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Computational Assessment of Polymer-Based Materials as Diagnostic X-Ray Beam Filters and their Implications on Environmental Challenges

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ABSTRACT
Conventional X-ray beam filters, such as Aluminum (Al), effectively remove low-energy photons but are often limited by rigidity, cost, and poor adaptability. Polymer-based materials offer a lightweight, flexible, and potentially sustainable alternative, although their filtration performance has not been comprehensively evaluated. This study computationally assessed seven polymers namely: Polymethyl Methacrylate (PMMA), Polycarbonate (PC), Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyvinyl Chloride (PVC), and Polytetrafluoroethylene (PTFE) as alternative diagnostic X-ray beam filters and compared with Al, Copper (Cu), Tin (Sn), and Tantalum (Ta). X-ray spectra were simulated using SpekPy v2.0.8 under routine diagnostic exposure conditions (66–90 kVp) with 2.5 mm inherent Aluminum filtration. PTFE transmitted significantly more photons than Aluminum ($p < 0.05$), while PVC demonstrated attenuation which is equivalent to Aluminum across all examinations. In contrast, Cu, Sn, and Ta produced excessive attenuation at the tested thickness. These findings identify PVC as a promising alternative diagnostic X-ray beam filter, combining attenuation performance comparable to Aluminum with the added advantages of reduced weight, flexibility, recyclability, and potential for sustainable reuse.

Keywords:
Polymer materials,
X-ray Filters,
Fluence Energy Spectrum,
Air Kerma,
Simulation.

INTRODUCTION

Ionising radiation has been beneficial to mankind in several ways. X-rays, an electromagnetic radiation, remains one of the vital tools in diagnostic radiology. The advent of technology has further enhanced its applications in the last three decades. In diagnostic radiology, x-rays are produced from x-ray tubes, a device designed and built to produce as many x-rays as feasible. The x-rays emitted during the process are focused to a target material (such as patient), thereby constituting to the diagnostic imaging quality. Improving the quality of the medical images always implies increasing the radiation exposure to the target, which invariably increases the risk (Bushberg *et al.*, 2020).

X-ray imaging requires a special approach since too low radiation could be as bad as too high, thereby making the images obtained to be unsuitable for diagnostic quality (IAEA, 2020). More so, since x-rays are heterogeneous in nature, the low energies produced during production are filtered out, as they contribute nothing to the image quality. But rather, these radiations increase the amount of energy deposited on the target material. This therefore necessitates the application of filterers, a device that remove low energy photons and preventing them to get to the target (Bushberg *et al.*, 2020). Hence, x-ray filters play a significant role by minimising the radiation dose to the patient and improving image quality.

Traditionally, x-ray filtering materials has been Aluminum and Copper for general purpose x-ray systems. However, in a situation where low energy beams are required such as in mammography, materials such as molybdenum and rhodium are used (Goel *et al.*, 2025). These materials decrease image contrast as they filter out low-energy photons, increased tube load and exposure time which invariably requires longer exposure time, as well as increase in the production of Compton scattering which can degrade image quality. In addition, these traditional materials are categorised as lightweight metals, but advances in materials science and metallurgical are moving towards a lighter, more flexible, and cheap materials for radiation applications. It is in view of this, that polymer materials are gaining significant attention in radiation application, not only for shielding purposes, but also in radiation dosimetry and biomedical devices.

Hence, this study aims to computationally explore the potential of polymer materials for use as x-ray filters to address some of the challenges of the traditional filters. The findings of this study will contribute to existing body of knowledge from the perspective of material development and radiation protection in radiation environment, and also provides a new usefulness for these polymer materials, thus expanding the scope of their functionalities and applications. This study will also intimate the manufacturer of medical appliances, most especially x-ray imaging modalities by identifying filtration alternatives that improve beam quality while limiting needless patient exposure. In addition, the integration of polymer materials as x-ray filters will combat environmental waste by sanitising the environment from the pollution induced by polymer materials and improve the global economy, an activity that aligns with the Sustainable Developments Goals of Life on Land.

MATERIALS AND METHODS

Filter Materials' Characteristics

Table 1 presented the characteristics of the polymer materials namely; Polymethyl Methacrylate (PMMA), Polycarbonate (PC), Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyvinyl chloride (PVC), Polytetrafluoroethylene (PTFE), and conventional materials considered in this study. The conventional materials (Aluminum and Copper) serve as the reference filters so as to compare the performance of the polymer materials as x-ray filters. The relevance of these materials for spectral shaping research lies in their varying elemental compositions and attenuation efficiencies.

X-ray Machine Specification

The study adopted the specification of MARS 50+ x-ray machine manufactured by Allengers Medical Systems Limited as the x-ray tube. The machine uses 2.5 mm Aluminum as the filtering material and rated at 800 mA by 50 kVp for x-ray tube output. This x-ray machine has been applied for various diagnostic examinations such as Skull (Cranial region), cervical spine (Neck region), Chest/Thorax (Upper torso), Thoracic spine (Middle and upper back), Abdomen (Belly area, just below the thorax), Lumbar spine (Lower back, behind the abdomen) and Pelvis (Lower torso, beneath the abdomen). Ayanlola *et al.* (2026) has earlier reported on applications of this x-ray machine for diagnostic examination.

Table 1: Characteristics of Materials Investigated

Materials	Density (g/cm^3)	Z_{eff}
Polymethyl Methacrylate	1.18	6.5-6.7
Polycarbonate	1.20	6.7-6.9
Polyethylene	0.94	5.7-6.0
Polystyrene	1.06	5.6-5.8
Polyvinyl Chloride	1.41	14-15
Polytetrafluoroethylene	2.25	8.3-8.5
Polypropylene	0.90	5.8-6.0
Aluminum	2.70	13
Copper	8.96	29
Tin	7.31	50
Tantalum	16.65	73

Computational Tools

This study made use of the SpekPy ver. 2.0.8. SpekPy is an open-source Python-based software toolkit, distributed under the MIT license and used for the simulation and calculation of diagnostic X-ray spectra. The software generates X-ray tube spectra by modeling bremsstrahlung production and characteristic X-ray emission from tungsten anodes under different operating conditions such as tube voltage (kVp), filtration, anode angle, and target material. The software is based on the well-established SpekCalc model developed by Gavin Poludniowski and later extended into a Python implementation. SpekPy enables users to compute photon fluence spectra, air kerma, half-value layer

(HVL), mean photon energy, and filtered beam characteristics. These outputs are important in diagnostic imaging system design and radiation dosimetry. The software is designed primarily for medical physics, diagnostic radiology, dosimetry, imaging optimization, and Monte Carlo radiation transport studies. It is widely used in research and clinical physics because accurate X-ray spectra are essential for estimating beam quality, patient dose, detector response, and shielding performance.

Simulation Procedure

Firstly, the tube potentials ranging from 66 kVp to 85.9 kVp was simulated to represent the full spectrum of conventional diagnostic radiographic examinations, encompassing low-energy extremity imaging, intermediate skeletal and chest radiography, and higher-energy abdominal and thoracic procedures. An inherent filtration equivalent to 2.5 mm of Aluminum was simulated as the reference filter to replicate regulatory requirements for minimum total filtration in diagnostic radiology. Additional filtration was modelled using 2.5 mm thicknesses of each selected polymer materials PMMA, PC, PE, PS, PVC, PTFE, and PP, to enable comparative evaluation of beam hardening and attenuation characteristics as a function of material composition, effective atomic number, and density while maintaining constant geometrical thickness to isolate compositional effects on spectral modification.

The photon energy spectrum was discretized using an energy bin resolution of 0.5 keV to ensure accurate representation of the bremsstrahlung continuum and tungsten characteristic emission peaks, improve numerical precision in spectral integration procedures, and enhance the reliability of derived beam quality metrics such as mean photon energy and Half value layer without imposing excessive computational demand. For each tube potential and filtration configuration, photon fluence spectra and air kerma was quantified thereby enabling quantitative assessment of spectral hardening effects and facilitating comparison across different polymer filtration materials. These processes are summarized with the flowchart in Figure 1. This process was repeated for all the diagnostic examinations listed in Table 2.

Table 2: The Types of X-Ray Examinations (Kvp and Mas) Selected for Investigation

Examination	kVp	MAs
Thorax	80.5	25.5
Pelvis	77.8	28.0
Cervical Spine	74.5	24.2
Thoracic Spine	72.2	40.3
Lumbar Spine	85.9	42.5
Chest	70	25
Abdomen	90	25
Skull	66	19

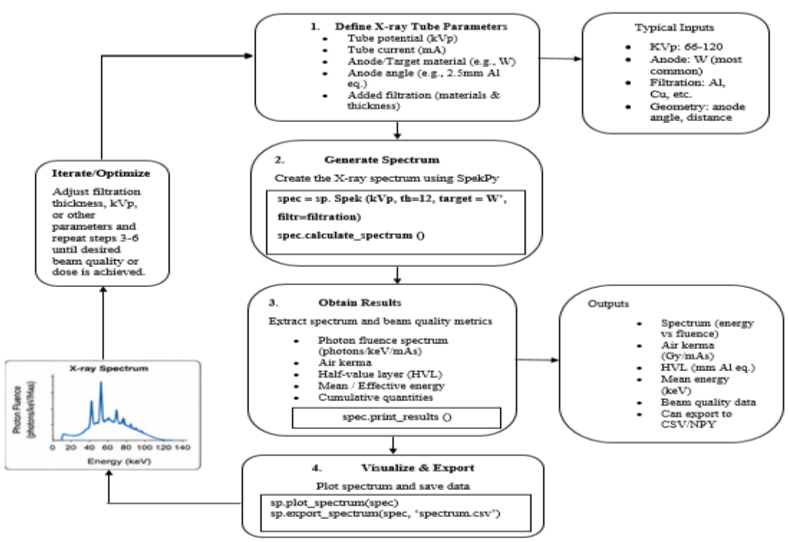


Figure 1: Workflow for the Computational Analysis

Data Analysis

The data obtained in this study were pre-processed with Microsoft Excel 2014 and analysed with OriginPro 2024.

RESULTS AND DISCUSSION

Effect of Filtering Material on X-Ray Fluence Spectra at Different Examination

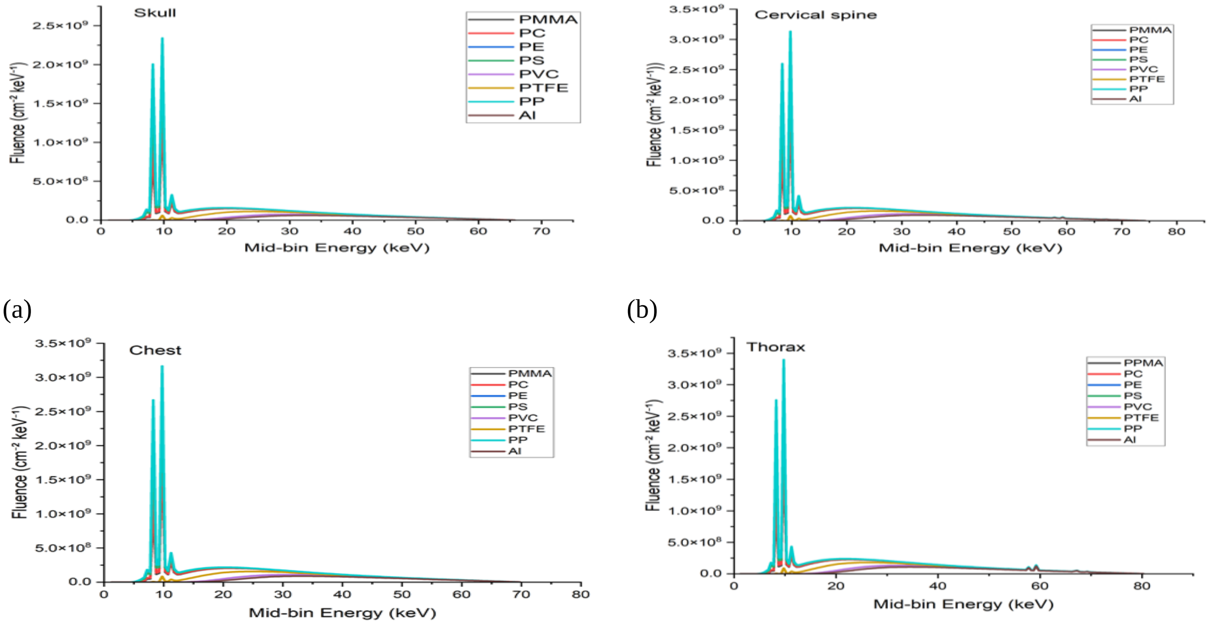
Presented in Figure 2 a – h are the results obtained for the effect of the investigated filtering materials on the x-ray fluence spectra as a function of photon energy for the seven selected x-ray diagnostic examinations. Fluence, a radiation parameter that quantify the total number of particles or radiation energy passing through a unit cross-sectional area over a specific time. Thus, its understanding allows for the evaluation of radiation safety limits and calculate potential dose rates from various radioactive sources and also optimize fluence maps, ensuring that the prescribed dose is accurately delivered to a target while sparing surrounding healthy tissue.

The spectra indicate how each material modifies the transmitted X-ray beam energy distribution in the diagnostic energy range, which is strongly governed by the photoelectric effect and Compton scattering interactions (Bushberg *et al.,* 2020). It was observed that for each of the examination, the most prominent feature in the spectra is the presence of very sharp peaks between 8 and 11 keV, especially for PP, PE, PMMA, and PC. These peaks correspond to characteristic low-energy X-ray photons, which are commonly produced from fluorescence interactions or selective attenuation processes in low-Z materials (Cherry *et al.,* 2012). This is followed by the broad bremsstrahlung distribution extending toward higher photon energies in nearly all materials, and this represent the transmitted portion of the diagnostic X-ray spectrum after interaction with the filtering materials and the target object. The decrease thereafter suggests that fewer high-energy photons are present in the original beam or survive attenuation through the medium (Wunderle, 2016; Bushberg *et al.,* 2020).

In all, PP exhibits the highest fluence, indicating that PP provides the least attenuation in the low-energy region, therefore allowing a greater transmission of low-energy photons compared with denser or higher-Z materials. Low-Z polymers generally have lower photoelectric absorption coefficients at diagnostic X-ray energies, resulting in higher photon transmission. Because PP is composed mainly of carbon and hydrogen, its effective atomic number is relatively low, reducing photoelectric absorption and permitting more photons to pass through the target region. However, PMMA, PC, PE, and PS show similar spectral distributions after the sharp low-energy peaks, with broad continua extending from approximately 15 to 60 keV. The gradual decrease in fluence with increasing energy indicates that lower-energy photons dominate the transmitted spectrum, while higher-energy photons are progressively fewer due to the original tube spectrum and attenuation processes. Whereas, PVC and PTFE exhibit lower fluence values than the hydrocarbon-based polymers. This reduction is likely due to the presence of higher-atomic-number elements such as chlorine in PVC and fluorine in PTFE. Higher-Z elements increase photoelectric absorption, particularly in the diagnostic energy range where the photoelectric effect is strongly dependent on approximately (Z^3/E^3). Consequently, these materials attenuate low-energy photons more effectively, leading to lower transmitted fluence.

Despite these, notable variations in spectral intensity and distribution were observed as a function of anatomical composition and thickness. Regions with lower density, such as the thorax and chest, demonstrated higher photon fluence in the low-energy range due to reduced attenuation, whereas denser regions such as the pelvis, abdomen, and skull showed diminished low-energy intensity and relatively hardened spectra. The cervical spine displayed intermediate spectral characteristics, reflecting its mixed composition of bone, soft tissue, and air cavities. The thoracic and lumbar regions exhibited broader and more extended spectra, reflecting increased tissue thickness and higher energy requirements for adequate penetration. The lumbar spine, in particular, showed the widest spectral distribution.

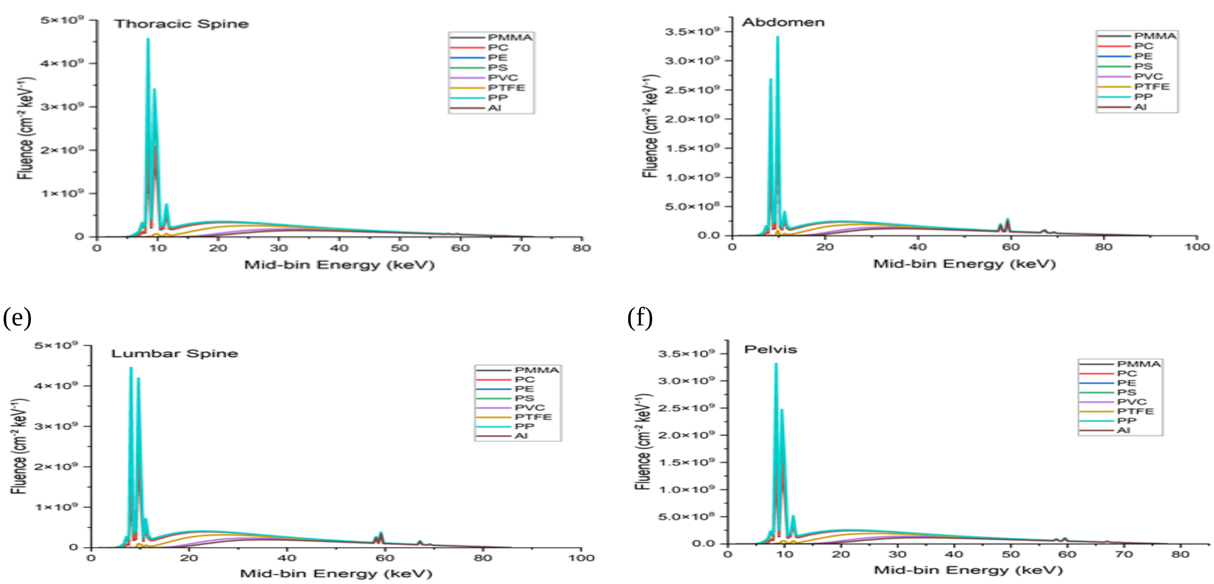
This response is consistent with existing observations that filter materials selectively remove low-energy photons, raising the mean beam energy, enhancing beam quality, and reducing patient dose (Bartzsch *et al.,* 2020; Ravanbakhsh *et al.,* 2025). Furthermore, polymer-based materials have been demonstrated to exhibit varying attenuation depending on their composition and density, with some high-performance polymers reaching the filtering capabilities of conventional metals (Belarra *et al.,* 2026). The findings suggest that, materials like PTFE and PVC may be feasible alternatives to Aluminum, providing good spectrum shaping while potentially allowing for more flexible or application-specific filter designs. Recent investigations on polymer-based X-ray attenuation materials reveal that composite and fluorinated polymers (e.g., PTFE) have superior attenuation capabilities due to higher electron density and molecular structure, making them appropriate for diagnostic filtration applications (Okonkwo *et al.,* 2022; Messele *et al.,* 2026). Thus, for pelvic imaging, where penetration is crucial, materials like PTFE and PVC, which effectively remove low-energy photons while keeping higher-energy components are superior for optimizing image quality and patient dose. Materials such as PMMA, PC, and PVC may provide an appropriate balance for cervical spine imaging by moderately attenuating low-energy photons without significantly lowering overall beam intensity. This supports the potential for polymer-based filters to be tuned for specific diagnostic applications, which is consistent with emerging trends in customized radiological materials.



(a) (b)

(c) (d)

Figure 2 a – d: X-ray Spectrum for Skull, Cervical Spine, Chest, and Thorax



(e) (f)

(g) (h)

Figure 2 e – h: X-ray Spectrum for Thoracic Spine, Abdomen, Lumbar Spine, and Pelvis

Quantify the Air Kerma Values of Each Material for Diagnostic Purposes

The results obtained for the x-ray fluence spectrum translated to the performance of each filtering material regarding air kerma values for different diagnostic examination (3 a – h). Air kerma represents the kinetic energy transferred from indirectly ionizing photons to charged particles in air and is widely used in diagnostic radiology dosimetry to monitor the amount of radiation being directed at the patient. Thus, as observed with the x-ray fluence spectrum, PP produces the highest air kerma across all the polymer materials in each of the diagnostic examination investigated, closely followed by PE and PS. Polyethylene and PP demonstrate particularly high air kerma values because they are primarily composed of carbon and hydrogen, elements with relatively low effective Z. The lower attenuation efficiency of such materials reduces photon absorption and enhances transmitted beam intensity. This result is consistent with the attenuation principles where photon attenuation decreases significantly for materials with lower Z and densities (Cherry *et al.*, 2012). This further confirms that these low-Z polymeric materials allow greater transmission of X-ray photons through the filter system, as low-Z materials exhibit lower photoelectric absorption coefficients in the diagnostic X-ray energy range, thereby permitting more photons to penetrate and contribute to air kerma (Busherg *et al.*, 2020).

PMMA and PC exhibit intermediate air kerma values respectively. These results suggest moderate attenuation properties compared with PE and PP, indicating a balance between attenuation and photon transmission, making them potential materials for optimized filtering. PMMA and PC contain oxygen-containing molecular structures, which slightly increase their effective Z and attenuation capabilities relative to hydrocarbon-based polymers. However, PVC and PTFE produce substantially lower air kerma values than the other polymers. This strong reduction is attributable to the presence of higher-Z elements such as chlorine in PVC and fluorine in PTFE. Higher-Z elements enhance photon attenuation through increased photoelectric absorption probability, particularly at lower diagnostic X-ray energies. This is consistent with accepted radiological principles, which state that beam filtration improves beam quality and lowers needless radiation dose by eliminating low-energy photons (Seibert, 2004; Bushberg *et al.*, 2020).

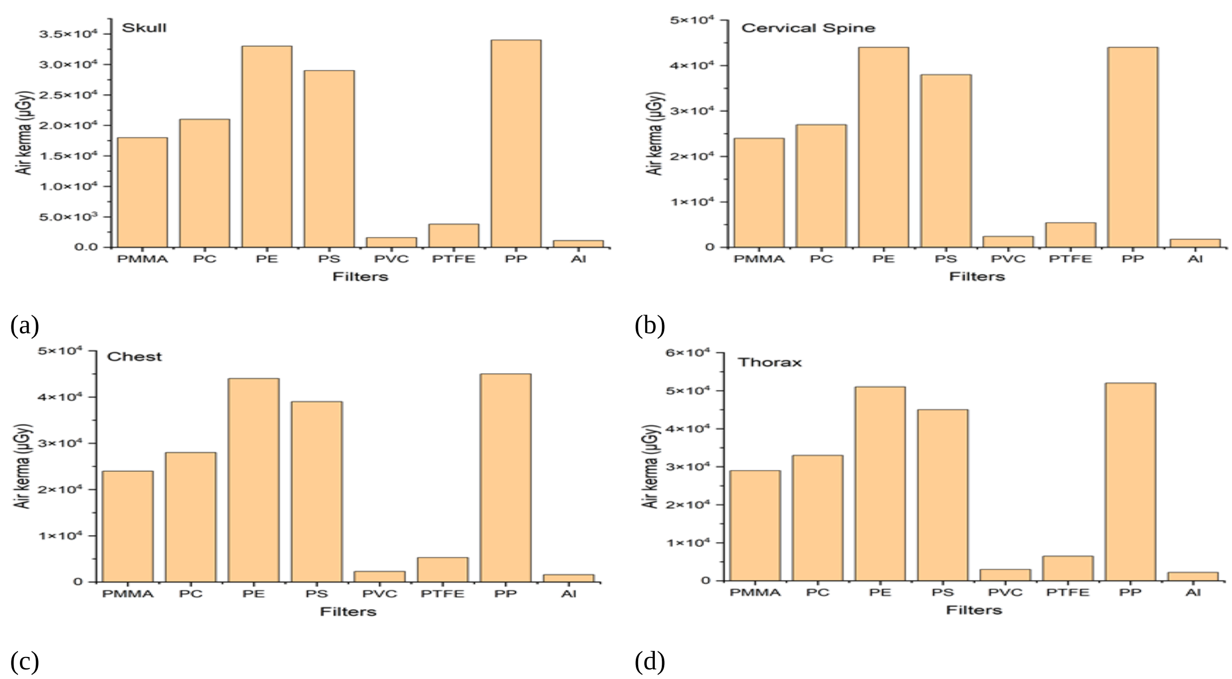
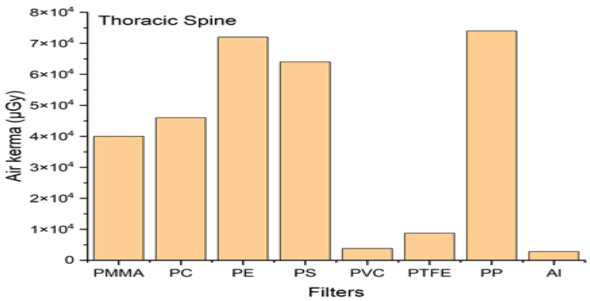
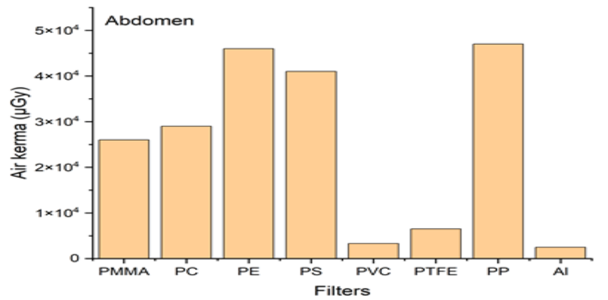
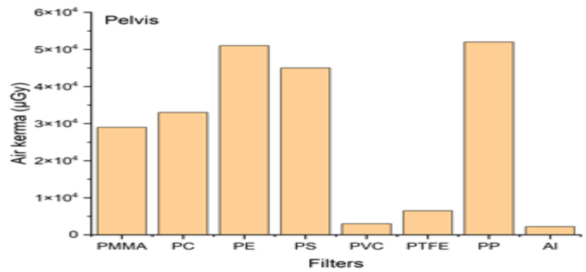


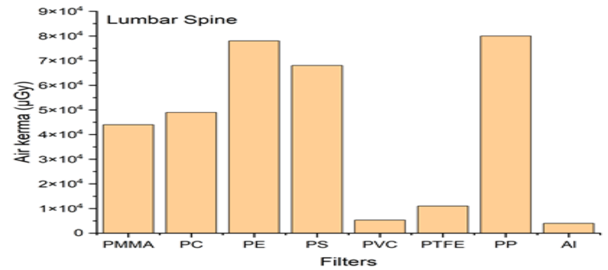
Figure 3 a – d: Air Kerma Distribution for Skull, Cervical Spine, Chest, Thorax





(g) (f)





(g) (h)

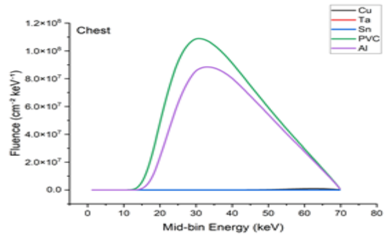
Figure 3 e – h: X-ray Spectrum for Thoracic Spine, Abdomen, Pelvis, and Lumbar Spine

Compare Best Performing Polymer Material with Conventional Filters

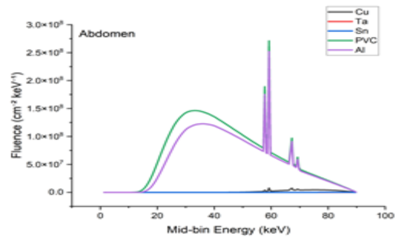
Presented in Figure 4 a – c is the result obtained for the performance of the best performing polymer material to the conventional filtering materials categorized as lower-Z materials (PVC and Aluminum) and high atomic number (Z) metals (Cu, Ta, and Sn). It can be inferred that for the chest spectrum Cu, Sn, and Ta considerably attenuate the beam while PVC and Aluminum produce broad bremsstrahlung distributions. The comparatively higher fluence across the spectrum is a result of the chest region's lower tissue density which permits stronger photon transmission. Because abdominal tissues are thicker and denser, the abdomen and pelvis spectra show more intricate relationship between filter material and photon dispersion, as evidenced by their higher fluence distribution of bremsstrahlung with a peak fluence of about 30 – 40 keV and distinctive peaks around 60 – 70 keV, when compared to other materials.

The sharp peaks in the PVC and Aluminum spectra indicate contributions from characteristic radiation, which becomes more noticeable after the bremsstrahlung continuum is partially filtered. The material's high Z and accompanying photoelectric absorption coefficients, which increase attenuation, especially at lower photon energy, are responsible for this phenomenon. Furthermore, selective attenuation and spectrum shaping caused by K-edge absorption effects in high-Z materials result in the observed suppression in fluence (Bushberg *et al.*, 2020). High-Z materials are very good at eliminating low-energy photons because this suppression is consistent with the photoelectric effect's dominance at lower photon energies, which is substantially dependent on atomic number (Z^3 dependency) (Seibert, 2004; Bushberg *et al.*, 2020). However, excessive attenuation, as seen with Ta and Sn, may result in inadequate photon flux reaching the detector, so reducing image quality, even though this lowers the patient dose (Kalender, 2011). Conversely, Aluminum preserves enough photon-energy photons while lowering low-energy contributions, maintaining a more balanced attenuation profile. Similar behavior is shown by PVC, though its transmitted fluence is marginally higher.

The implication of this fluence distribution on the air kerma values as shown in Figure 4 d - f is that Aluminum and PVC, demonstrate significant X-ray beam transmission compared to Cu, Sn, and Ta respectively. Although, Cu, Ta and Sn show substantial photoelectric absorption, especially in the diagnostic energy range, however, this leads to almost complete suppression of photon fluence and lowering air kerma. However, the incredibly low transmitted intensity indicates over-filtration, which could make the beam inadequate for diagnostic imaging. PVC and Aluminum, on the other hand, permit more photon transmission, preserving useable beam intensity while offering a modest level of filtration and dose. This confirms that excessive filtration can significantly reduce dose but may compromise diagnostic image quality. These results are in line with well-established radiological principles, which state that adequate photon flux for image creation and dose reduction must be balanced for optimum filtering (Bushberg *et al.*, 2020).



(a)



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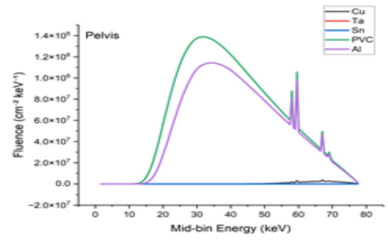

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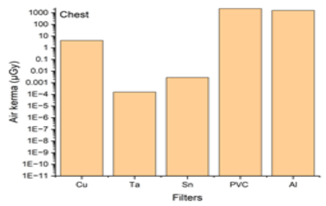

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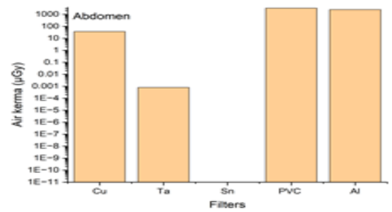
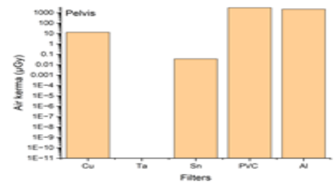


(e)



(f)

Statistical Significance of the Photon Fluence Distribution

The photon fluence results demonstrated statistically significant differences among the filter materials as shown in Table 3. The results show that filter material has a significant impact on photon transmission and beam quality, with increased fluence values recorded in thicker anatomical regions like the thoracic and lumbar spine due to greater penetration requirements.

Table 3: Mean Photon Fluence Distribution

	Al (cm^{-2} keV^{-1} × 10^7)	PTFE (cm^{-2} keV^{-1} × 10^7)	PVC (cm^{-2} keV^{-1} × 10^7)
Thorax	4.92 ± 3.97 [b]	8.12 ± 6.09[a]	5.93 ± 4.69[b]
Pelvis	5.18 ± 4.14 [b]	8.73 ± 6.47[a]	6.27 ± 4.94[b]
Cervical Spine	4.19 ± 3.39 [b]	7.26 ± 5.43[a]	5.11 ± 4.06[b]
Thoracic Spine	6.69 ± 5.42 [b]	11 ± 8.76[a]	8.22 ± 6.51[b]
Lumbar Spine	9.05 ± 7.35 [b]	14 ± 1.08[a]	10 ± 8.59[b]
Chest	3.95 ± 3.24 [b]	7.14 ± 5.35[a]	4.88 ± 3.91[b]
Abdomen	5.58 ± 4.69 [b]	8.63 ± 6.70[a]	6.60 ± 5.42[b]
Skull	2.76 ± 2.28 [b]	5.19 ± 3.87[a]	3.45 ± 2.77[b]

[A] indicates PTFE is statistically significance at $p < 0.05$ when compared with Aluminum. [b] indicates PVC is not statistically significance at $p < 0.05$ when compared with Aluminum.

Statistically, PTFE consistently recorded the highest mean fluence values across all anatomical regions and was significantly different at $p < 0.05$ whereas, there is no significant difference between Aluminum and PVC. This confirms that filter material significantly influences photon fluence, with PTFE favoring transmission, while Aluminum and PVC provide comparable attenuation. These findings therefore suggest that PVC and PTFE have the potential to function as substitutes for Aluminum in X-ray filtration applications, particularly where lightweight, flexible, or polymer-based filter systems are desired. Thus, their properties can be fine-tuned within the context material science for clinical diagnostic radiology systems.

Implication on Environmental Challenges

The use of PVC and PTFE as X-ray filtering materials could help to reduce environmental pollution caused by polymer waste if recycled or discarded polymer materials are repurposed for medical and radiation-shielding applications rather than accumulating in the environment. Globally, plastic littering has become a major environmental concern since large quantities of polymer materials survive for extended periods in soil, drainage systems, rivers, and seas due to their sluggish biodegradation rates, according to the United Nations Environment Programme (UNEP, 2026).

If waste PVC and PTFE materials can be treated and developed into functioning X-ray filters, it will open up new opportunities for value-added recycling and waste reutilization. This strategy accords with the concepts of the circular economy (Mugisha, 2025) and regularly promoted by Organisation for Economic Co-operation and Development (OECD, 2025), where waste materials are reused in productive applications rather than discarded into the environment. Polymer waste can be converted into radiation filtering materials, reducing the amount of plastic litter in landfills and adjacent ecosystems.

Thus, the current study found that PVC and PTFE had significant X-ray attenuation capabilities, notably in lowering low-energy photon fluence and air kerma. This improves beam filtration, lowering unnecessary patient radiation doses, which is beneficial to public health and aligns with the basic principle of keeping radiation As Low As Reasonably Achievable (ALARA), one of the basic tenets of radiation protection recommended by the International Commission for Radiological Protection (ICRP). This shows that these polymers have useful radiological properties and are not only waste items. Thus, if polymer filters can attain clinically acceptable filtration performance while reducing manufacturing costs or increasing flexibility, they may improve healthcare accessibility, particularly in low-resource settings. Their use in X-ray filtration systems could thus give two benefits: radiation beam optimization and reduced environmental waste. According to the World Health Organization, sustainable waste reuse initiatives are vital for lowering environmental pollution and health concerns linked with mismanaged plastic disposal (WHO, 2025).

PTFE and PVC are already commonly found in industrial and home waste streams, making them potentially inexpensive materials for experimental filter development. These are lightweight materials, and lighter medical components may have lower transportation energy costs and manufacturing resource needs than metallic filters. Furthermore, if these polymers are developed into durable, reusable, and long-lasting filtration systems, their environmental impact per usage cycle may be reduced. Furthermore, reusing waste polymers for medical physics applications may lessen the demand for virgin raw materials used in filter production. Manufacturing new industrial materials requires energy and natural resources, whereas recycling existing polymers conserves resources and reduces environmental impact.

Furthermore, the use of polymer waste in X-ray filtration research could spur innovation in sustainable healthcare technologies. The healthcare industry contributes significantly to global trash output, and including recyclable materials into imaging components could help promote environmentally responsible medical practices. This approach is consistent with the United Nations' global sustainability goals, particularly sustainable production and consumption initiatives categorized as Goal 12 (Responsible Consumption and Production), Goal 13 (Climate Action), Goal 14 (Life below Water), and Goal 15 (Life on Land).

Successful deployment would necessitate suitable processing and safety controls. Waste PVC, for example, may contain additives or impurities that can alter radiation attenuation consistency or release dangerous substances during processing. Purification, characterisation, and standardization would be required before recycled polymers could be properly used in diagnostic imaging systems.

CONCLUSION

This study evaluated the performance of conventional, polymer-based, and high atomic number (high-Z) materials as X-ray beam filters across eight routine diagnostic examinations, focusing on photon fluence, air kerma, beam attenuation, and dose optimization. The results demonstrated that filter material significantly influences X-ray beam quality and patient radiation dose. Polypropylene (PP) and Polyethylene (PE) transmitted more low-energy photons, resulting in higher photon fluence and air kerma, whereas Aluminum (Al) effectively hardened the beam by removing low-energy photons while preserving diagnostically useful higher-energy photons. PTFE and PVC exhibited moderate attenuation characteristics, with PTFE allowing greater photon transmission and PVC providing a more favorable attenuation profile despite slightly higher air kerma than Aluminum. High-Z materials reduced low-energy photon fluence through photoelectric absorption and beam hardening; however, Tin (Sn) and Tantalum (Ta) produced excessive attenuation at the tested thicknesses, making them unsuitable for routine diagnostic imaging because of potential image degradation from over-filtration. Copper (Cu) offered a more balanced compromise between radiation reduction and beam transmission. Overall, the findings highlight that appropriate filter selection is essential for optimizing image quality while minimizing patient dose. Although

Aluminum remained the benchmark filter, the balanced attenuation characteristics of PVC and PTFE suggest that, with further development and material optimization, polymer-based filters could serve as practical alternatives in diagnostic imaging while simultaneously helping to reduce environmental pollution through the beneficial reuse of polymer waste.

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