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Monte Carlo Radiation Transport and Dose–Response Modelling of Low-Energy X-Ray–Irradiated Beef Preservation: A Systematic Review

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ABSTRACT

Low-energy X-ray irradiation has emerged as a promising non-thermal technology for beef preservation due to its effectiveness in reducing microbial contamination while maintaining product quality. However, the predominance of photoelectric interactions and strong photon attenuation at low energies can result in non-uniform dose deposition within beef matrices, potentially influencing microbial inactivation and shelf-life outcomes. This study systematically reviewed the literature on low-energy X-ray irradiation of beef, with emphasis on radiation transport modelling, absorbed dose distribution, microbial inactivation kinetics, and packaging effects. A structured search of Scopus, PubMed, and Web of Science was conducted following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Studies addressing low-energy X-ray treatment of meat products, radiation transport simulation, dosimetry, microbial survival analysis, and packaging influence were evaluated. The review revealed that most published studies focused on empirical microbial dose–response relationships, while only a limited number incorporated Monte Carlo radiation transport modelling for spatial dose assessment. The findings further showed that low-energy X-ray irradiation effectively reduces populations of foodborne pathogens, including *Escherichia coli*, *Salmonella* spp., and *Listeria monocytogenes*, with microbial inactivation strongly dependent on absorbed dose and irradiation conditions. However, significant research gaps remain regarding three-dimensional dose mapping in beef, the integration of Monte Carlo-derived dose distributions with microbial survival models, and the influence of packaging geometry on dose heterogeneity and preservation outcomes. The review highlights the need for validated Monte Carlo-based predictive frameworks that integrate radiation transport, microbial inactivation, and packaging effects to optimize low-energy X-ray beef preservation and improve shelf-life prediction.

INTRODUCTION

The meat processing industry is seeking more sustainable solutions to ensure meat safety, quality and improved shelf life, while addressing the need to reduce a number of environmental impacts, such as, lower carbon dioxide emissions, lower energy consumption, more efficient use of water and reduced chemicals usage. This has led to a new approach to meat irradiation using low energy X rays based on relatively small devices that generate ionizing radiation with energies of hundreds of kilo-volts**.** There are several limitations of conventional meat irradiation technologies such as gamma-ray, electron beam and high energy X-ray (Pang et al., 2022a). These limitations and drawbacks include the use of radioactive isotopes in gamma - ray, low penetration ability in electron beam and economical non-feasibility of high energy X ray respectively (Lima et al., 2018). Due to the current developments in instrumentation technology there are portable, compact and cheaper low-energy X-ray sources for meats irradiation. These low-energy X-rays do not involve radioactive isotopes and they are economically cheaper. They have high linear energy transfer (LET) which is the density of energy deposited along the path of a particle to be irradiated, high relative biological effect (RBE) value (Pang et al., 2022a) which is defined as an empirical value that is used to compare the biological effect of various forms of radiation. These advantages allow low-energy X-ray irradiation to provide a higher microbial inactivation efficacy than gamma-ray and high energy X-ray irradiation. Thus, low-energy X-ray irradiation has great potentials to become an alternative meat preservation technique.

Over the years, it has been established that meat irradiation has neither reduce the nutritional content of meats more than other preservation technologies nor to make meats radioactive or dangerous for consumption (Khalafalla et al., 2018). Hence, meats irradiation is a non-thermal processing technology and a process of exposing meat to appropriate doses of ionizing radiation in order to kill potentially harmful microorganisms for the purpose of preservation and safety (Mshelia et al., 2023)

The World Health Organization (WHO) and the Food and Agriculture Organization (FAO) have recognized irradiation as a safe and effective method for reducing pathogens in food (XAVIER et al., 2018).

Radiation transport is a physical process that governs the generation, propagation, interaction and attenuation of low energy X ray irradiation as it passes through beef (Liu et al., 2019). In the context of food irradiation which leads to microbial inactivation, radiation transport focuses basically on the action of photons and the secondary charged particles they generate within the food matrix. Thus, understanding the concept of radiation transport is key for accurately predicting absorbed dose distributions, energy deposition patterns and the subsequent biological effects on the food matrix.

When low energy X ray passes through the beef tissue they undergo many interactions with the atoms and molecules of the meat. These interactions eventually lead to the transfer of energy from the X ray to the irradiated beef resulting in ionization, excitation and the production of reactive oxygen species (ROS). The spatial and temporal characteristics of these interactions determine the effectiveness of radiation-induced inactivation of the microorganism in beef (Firmansyah & Walo, 2025).

A Monte Carlo simulation estimates the likelihood of different outcomes by accounting for the presence of random variables. It is a technique used to understand the impact of risk and uncertainty (Azevedo, 2025). Monte Carlo simulations can be applied to a range of problems in many fields including investing, business, physics and engineering. It is also referred to as a multiple probability simulation.

Interactions of X-ray Photon with Matter

The interaction of low energy X ray photons with matter is governed by radiation physics principles. The three primary interaction mechanisms that are relevant to beef irradiation are below.

Photoelectric Effect

This dominates at low energy X ray photons and in materials with relatively high atomic numbers (Z). Here, the X ray photon transfers all its energy to a tightly bound electron and subsequently eject it from the atom (Liang et al., 2025). This results in a localized energy deposition with a production of dense ionization tracks contributing significantly to direct DNA damage (Desouky et al., 2015). This energy appears in two forms. One part of this energy called the work function of the material is utilized to eject an electron the remaining energy of the incident photon is taken away by the electron as its kinetic energy. The ejected electron is called photoelectron (Badr et al., 2023).

Compton Scattering

The Compton Effect is actually a scattering process whereby the initial photon is deflected by an electron in a target atom. In this incoherent scattering, all atomic electrons act independently of one another (Badr et al., 2023). In Compton scattering, a single photon strikes an electron giving a part of its energy and momentum to the electron. This electron is stationary or almost stationary and is called a target electron. As a result, the photon scatters with a reduced energy and longer wavelength (Liang et al., 2025). The difference in the energy of photon before and after scattering is taken away by the electron as its kinetic energy. This electron is called recoil electron. If a beam of photons is interacting with matter or body tissues, then a number of photons are scattered by the electrons of the atoms that compose the matter or tissues. As a result, the beam attenuation occurs. Moreover, ionization of atoms also occurs as a result of such scattering (Bichsel, 2011).

The ejected secondary electrons play a major role in indirect biological damage through the generation of free radicals and reactive oxygen species (Maqbool, n.d.).

Pair Production

Pair production is dominant in interactions of higher-energy photons with matter. In this phenomenon, an X - ray photon passing near the nucleus of an atom is subjected to strong field effects from the nucleus and splits into an electron positron pair. A negatively charged electron (e) and a positively charged positron (e^+) are created from a photon interacting with the electromagnetic field while energy and momentum are conserved. Positron is a positively charged electron and is created as result of the conservation of momentum when a photon passes near the nucleus of an atom. Since electron (e^-) and positron (e^+) possess particle nature and take part in the construction of matter, pair production is also called materialization of energy. The photon should

have at least 1.022 MeV or more energy to take part in this process which is the sum of the rest mass energies of an electron (0.511 MeV) and a positron (0.511 MeV). If the energy of the photon is more than the sum of the rest mass energies of both electron and positron, then the remaining energy is taken by the electron and positron as their kinetic energies (Bichsel, 2011).
The objective of this review was to identify, evaluate and synthesize published studies on Monte Carlo based radiation transport, dose response modelling, microbial inactivation and shelf-life extension in low-energy X-ray irradiated beef under aerobic and vacuum packaging conditions.

MATERIALS AND METHODS

Search Methodology

The methodology adopted in this systematic literature review is in line with the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). Systematic review tools were used to remove duplicates and screen for eligible studies. The inclusion and exclusion criteria are presented in table 1. Literature searches were conducted in Scopus, Web of Science and PubMed. The search methodology combined terms related to radiation transport modelling, low-energy X-ray irradiation, microbial inactivation, dose–response modelling, beef and packaging atmosphere Table 2. The results were filtered to include articles published in English in the last two decades.
Studies were included if they reported experimental or computational dose estimation, microbial inactivation metrics or shelf-life indicators following X-ray or ionizing radiation treatment of meat products. Review articles, conference abstracts without full text and studies unrelated to food irradiation were excluded.
Search string used in advanced setting of Scopus, PubMed etc

("Monte Carlo" OR "Radiation" OR "Dose deposition")
AND
("low energy X ray" OR "X ray irradiation")
AND
("Microbial inactivation" OR "dose response" OR "log reduction")
AND
("Meat" OR "Beef")
AND
("Aerobic" OR "Vacuum")

RESULTS AND DISCUSSION

Results

Study Selection

The search yielded studies from multiple disciplines including food science, radiation physics, and microbiology. After screening and eligibility assessment, relevant articles were synthesized qualitatively.
The identification, screening and eligibility processes as displayed in figure 1 were instrumental in selecting the included studies which summed up to 145. 14 studies that were published in the last two decades were selected. The screening process involved various modalities such as radiation transport, low energy X ray, microbial inactivation and packaging. 56 studies were eliminated based on the criteria outlined in table 1. Notably, studies on gamma irradiation of microorganisms without the integration of radiation transport and packaging materials were higher than those of the low energy X rays. The author's name, year of publication, radiation source, energy (kev), Monte Carlo codes, dose range, microorganisms and packaging materials are presented in table 3. The outcomes of each study varied and the details were carefully considered.

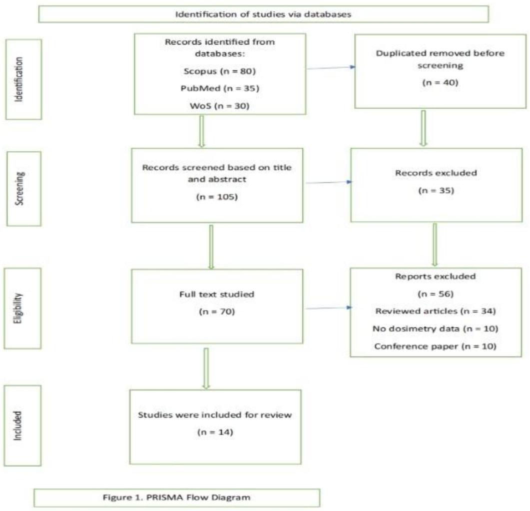

Figure 1: Process of Identification, Screening and Eligibility of Included Studies

Table 1: Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Setting	All countries	Non
Modality	i. Radiation transport modelling ii. Low energy X ray irradiation iv. Microbial inactivation v. packaging	Studies that did not involve these
Outcomes	i. X-ray beam parameters (kVp, filtration) ii. Dosimetry technique iii. Sample thickness iv. Packaging type v. Microbial species vi. Dose–response model vii. Shelf-life metrics viii. Use of computational modelling	Studies that did not detailed the above outcomes
Publication type	All journals	i. Review articles (except for reference mining) ii. Conference abstracts without full data
Publication year	Articles published in the last two decades	Articles published before the last two decades
Language	English	All other languages

Radiation Transport and Microbial Inactivation Models

To evaluate the biological effectiveness of low energy X ray, simulated dose data are coupled with microbial survival models (Peleg, 2023). Log reduction values and D_{10} parameters are derived by correlating absorbed dose with experimentally observed reductions in food matrices (Moreira et al., 2010). This integrated approach enables prediction of microbial inactivation under varying irradiation conditions and supports optimization of dose levels to achieve food safety objectives while preserving nutritional and sensory quality (Acuff et al., 2020).

Dose Calculation Methods

Accurate and precise dosimetry is a key requirement for a successful meat irradiation process, ensuring the required and appropriate radiation dose are delivered uniformly and effectively for safety assurance and microbial inactivation (Firmansyah & Walo, 2025). To achieve this, three primary methods are commonly used in the radiation processing field: (i) experimental measurement (ii) simulation (iii) theoretical calculation.

Experimental dosimetry involves direct measurements of absorbed dose using calibrated dosimeters placed strategically within or around the irradiated beef, providing reliable dose values under real irradiation conditions (Firmansyah & Walo, 2025). Because they capture the actual irradiation environment, including scatter and attenuation effects, experimental methods remain the gold standard for process validation and regulatory compliance. However, the following constraints are associated with experimental dosimetry (Kim, 2007): In systems involving complex geometries such as meat cuts, heterogeneous compositions (tissue, fat and bone) or bulk packaging configurations, accurate dose mapping may require a large number of dosimeters this may lead to high cost, time consuming and labour intensive.

A Monte Carlo program is a method of simulating physical processes on a computer. It is often leverage on the widely used Monte Carlo code system such as, Monte Carlo N Particle transport (MCNP), PENetration and Energy Loss of Positrons and Electrons (PENELOPE), Geometry and Tracking (GEANT) (Azevedo, 2025; Matuszak et al., 2024; H. Park et al., 2022; Shin et al., 2021). These codes offer a robust means of calculating doses while providing valuable insights into the complex physical interactions between radiation and matter. The Monte Carlo method simulates the paths of particles such as electrons and photons and estimates dose by summing and averaging the histories of many particles (Firmansyah & Walo, 2025; Kim, 2007). For low-energy X-ray irradiation of meat, MC simulations are particularly valuable for predicting dose distribution within heterogeneous tissues where attenuation and scatter significantly influence dose uniformity. This calculation proceeds by constructing a series of trajectories each segment of which is randomly chosen from a distribution of applicable processes. Monte Carlo simulation however, require large amount of computing time to obtain satisfactory precision of dose estimates (Firmansyah & Walo, 2025).

Complementing these is the theoretical method, which applies fundamental physics and mathematical principles to estimate the absorbed doses. These methods are advantageous for quick dose estimations and cost reduction particularly in simple geometries with uniform materials. However, their reliance on simplifying assumptions has limited their applicability in realistic meat irradiation scenarios (Firmansyah & Walo, 2025).

Importance of Monte Carlo Radiation Transport Modelling

The application of Monte Carlo radiation transport modelling provides a robust physics-based framework for understanding and optimizing low energy X ray irradiation processes (Liu et al., 2019). By capturing the stochastic nature of low energy X ray interactions and dose deposition, this approach enhances the reliability of dose response relationships and strengthens the scientific basis of irradiation-based interventions against meat spoilage (Van Hoof et al., 2013). The integration of radiation physics with microbiological outcomes represents a critical advancement in the development of safe, efficient and scientifically justified food irradiation technologies (Afrough et al., 2020).

Table 2: Search Methodology

S/N	CONCEPT AREA	KEY WORDS USED
1.	Radiation and Modelling	Monte Carlo simulation, radiation transport, dose deposition, photon transport
2.	Radiation source	Low energy X Ray, X r irradiation
3.	Biological effect	Microbial inactivation, dose response, log reduction and D10 value
4.	Food matrix	Beef, meat, food irradiation
5.	Packaging	Aerobic packaging, vacuum packaging

Table 3: Number of Studies on the Monte Carlo Radiation Transport and Dose–Response Modelling of Low-Energy X-Ray–Irradiated Beef Preservation

Author/Year	Radiation Source	Energy (keV)	MC Method	Dose Range	Microorganism	Packaging
Jeon & Ha (2020)	X-ray	Not reported	No	0.05–0.3 kGy	*E. coli* O157:H7, *S. Typhimurium*, *L. monocytogenes*	Not reported
Pang et al. (2022)	Low-energy X-ray	20	No	25–125 Gy	*P. fluorescens*	Not reported
Zhang et al. (2020)	Low-energy X-ray	150	No	100–400 Gy	*E. coli* O157:H7, *S. Typhimurium*	Not reported
Mahmoud et al. (2010)	X-ray	Not reported	No	0.1–2 kGy	*E. coli*, *Listeria*, *Salmonella*, *Shigella*	Not reported
Park & Ha (2019)	X-ray	Not reported	No	0.2–0.8 kGy	*E. coli* O157:H7, *S. Typhimurium*, *L. monocytogenes*	Not reported
Cha & Ha (2022)	Low-energy X-ray	Not reported	No	NR	*E. coli* O157:H7, *S. Typhimurium*, *L. monocytogenes*	Not reported
Son et al. (2022)	Low-energy X-ray	160	No	0–5000 Gy	Mixed microbial population	Not reported
Yeom et al. (2024)	X-ray	2500	No	NR	Foodborne pathogens	Not reported
Liu et al. (2019)	Radiation Transport Simulation	Not reported	Geant4-DNA	Simulated	Cellular dose/DNA damage	Not reported
Shin et al. (2021)	Radiation Transport Simulation	Not reported	Geant4-DNA	Simulated	DNA damage modelling	Not reported
Matuszak et al. (2024)	Radiation Transport Simulation	Not reported	Monte Carlo	Simulated	Biological response modelling	Not reported
Kim (2007)	Food Irradiation Dosimetry	Not reported	Monte Carlo-based	Simulated	Food irradiation dose calculation	Not reported
Firmansyah & Walo (2025)	Radiation Processing	Not reported	Monte Carlo	Simulated	Dose calculation methods	Not reported

Author/Year	Radiation Source	Energy (keV)	MC Method	Dose Range	Microorganism	Packaging
Liu et al. (2019) / Computational Framework	Radiation Transport	Not reported	Geant4	Simulated	Dose distribution modelling	Not reported

Discussion

Radiation Physics Gap

Researches have showed that low-energy X-ray irradiation leads to highly inhomogeneous dose deposition within meat matrices due to the predominance of photoelectric effects at photon energies below 300 keV (Farkas et al., 2019). Monte Carlo radiation transport codes such as MCNP, GEANT4 and PENELOPE have been widely employed to model photon transport and energy absorption in inhomogeneous food systems (Matuszak et al., 2024). However, most reviewed studies relied on averaged absorbed dose values (Farkas et al., 2019) not minding the dose fall off gradients predicted by Monte Carlo simulations (H. Park et al., 2022). This simplification limits the accurate interpretation of microbial inactivation kinetics particularly under vacuum packaging conditions where oxygen-mediated indirect damage is reduced.

Dose Response Modelling

The D_{10} Value and Log Linear Dose Response Models are very crucial in describing the microbial inactivation in low energy X-ray irradiation (Xiong et al., 1999). D_{10} value is defined as the absorbed dose required to achieve a one-log reduction in microbial population (Ebrahim et al., 2022). While these models are simple and widely adopted, they assume uniform dose distribution and non heterogenous microbial response (Yeom et al., 2024). Alternative models such as the Weibull and Multi Target Models have been proposed to account for non-linear survival curves and tailing effects (Dementavicius et al., 2016). Nevertheless, the reviewed literature reveal limited integration of these biological models with Monte Carlo derived spatial dose distributions representing a significant gap in predictive modelling.

Discussion of Included Studies

The studies summarized in Table 3 demonstrate that low-energy X-ray irradiation is an effective intervention for reducing microbial contamination in food products. The reviewed investigations reported significant reductions in important foodborne pathogens such as *Escherichia coli* O157:H7, *Salmonella Typhimurium*, *Listeria monocytogenes*, and *Pseudomonas fluorescens* following exposure to low-energy X-rays. Microbial inactivation generally increased with increasing absorbed dose, confirming a strong dose-dependent response.

Among the reviewed studies, Pang et al. (2022) and Zhang et al. (2020) demonstrated that low-energy X-rays between 20 and 150 keV achieved substantial microbial reductions while maintaining product quality. Similarly, Jeon and Ha (2020), Park and Ha (2019), and Cha and Ha (2022) reported effective inactivation of major foodborne pathogens on food matrices and contact surfaces, highlighting the potential of low-energy X-ray technology for food safety applications.

Despite the promising microbial reduction results, most studies relied primarily on experimental dose measurements and microbial survival data. Only a limited number incorporated computational radiation transport approaches, while explicit Monte Carlo-based modelling of absorbed dose distribution was largely absent. Furthermore, none of the identified studies comprehensively integrated Monte Carlo-derived spatial dose distributions with microbial dose–response models for beef preservation.

The review also revealed a lack of studies investigating the influence of packaging conditions on photon attenuation and dose heterogeneity. Although packaging atmosphere is known to affect microbial survival and shelf-life, its interaction with low-energy X-ray transport within beef matrices remains poorly understood. This gap highlights the need for future research combining Monte Carlo radiation transport simulations, three-dimensional dose mapping, microbial inactivation kinetics, and packaging effects to develop predictive and optimized beef preservation frameworks.

Overall, the studies reviewed confirm the effectiveness of low-energy X-ray irradiation for microbial control but reveal significant opportunities for advancing the field through the integration of radiation physics and microbiological modelling approaches.

(Begum et al., 2020) carried out a comparative study to evaluate the radiation sensitivity of *Escherichia coli*, *Salmonella Typhimurium*, and *Listeria monocytogenes* inoculated in rice and exposed to cobalt-60 gamma rays and low-energy (125 keV) X-rays at varying dose rates. While changes in gamma dose rate did not significantly influence D_{10} values, low-energy X-ray treatment resulted in significantly higher D_{10} values, indicating lower microbicidal effectiveness compared to gamma irradiation

(Yeom et al., 2024) evaluated the effectiveness of low-energy X-ray irradiation in inactivating biofilms of *Escherichia coli* O157:H7, *Salmonella Typhimurium*, and *Listeria monocytogenes* formed on common food contact surfaces, including PVC, stainless steel (STS 2B), and Teflon. Microbial populations decreased significantly with increasing irradiation dose, although inactivation efficiency varied depending on surface type.

Teflon exhibited the lowest D_{10} values, indicating greater susceptibility to irradiation, while PVC showed comparatively higher resistance. Mechanistic analysis revealed that X-ray treatment disrupted extracellular polymeric substances (EPS), particularly exopolysaccharides, and that EPS degradation correlated strongly with biofilm reduction. The findings demonstrate that low-energy X-ray irradiation is an effective strategy for controlling biofilm-associated foodborne pathogens on industrial surfaces and provide insight into its underlying antibiofilm mechanisms.

(Pang et al., 2022b) investigated the effectiveness of low-energy X-ray irradiation against *Pseudomonas fluorescens* in both planktonic form (in phosphate-buffered saline) and biofilm form on stainless steel surfaces. Irradiation at 125 Gy achieved approximately 4.60 log CFU/mL reduction in planktonic cells and 4.21 log CFU/cm² reduction in biofilm cells. Weibull model analysis yielded tR_1 values of 14.8 Gy for planktonic cells and 11.6 Gy for biofilm cells, indicating strong dose-dependent inactivation. Beyond microbial reduction, irradiation disrupted extracellular polymeric substances (EPS), impaired glucose uptake systems, and partially compromised membrane integrity and potential. The findings demonstrate that low-energy X-ray irradiation effectively inactivates *P. fluorescens* and damages biofilm structure, supporting its potential application for surface decontamination in food processing environments.

(Zhang et al., 2020) assessed the effectiveness of polychromatic low-energy X-ray irradiation (cut-off energy 150 keV) for inactivating *Escherichia coli* O157:H7 and *Salmonella Typhimurium* in dry edible bird's nest (EBN). Irradiation doses of 350–400 Gy reduced both pathogens to undetectable levels. The reported D_{10} and tR_1 values indicated that *S. Typhimurium* exhibited greater resistance than *E. coli* O157:H7. Dose distribution analysis demonstrated that two-sided irradiation improved processing uniformity. Although irradiation increased product yellowness, no sulfur-containing volatile compounds were detected, suggesting minimal adverse quality effects. Overall, the findings support low-energy X-ray irradiation as an effective non-thermal intervention for controlling foodborne pathogens in low-moisture food matrices.

(Liu et al., 2019) developed a computational framework to quantify cellular dose and DNA double-strand break (DSB) distribution in multicellular tissue systems under irradiation. Using the Geant4 radiation transport package with Geant4-DNA physics, the model simulated radiation interactions in both 2D and 3D cell cultures. A custom program (CelllMaker) was used to generate multicellular geometries, enabling detailed radiation transport simulations to estimate cellular absorbed dose and corresponding DSB yields simultaneously. The model provides a physics-based approach for assessing microscale dose deposition and DNA damage, addressing limitations of experimental radiobiology in measuring cellular-level effects. Although preliminary and requiring further validation, the framework establishes a foundation for integrated cellular dose–damage simulation tools in radiobiological research.

(Seyed Mostafa, 2022) investigated the dose-dependent effects of β-radiation from a strontium source on K562 cancer cells using both experimental assays and Monte Carlo simulation (MCNPX). Cells were irradiated repeatedly over three days, and viability, cytotoxicity, apoptosis, and DNA fragmentation were assessed using biochemical and microscopic techniques. Absorbed doses were calculated via Monte Carlo simulation and verified experimentally using a Geiger–Muller counter. Results demonstrated time-dependent cytotoxic and apoptotic effects, with the strongest response observed after 120 minutes of daily irradiation. No significant hyper-radiosensitivity was detected. The findings highlight the reliability of Monte Carlo simulation for accurately estimating absorbed dose at the cellular level and correlating theoretical dose calculations with biological outcomes.

Research Gaps Identified

The following gaps were identified during the course of this review: Lack of three-Dimensional absorbed dose mapping in beef under low-energy X-rays, minimal integration of Monte Carlo modelling with microbial survival data, limited investigation of packaging induced attenuation effects, scarcity of predictive shelf-life models integrating transport physics

Recommendations for Future Research

Further research should be conducted to cover the following areas

i. Develop validated Monte Carlo models of beef irradiation geometry
ii. Perform voxel-based microbial survival integration
iii. Quantify dose heterogeneity impact on D_{10} values
iv. Develop predictive preservation optimization frameworks

CONCLUSION

Low-energy X-ray irradiation has the capacity to reduce the microbial load and extend beef shelf-life effectively. However, the reviewed literatures predominantly relied on empirical dose–response approaches without the integration of radiation transport. Therefore, there is need to incorporate a physics-based framework with Monte Carlo simulation and spatially resolved absorbed dose modelling for an advanced low-energy X-ray beef preservation toward predictive, optimized, and mechanistically grounded applications.

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