Original Article

PLA-Based Simulator for Dosimetry Assessment of Healthcare Waste

Silva[a*], H. L. L.; Cussiol[b], N. A. M.; Campos[c], T. P. R.

[a] Federal University of Minas Gerais, Itacon Oncology Services Ltda, radioterapiahugo@gmail.com, Belo Horizonte, Minas Gerais, Brazil. Gerais, Brazil.
[b] Projeto Hospitais Saudáveis – PHS/ONG, noilcussiol@gmail.com, Belo Horizonte, Minas Gerais, Brazil.
[c] Federal University of Minas Gerais, tprcampos@yahoo.com.br, Belo Horizonte, Minas Gerais, Brazil.

*Correspondence: radioterapiahugo@gmail.com

Abstract: Healthcare waste (HCW) requires efficient treatment prior to final disposal to prevent the spread of pathogens and environmental contamination. Ionizing irradiation has emerged as a promising alternative to incineration; however, accurate absorbed-dose determination depends on knowledge of the material's radiological properties. This work aims to develop a physical simulator for HCW to support dosimetric evaluation of irradiated waste, including experimental and computational validation. Data from the National Institute of Standards and Technology (NIST), along with the XCOM and ESTAR programs, were used to obtain mass energy-absorption coefficients for photons and mass stopping power for electrons in the energy range of 0.1 to 20 MeV. Two approaches were considered: a full compositional model representative of typical HCW, and a simplified model based on Polylactic Acid (PLA), containing only C, O, and H, assuming that PLA adequately reproduces the predominant elemental fraction of the waste. Dosimetric validation was performed by comparing mass attenuation coefficients (μ) and stopping power (S) between HCW and PLA. Computational simulations using PHITS evaluated the spatial dose distribution from photons and electrons. A physical simulator was subsequently manufactured by 3D printing in PLA, with a density of 0.15 g/cm³ and internal hexagonal geometry to reflect realistic waste packing characteristics. Comparisons of attenuation and stopping power coefficients showed minimal differences between HCW and PLA, demonstrating radiological equivalence. Simulations and analyses confirmed that the simulator effectively reproduces the spatial dose distribution, with good homogeneity and fidelity to real behavior. The use of PLA proved to be a practical, economical, and technically consistent solution for constructing simulators aimed at improving dosimetric processes in ionizing radiation treatment of healthcare waste, while also enabling reproducible studies with strong potential for practical application.

Keywords: Healthcare Waste; Dosimetry; PLA Phantom; 3D Printing; Monte Carlo Simulation; Industrial Radiation Processing.

Simulador de PLA para Dosimetria em Resíduos de Saúde

Resumo: Os resíduos de serviços de saúde (HCW) exigem tratamento eficiente antes do descarte para evitar a disseminação de patógenos e a contaminação ambiental. A irradiação ionizante surge como alternativa promissora à incineração, porém requer conhecimento das propriedades radiológicas do material para determinação precisa da dose. Este trabalho tem o objetivo de desenvolver um simulador físico para HCW visando auxiliar na avaliação dosimétrica de resíduos irradiados, com validações experimentais e computacionais. Foram utilizados dados do National Institute of Standards and Technology (NIST) e os programas XCOM e ESTAR para obter coeficientes de absorção de energia de massa para fótons e poder de freamento de massa para elétrons entre 0.1 e 20 MeV. Consideraram-se duas abordagens: um modelo completo com a composição típica dos HCW e um modelo simplificado baseado em Poliácido Lático (PLA), contendo apenas C, O e H, assumindo que o PLA reproduz adequadamente a fração elementar predominante dos resíduos. A validação dosimétrica consistiu na comparação dos coeficientes de atenuação mássica (µ) e de freamento (S) entre HCW e PLA. Simulações com PHITS avaliaram a distribuição espacial de dose para fótons e elétrons. Um simulador físico foi então produzido por impressão 3D em PLA, com densidade de 0.15 g/cm³ e geometria interna hexagonal para representar o empacotamento real dos resíduos. As comparações entre os coeficientes de atenuação mássico e poder de frenagem indicaram diferenças mínimas entre HCW e PLA, demonstrando equivalência radiológica. As simulações e análises confirmaram que o simulador reproduz adequadamente a distribuição espacial de dose, com boa homogeneidade e fidelidade ao comportamento real. O uso de PLA mostrou-se uma solução prática, econômica e tecnicamente consistente para construção de simuladores destinados ao aperfeiçoamento de processos dosimétricos em tratamento de resíduos por radiação ionizante, além de favorecer estudos reprodutíveis com elevado potencial de aplicação.

Palavras-chave: Resíduos de Serviços de Saúde; Dosimetria; Simulador de PLA; Impressão 3D; Simulação Monte Carlo; Processamento por Radiação Industrial.

1. INTRODUCTION

The treatment of HCW with ionizing radiation has proven to be a promising alternative to conventional methods, such as incineration or chemical treatments for pathogenic inactivation of this waste, with the effectiveness of the process depending on the precise dose distribution within heterogeneous waste, according to TATA and BEONE [8]. Healthcare waste presents a complex chemical composition according to ADUAN *et al.* [1], making dosimetry calculations challenging.

Studies carried out by SILVA *et. al.* [7] demonstrated that the predominant elements in HCW are carbon and oxygen, followed by chlorine, hydrogen, and sodium. Our hypothesis is to analyze whether only three of these main elements (C, O, H) would be sufficient to radiologically mimic HCW with low relative uncertainties, thus simplifying both computational simulations and the development of physical simulator objects for dosimetric purposes. To test and optimize radiological waste treatment processes, a solid simulator capable of reproducing or mimicking the average elemental properties of hospital waste is necessary, allowing reproducible assessments without biological risks.

In addition to the need for solid simulators and consistent dose models, the industrial context of healthcare waste sterilization requires increasing attention to the final destination of the post-irradiation material. Ionizing radiation does not reduce the physical volume of waste but transforms potentially infectious biological material into a stable and safe Healthcare waste compatible with conventional disposal routes, such as industrial landfills. Therefore, dosimetric validation becomes essential to ensure that irradiation not only eliminates microorganisms but also guarantees that the resulting waste complies with current sanitary and environmental regulations.

The use of high-dose-rate linear and circular industrial accelerators, such as Rhodotron®, Dynamitron®, linacs, and betatrons, has increased significantly in the last

decade, enabling continuous processing of large volumes of healthcare waste with high energy efficiency and excellent operational repeatability. These systems allow dose rates exceeding tens of kGy/s, drastically reducing the exposure time required for sterilization and increasing installed treatment capacity. The optimization of dosimetry systems and physical simulators, such as the one proposed in this study, strengthens quality control in these facilities by providing a reliable metrological basis for periodic process validation.

Additionally, the use of high-energy beams in waste treatment systems enables the exploration of more sophisticated dose deposition conditions. For the scientific field, this represents the opportunity to develop standardized process qualification methodologies, which are essential to transform radiological treatment of healthcare waste into a widely adopted and auditable reference technology.

This study proposes the construction of a simulator object to the healthcare waste, minimizing risk in HCW manipulation on the dosimetry protocol setups. To achieve such goal, the comparison of the dosimetry between HCW and the simulator object will be carried out. Subsequently, computational simulations of the absorbed dose deposition at 25 kGy, a typical of pathogenic inactivation, will be considered using the PHITS - Particle Transport Software [5]. The PHITS particle transport software employs the Monte Carlo method to track the trajectory and energy deposition of photons and electrons in matter. Such simulations support the feasibility of replacing the average chemical composition of healthcare waste with a simplified material, offering a practical solution for the development of HCW simulator objects.

2. MATERIALS AND METHODS

2.1. Chemical composition of the HCW and simplified material models

The Brazilian National Health Surveillance Agency - RDC 222 [6] classifies HCW into groups and subgroups, each with distinct requirements for storage, segregation, and treatment.

Due to insufficient segregation, most HCW in Brazil is composed of a mixture of groups A1, A4, B, and D. The stoichiometric proportion of chemical elements in unsegregated HCW as determined by SILVA *et al.* [7] is as follows: Carbon (C) 52.526%, Oxygen (O) 25.349%, Chlorine (Cl) 9.851%, Hydrogen (H) 6.770%, Sodium (Na) 1.395%, Calcium (Ca) 0.528%, Sulfur (S) 0.400%, Silicon (Si) 0.155%, Nitrogen (N) 0.086%, Fluorine (F) 0.053%, Iron (Fe) 0.042%, Boron (B) 0.018%, Potassium (K) 0.018%, Chromium (Cr) 0.011%, Aluminum (Al) 0.006%, Nickel (Ni) 0.001%, Titanium (Ti) 0.001%, Copper (Cu) 0.001%. The total characterized proportion is 97.211%, with miscellaneous elements (unknown proportion) constituting 2.789%.

For simplification, only the three most abundant elements (C, O, and H) were used in the simplified dosimetric model, representing approximately 84.6% of the elements characterized in HCW. Thus, for the development of the simulator object representing HCW, we used PLA – Polylactic Acid $[-O-CH(CH_3)-CO-]n$, whose proportions of chemical elements are presented in Table 1.

Table 1- Proportions of elements in the material PLA.

Formulation	C (%)	H (%)	O (%)	Total (%)
$[-O-CH(CH3)-CO-]n$	50.0	5.6	44.4	100.0

Source: Authors.

2.2. Differences in the mass energy-absorption for photons and electron stopping power coefficients

The mass energy-absorption for photons and mass stopping powers for electrons coefficients were determined using NIST databases through the XCOM and ESTAR software, for energies ranging from 0.1 to 20 MeV. Both the complete HCW composition (18 elements) and simplified material model of PLA were evaluated. The density of HCW (0.15 g/cm³), as determined by NEVES [2], was kept constant in the simulator object.

2.3. HCW and Simplified material model Simulation on PHITS

We performed the irradiation simulation of a PHITS package representing HCW as a cylindrical shape, 0.53 m in height and 0.14 m in radius, irradiated by electron and photon beams at a distance of 0.10 m from the edge of the package. The particle source generation was based on an industrial Rhodotron TT300 accelerator with a power of 50 kW, as shown in Figure 1. The irradiation field has rectangular dimensions at its exit measuring 1.00 m in length and 0.30 m in width and is sealed by a thin 1.0 mm titanium plate to maintain the vacuum inside the beam steering horns. The simulation was performed so that the packages were irradiated by two parallel and opposite fields.

We used an average photon and electron beam energy of 10 MeV in the form of an energy spectrum for the simulation, since in the analysis between HCW and PLA, both the mass energy-absorption coefficient and the mass stopping power showed percentage differences below 3.0%. Additionally, this energy is characteristic of sterilization processes ZHAO, Y *et. al* [9] for medical–hospital materials prior to use, ensuring good beam penetration and dose uniformity.

Figure 1. Schematic representation of the irradiation of the package containing HCW by an industrial linear accelerator using PHITS. Source : Authors
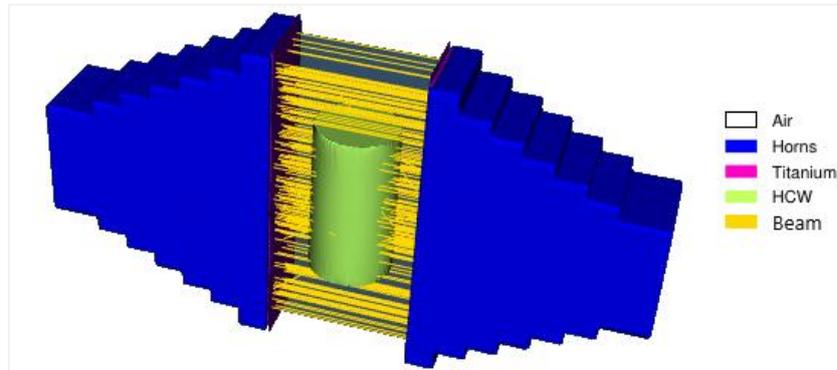
The HCW simulator made of PLA was modeled with the same dimensions and a density of 0.15 g/cm³, characteristic of HCW, using the setup represented in Figure 1.

The package containing HCW with 18 chemical elements and the PLA simulator were modeled in PHITS so that the pathogenic inactivation dose of 25 kGy was delivered to both. The time required to deliver the absorbed pathogenic dose and the absorbed dose homogeneity throughout the package were analyzed to verify the similarity of dose absorption between the package containing HCW and the simulator made of PLA.

The selection of PLA as the simulator material was not based solely on elemental composition, but rather on an integrated set of radiological, operational, and practical criteria. PLA demonstrated dosimetric equivalence with HCW within the energy range relevant to industrial irradiation processes, as confirmed by the results presented in this study. In addition, PLA offers excellent dimensional stability and geometric reproducibility in fused deposition modeling (FDM) additive manufacturing. In contrast PVA and PETG that have C and O fractions similar to HCW, polyvinyl alcohol (PVA) is highly hygroscopic and mechanically unstable, while PETG presents higher thermal shrinkage and greater difficulty in achieving dimensional control for low-density internal structures. Moreover, PLA shows significantly lower sensitivity to humidity when compared to PVA, which undergoes rapid degradation under such conditions. Finally, PLA is widely available, low cost, and biologically

safe, characteristics that are particularly relevant for applications related to healthcare waste. These combined factors justify the choice of PLA as the most suitable material for the development of a reproducible and practical physical simulator.

2.4. Simplified object simulator construction

For the development of the PLA simulator object using a 3D printer, the model was manufactured with 50 stacked layers, each composed of 91 hexagonal cells with side dimensions and wall thicknesses evaluated to produce in a final material density of $0.15 \ \mathrm{g/cm^3}$.

The hexagonal configuration was adopted since enables control of longitudinal heterogeneity within the simulator volume, while also providing space between layers for the insertion of dosimetric films or alternative detectors to verify the absorbed dose during irradiation experiments.

3. RESULTS

3.1. Chemical composition of the simple material model

Table 2 compares the resulting proportions of the 3 elements obtained in the PLA, with the 3 same elements of the HCW.

Table 2 - Comparison between PLA elements and the 3 same elements of HCW.

| Material/Element	C (%)	O (%)	H (%)	Total (%)
PLA	50.00	44.40	5.60	100,00
HCW	52.53	25.35	6.77	84,60
Δ% p.p	+2.53	+19.05	-1.17	+15.40

Source: Authors.

The use of PLA for HCW simplification provided similarity in the proportion of the three main elements in HCW, with differences of approximately: C (+2.55 p.p), O (+19.05 p.p), and H (–1.17 p.p).

The simplification of the healthcare waste object composition, reducing it from 18 elements (C, O, Cl, H, Na, Ca, S, Si, N, F, Fe, B, K, Cr, Al, Ni, Ti, Cu) to only 3 (C, O, and H), proved to be an effective approach for representing radiation interaction properties while maintaining an acceptable margin of global uncertainty of <0.8% for a coverage factor of k = 2, ensuring a confidence level of approximately 95%.

3.2. Coefficient differences in the photon mass energy-absorption and electron stopping power at HCW and simplified material model.
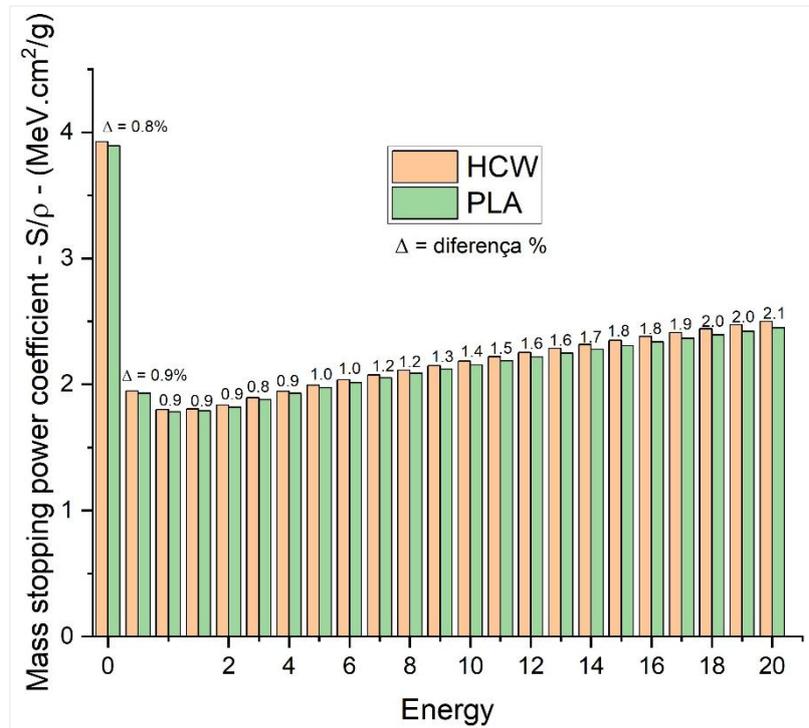
The coefficient differences of the mass energy-absorption for photons and electron stopping power between HCW and simplified material model are presented in Figures 2 and 2, respectively. For each energy level, the absolute percentage difference between the full-composition and simplified-composition models was calculated.

Figure 2. Percentage difference of the mass energy-absorption coefficient between complete HCW and simplified model (PLA) as a function of photon beam energy (0.1-20 MeV).
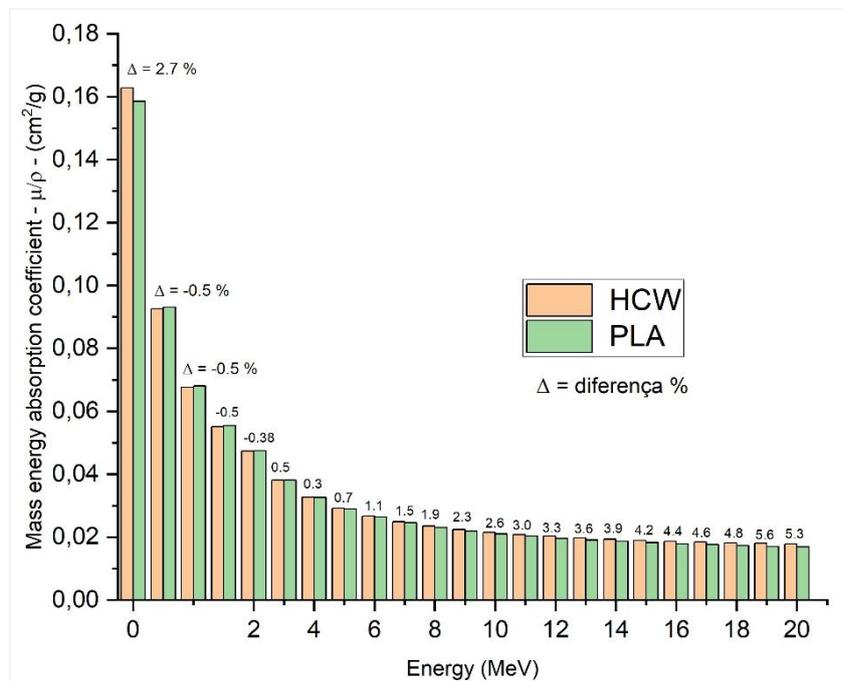
Source : Authors

Figure 3. Percentage difference of the mass stopping power between complete HCW and simplified model (PLA) as a function of electron beam energy (0.1 – 20 MeV)

Source: Authors

The comparison between complete HCW and simplified PLA models revealed a maximum absolute percentage difference of 5.6% for the mass energy-absorption coefficient and 2.1% for the mass stopping power coefficient. For an energy of 10 MeV, which is the most commonly used for pathogenic inactivation in medical materials, the variation was 2.6% for photons and 1.4% for electrons. This small variation confirms that the 15 removed HCW elements, which collectively account for less than 15.4% of the total mass composition, had negligible influence on the overall attenuation and stopping properties of the material.

Furthermore, maintaining the same density (0.15 g/cm³) in the simplified PLA model ensured that variations in linear coefficients (μ and S) were exclusively due to elemental composition rather than density changes.

3.3. HCW and Simplified material model Simulations on PHITS

The irradiation simulations performed with PHITS over an exposure time of 1.0 s demonstrated that the average absorbed dose rate for photons throughout the HCW package was (0.13 ± 0.02) kGy/s, as shown in Figure 4 A, and (0.12 ± 0.01) kGy/s for the PLA simulator, as shown in Figure 4 B, demonstrating high homogeneity in both methods, indicated by the dose plateau along the longitudinal axis of the package.

The time required to deliver the pathogenic inactivation dose of 25 kGy was (192.3 ± 0.5) s for HCW and (208.3 ± 0.5) s for PLA, representing an increase of only (16.0 ± 0.5) s in the delivery time of the absorbed pathogenic dose.

Figure 4. Absorbed dose profile across the whole diameter simulated using PHITS, showing high dose homogeneity throughout the irradiated volume for (A) the HCW package at 10 MeV photons; (B) the PLA simulator object at 10 MeV photons; (C) the HCW package at 10 MeV electron; and (D) the PLA simulator object at 10 MeV electron.
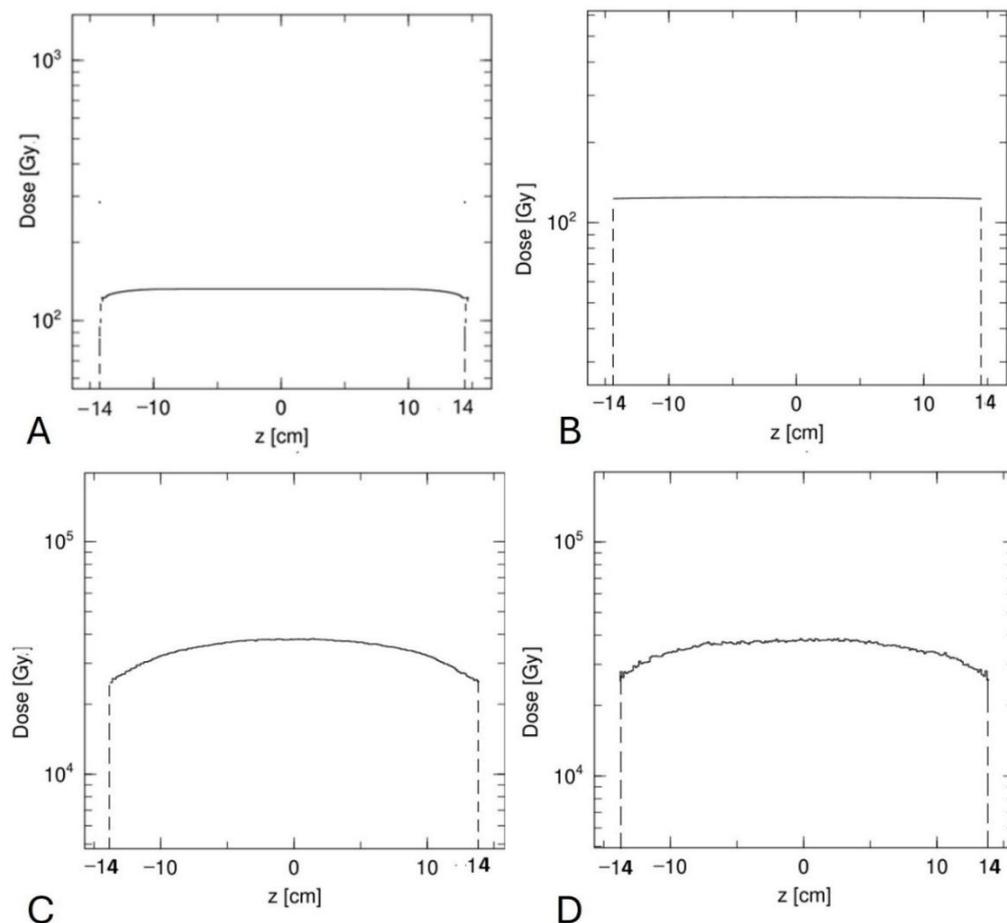
In the simulations performed using electron beams with an irradiation time of 1 s, the mean absorbed dose rate throughout the entire HCW package was found to be (31.5 ± 6.5) kGy/s, as shown in Figure 4 C, while the PLA simulator presented a dose rate of (32.0 ± 6.0) kGy/s, as illustrated in Figure 4 D. These results indicate lower dose homogeneity compared to the photon irradiation method; however, the electron beam delivered a significantly higher absorbed dose rate, compensating for the spatial non-uniformity of dose deposition along the irradiated volume.

The average time required to deliver the pathogenic inactivation dose of 25 kGy uniformly throughout the package was (0.79 ± 0.05) s for HCW and (0.78 ± 0.05) s for the PLA simulator, corresponding to a minimal increase of only (0.01 ± 0.05) s in the absorbed dose delivery time between the two models. The declared global uncertainty for both absorbed dose and irradiation time using electron beams is based on a standard uncertainty multiplied by a coverage factor k = 2, corresponding to a 95% confidence level, in accordance with international metrological recommendations.

Although the Monte Carlo simulations modeled both HCW and PLA as homogeneous media, the presence of internal voids in the physical PLA simulator does not compromise the dosimetric equivalence. The hexagonal internal structure was designed to reproduce the same apparent density (0.15 g/cm³) used in the simulations, ensuring mass thickness equivalence. In the megavoltage energy range, dose deposition is mainly governed by mass density and mass interaction coefficients and is weakly sensitive to small-scale geometric heterogeneities. Therefore, the internal voids realistically represent the HCW structure and do not invalidate the computational results.

The apparent density of 0.15 g/cm³ adopted in this study represents a widely reported operational average for healthcare waste (HCW). In practice, HCW density may vary depending on waste segregation, composition, and degree of compaction, with typical values reported in the range of approximately 0.10 - 0.25 g/cm³. Within this realistic variability range, changes in density primarily affect linear attenuation and energy deposition

parameters, while mass-based coefficients remain essentially unchanged. For the megavoltage energy range investigated, such density variations are expected to result in absorbed dose differences below 5%, which are within the uncertainty margins considered in this work and do not alter the dosimetric equivalence or the conclusions of the study.

The small percentage difference observed between the mass energy-absorption coefficient and the mass stopping power of complete HCW material (composed of 18 chemical elements) and the PLA-based simulator, combined with the computational particle transport simulations performed in both media, demonstrated consistent similarity in absorbed dose deposition, dose homogeneity, and mean pathogenic dose delivery time. These results supported the technical feasibility of developing a PLA-based simulator object for dosimetric applications in HCW treatment processes.

The uncertainty budget applies to all dosimetric results reported in this study, as they are derived from the same Monte Carlo simulation framework using identical radiation interaction data (NIST XCOM and ESTAR), material models, geometry, and an apparent density of 0.15 g/cm³. The main independent contributions include 0.3% from radiation interaction data, 0.2% from Monte Carlo statistical uncertainty, and 0.2% from material composition and density assumptions. Although their relative impact may vary among quantities, these common sources result in a combined standard uncertainty of approximately 0.4% and an expanded uncertainty of approximately 0.8% (k = 2), which are representative and conservative for all results presented.

3.4. Simplified object simulator construction

The geometry of the model was set as presented in Figure 5. Each layer contains a central rotational axis, as illustrated in Figure 6, which allows the plates to be rotated relative to each other. The PLA simulator object is presented in Figure 7, manufactured by additive 3D printing, not only reproduces the energy absorption characteristics of HCW for photons and electrons in the energy range typically used for industrial sterilization of medical

products, but also matches the characteristic material density reported for HCW in the literature. These features establish the object as a suitable and reliable physical simulator for dosimetric studies in the radiation treatment of healthcare waste.

Figure 5. Geometric representation of a single structural plate of the PLA simulator object, showing top and side views of the hexagonal cell arrangement.

Figure 6. Geometric representation of the central rotational axis of the PLA HCW simulator plates, enabling mechanical adjustment and dosimeter insertion.

Figure 7. PLA simulator object manufactured using 3D printing, showing the stacked layers and the ability to rotate plates to adjust internal heterogeneity.
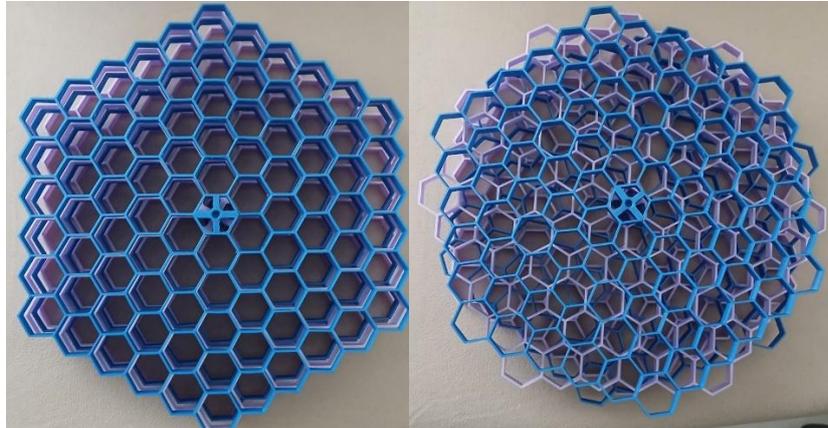
4. DISCUSSION

The identification of the three most abundant elements in HCW, specifically those that constitute more than 1.0% of its composition was performed. One can observe that those elements are also part of the composition of PLA. The elements C, O, and H in HCW is included on the chemical composition of PLA, whose formula is $[-O-CH(CH_3)-CO-]n$ in repetitive chains.

Thus, the full composition of HCW, composed of 18 elements, was radiologically compared with the composition consisting only of C, O, and H present in PLA. The mass and volume ratio of the PLA simulator object was meticulously calculated to replicate the apparent density characteristic of HCW, established at 0.15 g/cm³.

Once the proportion of each chemical element in PLA and in the complete HCW was established, a comparative analysis was performed using data from the XCOM and ESTAR software databases [3,4] of the National Institute of Standards and Technology (NIST). The mass energy-absorption coefficients for photon (X-ray) beams and the mass stopping power coefficients for electron beams were calculated for PLA, and the results were rigorously compared with the corresponding coefficients derived from the complete chemical profile of HCW, which comprises eighteen elements.

This comparative approach allowed an analysis to determine whether the simplified PLA substance, consisting of only three elements, exhibits radiological energy absorption properties equivalent to those of the complete eighteen-element composition of HCW, which will support the execution of computational irradiation simulations using the PHITS particle transport software. The computational simulations helped to evaluate the radiological similarity between PLA and HCW.

It is expected that future experimental validation of this chemical simplification will support the feasibility of the development of the solid HCW simulator object. Such a simulator could be applied in the calibration of irradiation equipment, quality assurance protocols, and optimization of radiological processes for HCW treatment with relatively low uncertainties for pathogenic inactivation processes.

5. CONCLUSIONS

This study demonstrated the technical feasibility of a highly simplified radiological model for healthcare waste (HCW), reducing its elemental composition from eighteen constituents to only three (C, O, and H) without compromising dosimetric accuracy. The comparison between complete HCW and PLA-based simplified models showed maximum deviations of 5.6% for the mass energy-absorption coefficient and 2.1% for the mass stopping power across the energy range of 0.1–20 MeV.

At 10 MeV, a reference energy widely used in industrial radiation sterilization, the simplified PLA model reproduced the absorbed dose behavior of real HCW with negligible impact on sterilization performance. The delivery time for the 25 kGy pathogenic inactivation dose was (192.3 ± 0.5) s for HCW and (208.3 ± 0.5) s for PLA under photon irradiation, representing a difference of only (16.0 ± 0.5) s. For electron beams, the average irradiation time required to achieve 25 kGy was (0.79 ± 0.05) s for HCW and (0.78 ± 0.05) s for PLA, indicating a minimal difference of (0.01 ± 0.05) s between materials. These results demonstrate

that the fifteen excluded elements, representing less than 15.4% of the total mass, exert minimal influence on large-scale radiation interaction processes at industrial energies.

The validated simplification enabled the development of a PLA-based solid HCW phantom with realistic density and radiation response, providing a practical, reproducible, low-cost, and biologically safe material for dosimetric verification. This advancement addresses a significant gap in radiation processing of HCW. The absence of standardized physical phantoms for calibration and routine quality assurance. Additionally, reducing elemental complexity by 72% significantly improved Monte Carlo simulation efficiency, enabling faster and more accessible computational workflows.

PLA solid phantoms can therefore support process validation, optimization of industrial irradiation cycles, and implementation of robust quality control programs in HCW treatment facilities, potentially improving safety and sterilization reliability. Future work should focus on experimental benchmarking using real HCW to confirm theoretical predictions and support standardization for industrial deployment and regulatory alignment.

CONFLICT OF INTEREST

The authors declare that they have no competing financial interests or personal relationships that may have influenced the work reported in this study.

DATA AVAILABILITY STATEMENT

The authors declare that the data supporting the results of this study are available in the article. Derived data supporting the conclusions of this study are available upon request from the corresponding author.

REFERENCES

[1] ADUAN, S. A., BRAGA, F. dos S., ZANDONADE, E., SALLES, D., CUSSIOL, N. A. de M., LANGE, L. C. Avaliação dos resíduos de serviços de saúde do Grupo A em hospitais de Vitória (ES), Brasil. **Engenharia Sanitária e Ambiental**, Brazil, v.19, n. 2, p. 133–141, 2014. Available at: https://www.scielo.br/j/esa/a/W7xmt9JKzJ59Nq8psXLx3Bt/?lang=pt access: 15/07/2025

[2] NEVES, A.C; MAIA, C. C; SILVA, M.E.C; VIMEIRO, G.V.V; MOL, M. P. G; Analysis of healthcare waste management in hospital of Belo Horizonte, Brazil. **Environmental Science and Pollution Research**; v.29; 2022. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC9308478/

[3] NIST, ESTAR: Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions. Gaithersburg, MD**: National Institute of Standards and Technology**, 2024. [Online]. Available at: https://physics.nist.gov/PhysRefData/Star/Text/method.html - access: 20/07/2025.

[4] NIST, *XCOM: Photon Cross Sections Database*. Gaithersburg, MD: **National Institute of Standards and Technology**, 2024. [Online]. Available at: https://www.nist.gov/pml/xcom-photon-cross-sections-database - access: 20/07/2025.

[5] PHITS - Particle and Heavy Ion Transport Code System – version 3.34 -T. Sato, Y. Iwamoto, S. Hashimoto, T. Ogawa, T. Furuta, S. Abe, T. Kai, Y. Matsuya, N. Matsuda, Y. Hirata, T. Sekikawa, L. Yao, P.E. Tsai, H.N. Ratliff, H. Iwase, Y. Sakaki, K. Sugihara, N. Shigyo, L. Sihver and K. Niita - J. Nucl. Sci. Technol. 61, pg. 127-135, 2024.

[6] RDC - RESOLUÇÃO DA DIRETORIA COLEGIADA nº 222 de 28 de março de 2018 - Regulamenta as Boas Práticas de Gerenciamento dos Resíduos de Serviços de Saúde e dá outras providências. **Ministério da Saúde. Agência Nacional de Vigilância Sanitária**, Brasil; Available at: https://bvsms.saude.gov.br/bvs/saudelegis/anvisa/2018/rdc0222_28_03_2018.pdf access: 20/07/2025.

[7] SILVA, Hugo Leonardo Lemos; CUSSIOL, Noil Amorim de Menezes; CAMPOS, Tarcísio P. R.. ELEMENTAL COMPOSITION OF HEALTHCARE WASTE FOR DEVELOPING SIMULATOR OBJECTS IN RADIATION STERILIZATION.. In: **Semana Nacional de Engenharia Nuclear e da Energia e Ciências das Radiações**. Anais...Belo Horizonte(MG) UFMG, 2024. Available: https://www.even3.com.br/anais/vii-sencir-semana-nacional-de-engenharia-nuclear-e-

da-energia-e-ciencias-das-radiacoes-449507/893499-elemental-composition-of-healthcare-waste-for-developing-simulator-objects-in-radiation-sterilization/ , access at: 19/07/2025

[8] TATA, A.; BEONE, F.; Hospital waste sterilization: a technical and economic comparison between radiation and microwaves treatments; **Radiation Physics and Chemistry**; Amsterdam, Netherlands; v.46, n.4-6, p. 1153-1157, 1995.

[9] ZHAO, Y.; PENG, W.; LIU, L.; LYU, J.; SUN, F.; JING, K.; LI, W.; FU, Y. Dose control and preliminary applications of radiation sterilization of medical and healthcare products using 10 MeV electron beams. Journal of Radiation Research and Radiation Processing, China, v.40, n.1, p.72–79, 2022. Avaiable at: https://www.fs.sinap.ac.cn/en/article/doi/10.11889/j.1000-3436.2021-0109/ access: 20/07/2025.

LICENSE

Braz. J. Radiat. Sci., Rio de Janeiro, 2026, 14(1): 01-19. e3037.

p. 19