density, exhibited the lowest MFP values in our findings. These results suggest that neoprene has superior characteristics for shielding gamma radiation when compared to the other rubber types that were tested. Neoprene's ability to effectively reduce gamma radiation is emphasised by its higher density and lower MFP values. This highlights its potential as a strong shielding material in situations where the highest level of radiation protection is crucial.

Effective atomic number (Z_{eff}) values of the examined rubbers

Figure 7 depicts the relationship between the effective atomic number (Z_{eff}) and electron energy for the rubber being studied. Significant variations in the effective charge have been observed, which can be attributed to the dominance of different interaction mechanisms [45]. There is a clear pattern of decreasing effective nuclear charge values

Fig. 6 Variation of mean free path (cm) for different types of rubber as a function of photon energy

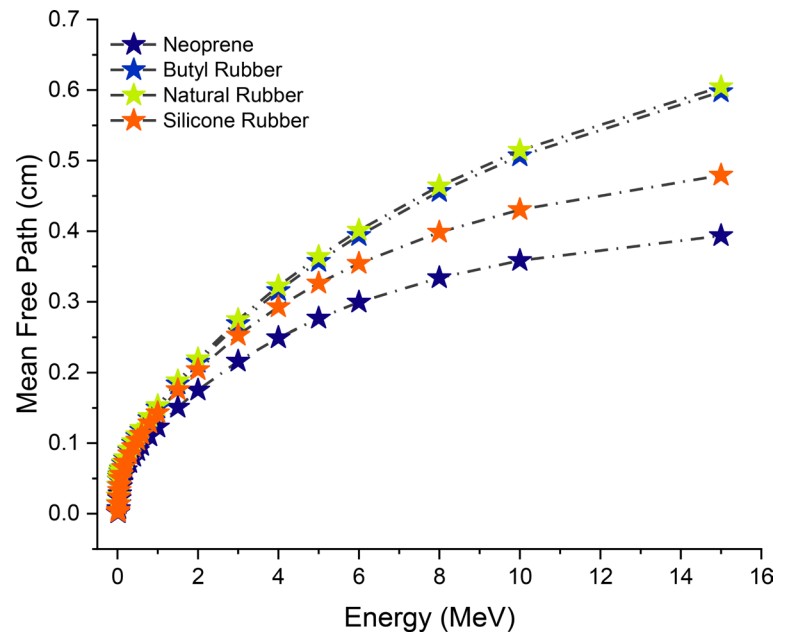
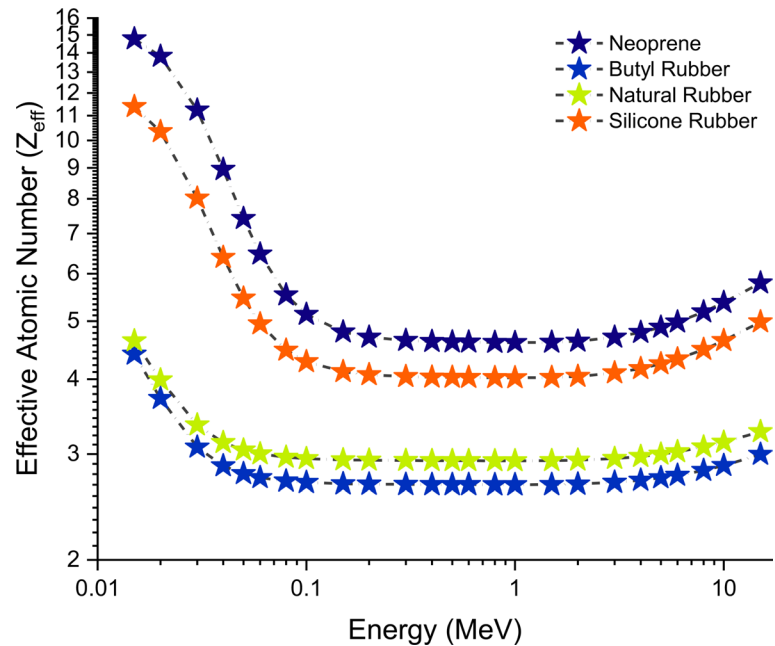


Fig. 7 Variation of effective atomic number (Z_{eff}) for different types of rubber as a function of photon energy



as electron energy increases. The highest effective efficiency values are observed in the low-energy region, indicating that the photoelectric effect is the dominant factor. In the mid-energy range, which is defined by Compton scattering, the effective atomic number (Z_{eff}) experiences a significant decrease, reaching its lowest point. Remarkably, in the energy range from 0.3 MeV to 2 MeV, the effective atomic number (Z_{eff}) remains relatively constant. This may be related to the balance between different interaction processes taking place within this energy range [46]. When the energy exceeds 2 MeV, the dominance of the pair production mechanism becomes more noticeable, leading to a

significant increase in the effective atomic number values. Significantly, among these different types, neoprene stands out due to its increased density and the inclusion of chlorine (Cl, $Z=17$), which has the highest atomic number among the elements studied. Based on our result, neoprene demonstrates the highest effective nuclear charge (Z_{eff}) values.

Effective electron density (N_{eff}) values of the examined rubbers

Figure 8 shows the variation in Effective Electron Density (N_{eff}) for different types of rubber, spanning the photon

energy spectrum from 0.015 MeV to 15 MeV. N_{eff} serves as a comprehensive framework, facilitating the understanding of intricate interactions between rubber samples and ionising radiation and enabling the quantification of the materials' radiation attenuation capabilities [47]. As depicted in the figure, the effective electron density values gradually decrease for all types of rubber as photon energy increases. Notably, this decrease persists, reaching the lowest values in the intermediate energy range. Within this specific range, the influence of density becomes less pronounced, yielding to the dominance of Compton scattering. N_{eff} remains relatively stable, signifying a balance between different interaction processes in this energy range. Beyond the 2 MeV threshold, an obvious increase in N_{eff} values is observed, indicating a shift in the dominant interaction mechanism.

Fast neutron effective removal cross-section (Σ_R) values of the examined rubbers

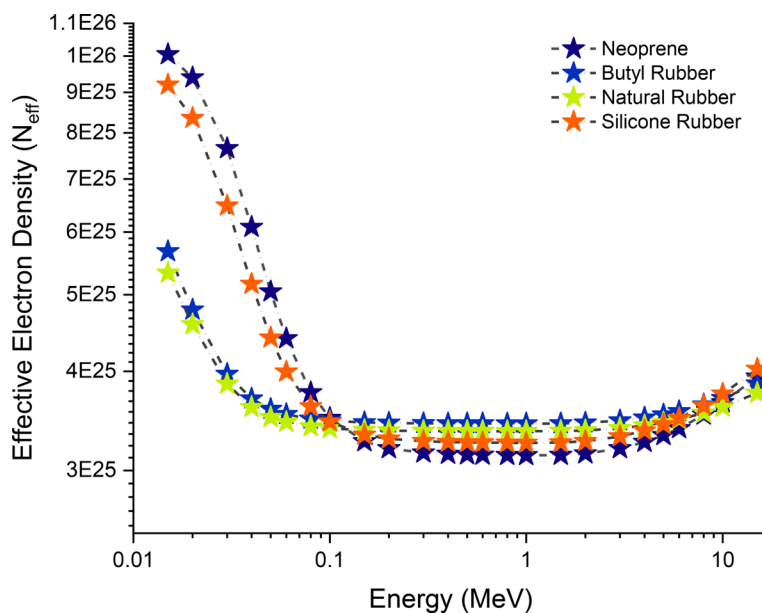
Neutron shielding materials necessitate specific properties to effectively counter the complex nature of neutron radiation. In order to effectively serve as shields, these materials must possess specific capabilities, including the ability to moderate and slow down neutrons, as well as absorb them [48]. Effective neutron shielding necessitates key properties such as a high neutron absorption cross section, which enhances the probability of absorption rather than scattering or transmission. Furthermore, these materials must possess the ability to moderate or decelerate fast neutrons. This is essential for promoting neutron capture reactions and transforming fast neutrons into thermal neutrons, which can be more easily absorbed by shielding materials [49]. Neutron capture reactions are promoted by this process, resulting

in the conversion of fast neutrons into thermal neutrons. Thermal neutrons are more readily absorbed by shielding materials, making this process crucial [50]. Elements with low atomic numbers, especially hydrogen, are important for moderating and decelerating fast neutrons because they have a strong tendency to engage in elastic scattering interactions. The effectiveness of hydrogen in moderating neutrons is due to its low mass [51]. Figure 9 displays the Fast Neutron Effective Removal Cross-Section (Σ_R) values for each rubber type that is investigated in this study. The results clearly indicate butyl rubber as the most favourable choice for neutron shielding with a result of 11.861, being the highest Σ_R value compared to the other rubber types examined. This observation highlights the superior effectiveness of this material in reducing the impact of fast neutrons, making it the preferred option for applications involving neutron shielding. The reason for this significant outcome can be attributed to the high hydrogen (H) content of butyl rubber, which has been measured at a weight% of 14.37%. The high concentration of hydrogen atoms in butyl rubber improves its capacity to moderate and decelerate fast neutrons, thereby greatly augmenting the probability of neutron capture reactions and subsequent reduction in intensity [52].

Energy absorption buildup (EABF) factor values of the examined rubbers

Figure 10 (a-d) presents information regarding Energy Absorption Build-up Factor (EABF) values for different types of rubber at varying mean free path (mfp) values as a function of photon energy. EABF is a precise measurement that represents the ratio between the total value of a specific

Fig. 8 Variation of effective electron density (N_{eff}) for different types of rubber as a function of photon energy



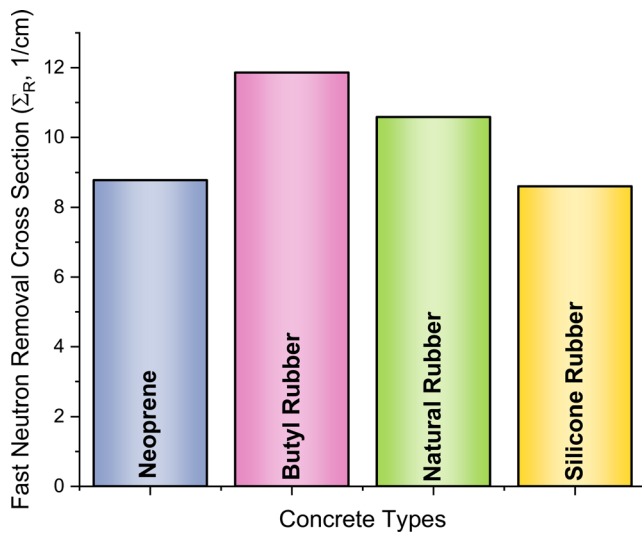


Fig. 9 Variation of fast neutron removal cross section (Σ_R , 1/cm) values for different types of rubber

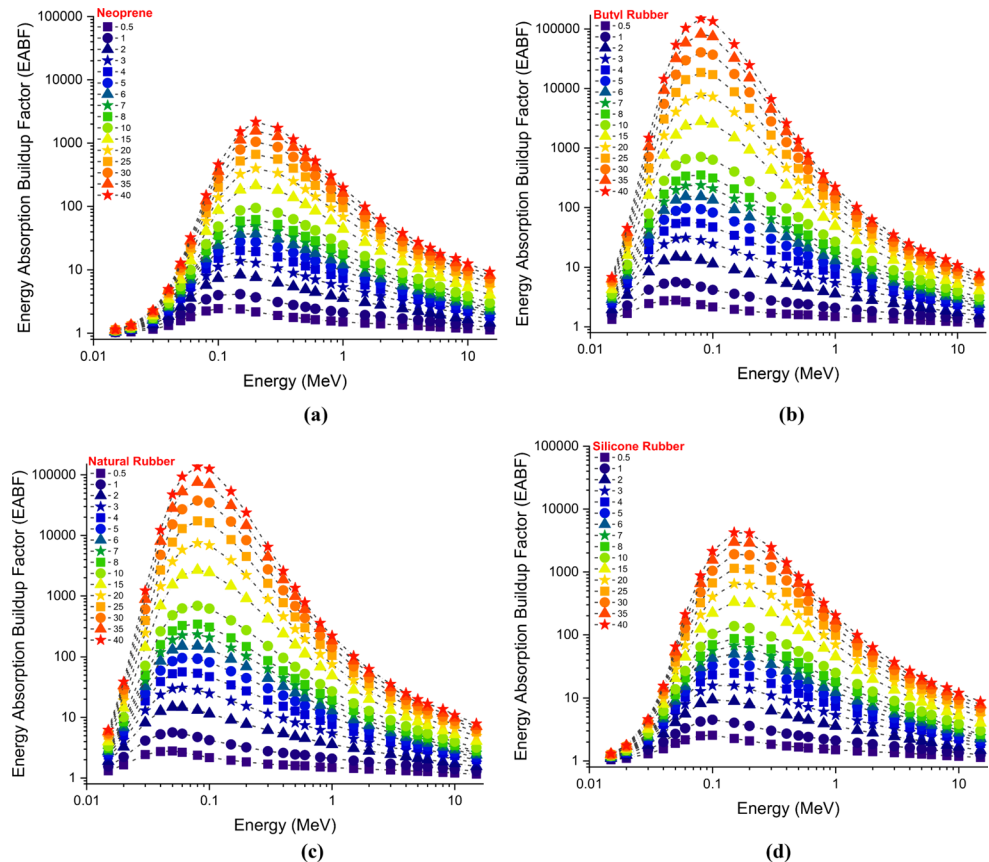
radiation quantity as it passes through a medium and the amount of radiation that reaches a specific point without any collisions occurring [53]. In the overall visual demonstration in Fig. 10, a clear pattern becomes apparent, indicating that EABF values show a consistent increase as energy levels rise, reaching a maximum point in the middle energy range. As the photon energy increases, there is a subsequent

decrease in the values of EABF. The observed behaviour can be explained by various interaction mechanisms that operate at different energy levels. In the low-energy region dominated by the photoelectric effect, a high quantity of photons is absorbed or eliminated, leading to low values of EABF. As energy levels rise, Compton scattering becomes more dominant. This process involves photons losing some of their energy instead of being completely removed [54]. The EABF values are further reduced in the high-energy regions by pair production, which is a distinct absorption process that becomes the dominant mechanism [55]. Another finding from Fig. 10 is that, as the mean free path increases, the multiple scattering events cause the EABF values to increase as well [56]. Based on the comprehensive EABF graphs presented in Fig. 10, it can be observed that neoprene exhibits the lowest value, suggesting its superior ability to absorb or interact with radiation. Considering the overall outcomes, one can say that neoprene may be more suitable for gamma-ray shielding applications due to its lower EABF values.

Benchmarking of EBF values at fixed 5 mean free path

Further investigation of the Energy Absorption Build-up Factor (EABF) was conducted to examine its behaviour at

Fig. 10 (a-d) Energy absorption build-up factor (EABF) values of (a) Neoprene (b) Butyl rubber (c) natural rubber and, (d) silicon rubber at various mean free path (mfp) values



a specific mean free path (mfp) value of 5 and represented in Fig. 11. The focus on this particular mfp value aims to provide a detailed analysis of the EABF trends under these conditions. Neoprene, in comparison to other rubber types, demonstrates an overall enhancement in attenuating incident photons across all energy levels. This improved performance can be attributed, in part, to the incorporation of chlorine in the neoprene composition, resulting in a higher density relative to the other rubber types examined. The elevated atomic number of chlorines, in contrast to other elements present in rubber, enhances the efficacy of its interaction with gamma-ray photons, contributing to the observed enhanced attenuation of Neoprene.

Transmission factor (TF) values of the examined rubbers

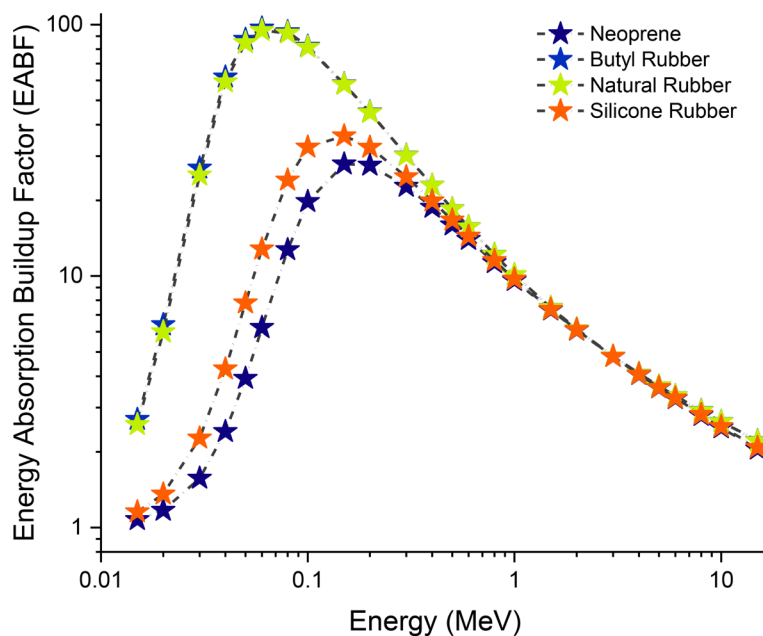
The Monte Carlo simulation study using MCNP 6.3 has revealed distinct photon transmission behaviours across four types of rubber materials at various thicknesses and energies (0.662, 1.1732, and 1.3325 MeV). Notably, Neoprene consistently exhibited the lowest transmission factors (TF), indicating superior photon attenuation properties compared to butyl rubber, NR and silicon rubber. The data, represented in Fig. 12a and c, and 12e, show that the TF decreases with increasing thickness for all materials, as expected from the physical law of exponential attenuation. However, neoprene's TF reduction is more pronounced across all measured thicknesses, signifying its effectiveness as a shielding material. The graphical representation of TF versus rubber thickness in Fig. 12b and d, and 12f for the respective energies illustrates a clear trend where the TF decreases as the photon energy increases. This is consistent

with the attenuation properties of materials, where higher energy photons are less likely to interact and are more penetrating. In the context of neoprene's performance, the results unequivocally demonstrate its superior shielding capacity across the spectrum of photon energies examined. This can be attributed to neoprene's unique composition and density, which influence its interaction cross-section for photons, thus enhancing its attenuation capabilities. The declining trend lines in the scatter plots, Fig. 12b, d and f, show a strong correlation between material thickness and TF, which is consistent across all materials but most pronounced for neoprene. The statistical significance of the difference in TF values between neoprene and other materials could be further analysed using regression analysis, providing a quantitative measure of neoprene's superior shielding effectiveness. Given neoprene's superior attenuation characteristics, it may be considered the preferable choice for applications requiring radiation shielding from photons, especially in fields where protection against specific photon energies is paramount.

Conclusion

This study evaluated the shielding efficacy of rubber materials against gamma rays and neutrons, underscoring their potential as innovative, non-toxic alternatives to traditional shielding materials. Through comprehensive computational analysis, neoprene and butyl rubber emerged as particularly effective for gamma ray and neutron shielding, respectively. Specifically, neoprene demonstrated exceptional gamma ray attenuation capabilities across a broad spectrum of energy levels, with mass attenuation coefficients reaching up to

Fig. 11 Comparison of energy absorption build-up factor (EABF) values of different rubber types as a function of photon energy at 5 mfp



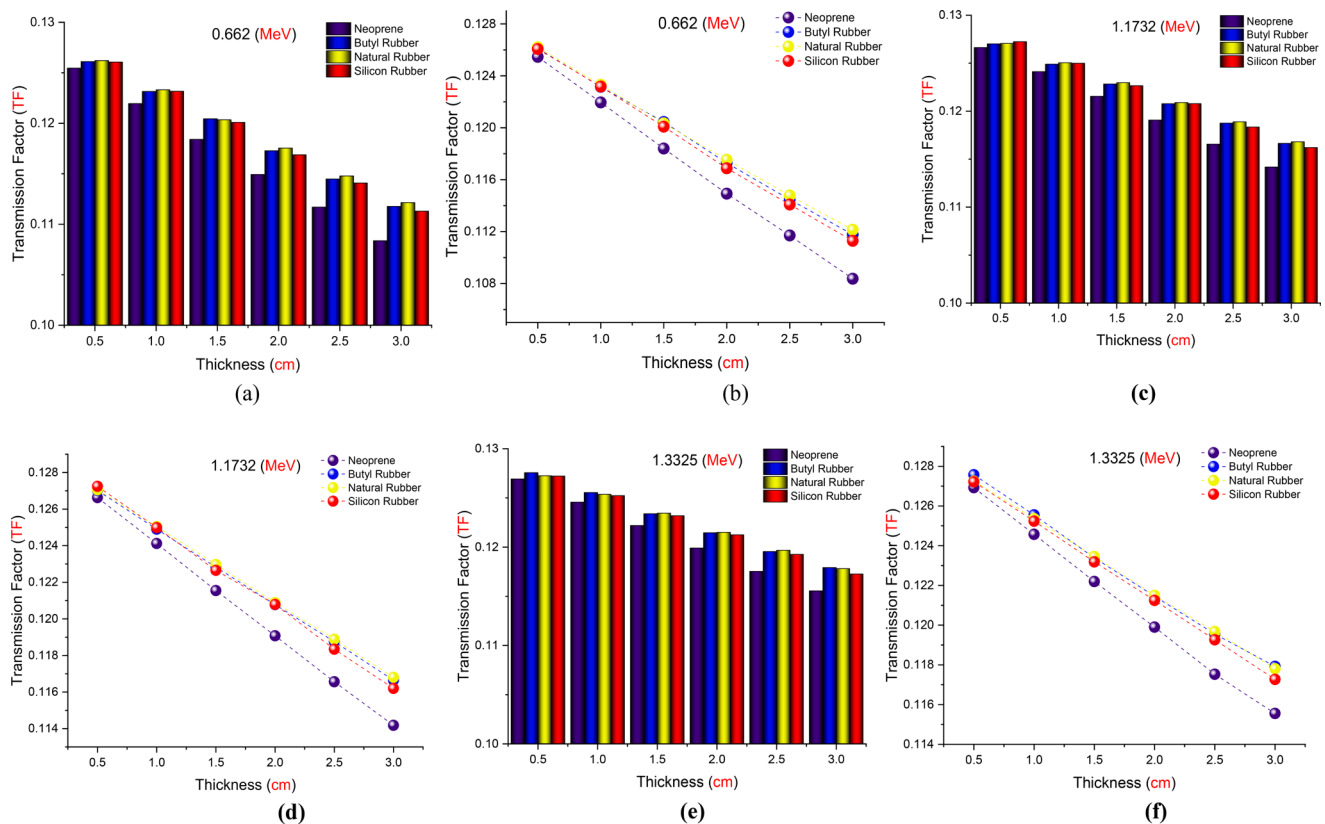


Fig. 12 (a–f) Transmission factors (TFs) for all rubber types as a function of (a–b) 0.662 MeV (c–d) 1.1732 MeV and (e–f) 1.3326 MeV radioisotope energy (MeV) at different sample thicknesses

760.446 cm²/g at 0.015 MeV. This superior performance is largely attributed to its enriched chlorine content, which significantly increases its density and enhances its radiation absorption properties. Conversely, butyl rubber showcased outstanding neutron attenuation, with the highest Fast Neutron Effective Removal Cross-Section (Σ_R) of 11.861 1/cm. This is primarily due to its high hydrogen content, which effectively moderates and absorbs neutrons, making it ideally suited for neutron-rich environments. Neoprene consistently displayed the lowest TF values, highlighting its superior attenuation properties across multiple photon energies and material thicknesses. The study identifies neoprene as a standout material with substantial gamma-ray shielding properties, surpassing butyl rubber, NR and silicon rubber in various parameters. Its superior performance can be attributed to its density, enhanced by chlorine content and its effective attenuation coefficients. Neoprene's characteristics make it a viable alternative to lead in various applications requiring radiation protection. The distinctive properties of these rubber materials, including their flexibility, high tear resistance, and significant impact strength, not only make them viable for protective applications but also offer enhanced safety features over conventional materials like lead, which poses health and environmental risks. The

findings from this investigation highlight the tailored functionalities of neoprene and butyl rubber, positioning them as customisable and sustainable solutions for radiation protection in medical, aerospace and industrial applications.

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Author contributions Hessa Alkarrani: Conceived and designed the experiments; performed the experiments; contributed reagents, materials, analysis tools or data; wrote the paper. Ghada ALMisned: Analysed and interpreted the data; contributed reagents, materials, analysis tools or data. H.O. Tekin: Contributed reagents, materials, analysis tools or data; performed the experiments; wrote the paper.

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Data availability Data will be made available upon request.

Declarations

Competing interests Not applicable.

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