Applications Of Gamma Irradiation for Food Preservation: Current Trends.

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Abstract—Gamma irradiation is an established non-thermal food preservation technology that employs ionizing radiation from Cobalt-60 or Cesium-137 sources to inactivate pathogenic and spoilage microorganisms, inhibit physiological processes such as sprouting and ripening, and achieve insect disinfestation. Unlike conventional thermal methods, gamma irradiation preserves the organoleptic and nutritional integrity of treated commodities across a broad spectrum of food categories including fresh produce, spices, cereals, seafood, poultry, and packaged ready-to-eat products. This comprehensive review synthesizes the mechanistic basis of radiation-induced microbial inactivation, dose-response relationships, regulatory frameworks, and commodity-specific applications reported in peer-reviewed literature from 2020 to 2025. The review further evaluates emerging combinatorial preservation strategies, consumer acceptance challenges, and technological advancements in dosimetry and radiation source development. Evidence from recent studies confirms that gamma irradiation at appropriately validated doses significantly reduces microbial load, extends shelf life, and maintains food safety with minimal impact on sensory quality. Ongoing research into electron beam and X-ray alternatives, combined hurdle approaches, and nano-dosimetry is expected to broaden the application scope and commercial adoption of food irradiation globally.

Index Terms—gamma irradiation; food preservation; ionizing radiation; microbial inactivation; Cobalt-60; non-thermal processing; shelf-life extension; food safety

I. INTRODUCTION

Ensuring adequate food supply at the global scale remains a formidable challenge, compounded by substantial post-harvest deterioration driven by microbial contamination, insect damage, and inherent physiological processes including senescence, sprouting, and ripening. According to the Food and Agriculture Organization of the United Nations, roughly one-third of all food intended for human consumption is never eaten, with losses concentrated disproportionately in low-income regions where reliable cold chain infrastructure is limited or absent (FAO, 2023). The consequences extend well beyond economic waste, encompassing heightened food insecurity and avoidable environmental burdens arising from the misuse of land, water, and energy resources.

Established preservation modalities refrigeration, thermal processing, chemical additives, and modified atmosphere packaging have collectively helped reduce commodity losses throughout supply chains. Yet each carries meaningful drawbacks: heat-based processes can degrade thermolabile nutrients and alter organoleptic properties; synthetic preservatives are subject to intensifying regulatory restrictions and growing consumer resistance; and mechanical refrigeration demands substantial energy inputs that are frequently unavailable in resource-constrained environments (Lacroix & Vijayalakshmi, 2022). Growing consumer preference for lightly processed, additive-free products with superior sensory characteristics has consequently directed research attention toward non-thermal alternatives.

Among non-thermal technologies, gamma irradiation stands out as one of the most extensively investigated and widely sanctioned approaches worldwide. Its regulatory history dates to 1963, when the U.S. Food and Drug Administration first permitted its use on wheat to control insect infestation; since then, approved applications have expanded across numerous food categories. The process relies primarily on ionizing photons generated by Cobalt-60 (^{60}Co) at characteristic energies of 1.17 and 1.33 MeV, with doses precisely calibrated to match the specific preservation objective (Farkas & Mohácsi-Farkas, 2011). Interaction of these photons with biological tissues generates reactive oxygen species (ROS) and free radicals that inflict irreparable damage on microbial DNA, ultimately preventing cellular replication and triggering cell death.

Although gamma irradiation carries regulatory endorsement in over 60 countries and boasts a well-documented safety and efficacy record, its wider uptake is hampered by substantial infrastructure investment, complex radiation safety governance, and lingering public apprehension fueled by its perceived association with nuclear technology (Byun et al., 2020). The present review consolidates current knowledge concerning the mechanistic underpinnings, dose-response behavior, commodity-specific outcomes, comparative performance, and evolving research directions in gamma irradiation for food preservation, drawing predominantly on peer-reviewed studies published from 2020 to 2025. It is intended to serve as a practical reference for food scientists, technologists, and regulatory practitioners seeking a current and comprehensive account of this field.

II. PRINCIPLE AND MECHANISM OF GAMMA IRRADIATION

2.1 Physics of Gamma Radiation

Gamma radiation consists of high-energy electromagnetic waves characterized by extremely short wavelengths in the range of 10^{-11} to 10^{-13} m, occupying the uppermost energy region of the electromagnetic spectrum. The radioisotope Cobalt-60 the predominant source employed in food irradiation facilities globally undergoes radioactive decay to stable Nickel-60, with a physical half-life of 5.27 years, emitting photons at discrete energies of 1.173 and 1.332 MeV in the process (Siddiqui et al., 2022). Although these photon energies are more than adequate to ionize atoms and rupture chemical bonds in biological macromolecules, they fall well short of the threshold needed (~10 MeV) to render food radioactive through neutron-induced activation. International regulatory authorities, including the Codex Alimentarius Commission, have therefore affirmed that properly irradiated foods do not become radioactive (CAC, 2023).

Compared with electron beam irradiation, gamma radiation penetrates food products to a substantially greater depth, allowing uniform energy deposition throughout bulky or densely packed items. Attenuation of the beam follows an exponential relationship consistent with the Beer-Lambert law; at ^{60}Co energies, the half-value layer (HVL) the depth at which beam intensity is reduced by half is roughly 11 cm in water and similar biological tissues (Khan et al., 2021). This exceptional penetration depth constitutes a key commercial asset, enabling the simultaneous treatment of large cartons and palletized loads with acceptable dose uniformity.

2.2 Direct and Indirect Action on Microorganisms

Gamma irradiation exerts its biological effects through two distinct mechanistic routes: direct and indirect action. In the direct pathway, gamma photons or the secondary electrons they liberate collide with critical cellular constituents most importantly DNA producing single- and double-strand breaks, base alterations, and covalent crosslinks between DNA strands or between DNA and associated proteins. The resulting genomic lesions block transcription and replication, condemning the cell to death or irreversible sterility (Hamby et al., 2023).

The indirect pathway, which dominates in foods with high water content, is initiated by the radiolysis of water, yielding highly reactive species including hydroxyl radicals (•OH), hydrogen radicals (H•), hydrated electrons ($e^{-}aq$), and hydrogen peroxide (H_2O_2). The hydroxyl radical is the most damaging of these species, reacting with DNA at rates approaching the diffusion limit ($\sim10^9$ $M^{-1}s^{-1}$) and accounting for the preponderance of radiation-induced genomic injury under aerobic irradiation conditions (Nagata et al., 2021). Free radical-mediated lipid peroxidation cascades further disrupt membrane structural integrity and contribute to broader cellular dysfunction in exposed microorganisms.

2.3 Radiation Dose and D_{10} Values

The absorbed radiation dose, expressed in grays (Gy; where 1 Gy equals 1 J of energy deposited per kilogram of material), is the governing parameter of microbicidal activity. Radiosensitivity among microorganisms is conventionally quantified by the D_{10} value the dose necessary to achieve a one-log_{10} (90%) reduction in viable population. As a general rule, Gram-negative bacteria are more susceptible to irradiation than Gram-positive species, while endospore-forming bacteria and exceptionally resistant organisms such as Deinococcus radiodurans require considerably higher doses, owing to their robust DNA repair capacity and enzymatic antioxidant defenses (Farkas & Mohácsi-Farkas, 2011).

Published D_{10} values from recent studies span a broad range depending on organism and food matrix: Salmonella Typhimurium in poultry meat, 0.4–0.7 kGy; Listeria monocytogenes in ready-to-eat products, 0.4–0.6 kGy; Escherichia coli O157:H7 in ground beef, 0.3–0.5 kGy; and Aspergillus niger spores in dried spices, 0.8–1.2 kGy (Park & Byun, 2020; Li et al., 2023). These organism-specific values serve as critical inputs when establishing minimum effective doses for commercial irradiation protocols.

Table 1. Classification of Irradiation Doses and Principal Food Applications

Dose Category	Primary Effect	Application	Reference
Low (< 1 kGy)	Insect disinfestation, sprout inhibition	Grains, potatoes, onions	Khan et al., 2021
Medium (1–10 kGy)	Pathogen reduction, shelf-life extension	Poultry, seafood, spices	Siddiqui et al., 2022
High (10–50 kGy)	Sterilization, elimination of all viable organisms	Packaged ready-to-eat foods	Fan & Sommers, 2013

Source: Adapted from Khan et al. (2021); Siddiqui et al. (2022); Fan & Sommers (2013).

III. APPLICATIONS OF GAMMA IRRADIATION IN FOOD PRESERVATION

3.1 Fresh Fruits and Vegetables

Application of gamma irradiation at low-to-medium doses (0.25–3.0 kGy) has proven effective in prolonging the postharvest marketable life of fresh produce through several concurrent mechanisms: slowing the rate of ripening, lowering surface microbial populations, and suppressing enzymatic browning. Studies on strawberries (Fragaria × ananassa) have shown that dose levels of 1.5–2.0 kGy can bring about reductions of 2–3 log CFU/g in total aerobic counts while leaving firmness, anthocyanin concentration, and titratable acidity essentially unchanged relative to untreated fruit stored at 4°C for periods of up to 14 days (Hossain et al., 2022).

Mango (Mangifera indica) irradiation at 0.4–1.0 kGy, approved as a phytosanitary measure by the USDA for import treatment of tropical fruits, has demonstrated effective control of fruit fly species (Bactrocera dorsalis, Ceratitis capitata) while delaying the climacteric respiratory peak and maintaining acceptable sensory quality for export shipments (Moy & Wong, 2020; Khan et al., 2021). A 2024 meta-analysis by Zhou et al. encompassing 45 independent trials across 12 fruit species confirmed a mean shelf-life extension of 3.8 days (95% CI: 2.9–4.7 days) per kGy applied within the low-dose range, without significant deterioration in consumer-reported sensory scores (Zhou et al., 2024).

In leafy vegetables, including spinach (Spinacia oleracea) and lettuce (Lactuca sativa), doses of 1.0–1.5 kGy reduced Salmonella and E. coli populations to undetectable levels while chlorophyll retention remained above 85% relative to controls. However, doses exceeding 2.0 kGy induced progressive softening attributable to pectin depolymerization, indicating commodity-specific dose optimization is essential (Araujo et al., 2023).

3.2 Spices, Herbs, and Dry Commodities

Spices and dried herbs are among the most heavily contaminated food commodities, with total aerobic plate counts frequently reaching 10^6–10^8 CFU/g and aflatoxin contamination prevalent in tropical producing regions (Lacroix & Vijayalakshmi, 2022). Gamma irradiation at medium doses (5–15 kGy) achieves substantial microbial reduction while preserving volatile oil profiles and organoleptic characteristics more effectively than steam sterilization or ethylene oxide fumigation. Studies on black pepper (Piper nigrum), cumin (Cuminum cyminum), and chili powder (Capsicum annuum) irradiated at 10 kGy demonstrated ≥5 log reductions in total mesophilic counts with essential oil retention exceeding 90% of unirradiated samples (Rao et al., 2021).

For cereal grains and pulses, low-dose irradiation (0.3–1.0 kGy) serves as an effective quarantine treatment replacing methyl bromide fumigation, which is being phased out under the Montreal Protocol due to its ozone-depleting properties (Byun et al., 2020). Dose-response studies on stored-grain insect pests (Sitophilus oryzae, Tribolium castaneum, Callosobruchus maculatus) have established that 0.3–0.5 kGy reliably achieves reproductive sterility, and 1.0 kGy achieves 100% mortality within seven days across all life stages (Park & Byun, 2020).

3.3 Poultry, Meat, and Seafood

Poultry meat is a well-recognized transmission vehicle for several foodborne pathogens, most notably Salmonella spp. and Campylobacter jejuni. When fresh or frozen chicken portions are subjected to medium-dose gamma irradiation (1.5–4.5 kGy), Salmonella populations are typically reduced by 3–5 log units, and Campylobacter jejuni one of the most radiosensitive enteric pathogens, with a D_{10} of approximately 0.18 kGy is effectively eliminated (Hamby et al., 2023). Regulatory authorities in the United States, through the FDA and USDA-FSIS, have set maximum permissible doses of 4.5 kGy for fresh poultry and 7.0 kGy for frozen poultry products.

In seafood, gamma irradiation at 1.0–3.0 kGy significantly extends shelf life of chilled fish fillets by reducing the initial bacterial load, thereby delaying spoilage-associated off-odor development and trimethylamine (TMA) accumulation. A recent study by Li et al. (2023) reported that irradiation of Atlantic salmon at 2.0 kGy combined with modified atmosphere packaging (70% CO_2/30% N_2) extended acceptable shelf life from 12 to 22 days at 4°C without significant changes in lipid oxidation indices (TBARS) beyond sensory detection thresholds.

In red meat applications, doses of 1.5–4.5 kGy effectively reduce E. coli O157:H7, Salmonella, and Toxoplasma gondii. Ground beef irradiation at 1.5–2.5 kGy is commercially practiced in the United States under USDA approval, marketed under the Radura logo (Siddiqui et al., 2022).

Irradiation of mechanically separated meat and ready-to-eat deli products at 4.5–7.0 kGy effectively eliminates L. monocytogenes, a critical concern for immunocompromised populations.

3.4 Packaged and Ready-to-Eat Foods

A particularly significant advantage that sets gamma irradiation apart from most other preservation techniques is its ability to decontaminate foods after they have been placed in their final sealed consumer packaging, thereby precluding any opportunity for post-treatment microbial recontamination. This attribute renders it especially well-suited for ready-to-eat (RTE) products, field rations for military personnel, and therapeutic diets for hospitalized patients requiring extended ambient-temperature shelf stability. High-dose applications in the 10–45 kGy range collectively termed 'radappertization' by analogy with commercial thermal sterilization have been employed to manufacture shelf-stable meat and poultry items for defense and space exploration programs (Fan & Sommers, 2013).

Recent investigations have focused on irradiation-compatible packaging materials to avoid radiation-induced migration of plastic components. Nagata et al. (2021) evaluated migration profiles of 12 packaging polymer types following exposure to doses up to 20 kGy, concluding that polyethylene terephthalate (PET), oriented polypropylene (OPP), and polyamide (PA) exhibited migration levels within EU legislative limits, supporting their suitability for irradiated food applications.

IV. EFFECTS ON NUTRITIONAL AND SENSORY QUALITY

4.1 Macronutrients

Proteins, carbohydrates, and lipids in irradiated foods are largely unaffected at doses below 10 kGy. Protein denaturation and amino acid racemization become measurable only at doses exceeding 20 kGy, and the extent is comparable to equivalent thermal treatments such as canning (Lacroix & Vijayalakshmi, 2022). Carbohydrate degradation, manifested as partial hydrolysis of starch and pectin, may contribute to texture softening in high-dose applications but does not significantly alter caloric or glycemic profiles at doses used for food safety purposes.

Lipid oxidation is the primary quality concern in fatty foods, as irradiation-generated radicals can initiate peroxidation chain reactions. This risk is substantially mitigated by conducting irradiation under frozen conditions, anaerobic packaging atmospheres, or with the incorporation of natural antioxidants such as rosemary extract, vitamin E, or green tea polyphenols (Hossain et al., 2022; Araujo et al., 2023). A 2021 dose-response study on pork sausage demonstrated that TBARS values at 5 kGy under nitrogen atmosphere were statistically indistinguishable from unirradiated controls, whereas equivalent doses under air produced a 2.3-fold increase in lipid oxidation markers (Rao et al., 2021).

4.2 Vitamins and Bioactive Compounds

Vitamins vary considerably in radiation sensitivity according to their redox chemistry. Thiamine (vitamin B_1) is among the most radiation-labile vitamins, exhibiting approximately 5–15% loss at doses of 1 kGy in aqueous food systems, with losses proportional to dose and inversely related to irradiation temperature (Park & Byun, 2020). Vitamins C and E, both radical scavengers, may be partially depleted through their antioxidative role in quenching radiolytic species, though losses at low doses (< 2 kGy) are typically within the range of variability attributable to storage conditions and comparable to thermal pasteurization.

Fat-soluble vitamins (A, D, K) and B-group vitamins other than thiamine demonstrate relatively high radiation stability. Carotenoids in fruits and vegetables, with their conjugated polyene structures facilitating efficient radical quenching, show moderate sensitivity; lycopene in tomato products irradiated at 2 kGy retained 92–96% of initial content (Zhou et al., 2024). Phenolic compounds and flavonoids, which constitute major classes of health-promoting bioactives in plant foods, are generally stable or may even increase in bioavailability following irradiation due to cell wall structural disruption improving extractability (Hamby et al., 2023).

4.3 Sensory Attributes

The principal sensory concern associated with gamma irradiation is the development of 'irradiation off-flavor,' particularly in high-fat foods. This phenomenon arises primarily from radiolytic cleavage of lipids generating volatile sulfur compounds, alkanes, alkenes, and carbonyl species detectable at doses above 1–2 kGy in sensitive commodities such as whole milk, certain cheeses, and fatty meats (Li et al., 2023). Irradiation of high-carbohydrate foods such as grains, pulses, and dried fruits generally produces minimal odor or flavor changes at approved doses. Texture modifications primarily softening in high-moisture produce can be addressed through combined low-dose irradiation and calcium chloride dipping, which stabilizes pectin cross-linking (Araujo et al., 2023).

V. GLOBAL REGULATORY FRAMEWORK

The global governance of food irradiation is anchored primarily in the Codex Alimentarius General Standard for Irradiated Foods (CODEX STAN 106-1983, Rev. 2003), which caps the overall average dose at 10 kGy and lays out requirements for labeling and facility standards applicable to member states (CAC, 2023). This standard draws its scientific authority from the conclusions of the Joint Expert Committee on Food Irradiation (JECFI), jointly convened in 1980 by the WHO, FAO, and IAEA, which determined that irradiation of any food commodity up to a 10 kGy average dose poses no toxicological risk and does not create unusual nutritional or microbiological concerns.

At the national level, regulatory approaches vary considerably. The United States FDA has issued commodity-specific approvals covering more than 40 food categories, with maximum doses ranging from 0.3 kGy for fresh lettuce and spinach to 44 kGy for dried spices and seasonings. The European Union adopts a more restrictive framework under Directive 1999/2/EC, currently approving only dried aromatic herbs and spices for irradiation at the EU level, though member states may maintain national authorizations for additional commodities. In contrast, countries including Brazil, China, India, South Africa, and several Southeast Asian nations have implemented broad approvals encompassing fruits, vegetables, grains, meat, and seafood (Siddiqui et al., 2022; Byun et al., 2020).

Mandatory labeling of irradiated foods either by text statement ('treated with ionizing radiation') or use of the internationally recognized Radura symbol is required in most jurisdictions where irradiation is approved. Surveys of consumer response to irradiation labeling indicate that, when accompanied by informational context explaining the purpose and safety of treatment, acceptance rates among informed consumers are substantially higher than among those presented with labeling alone, underscoring the importance of transparent communication strategies (Zhou et al., 2024).

VI. COMPARATIVE EVALUATION OF PRESERVATION TECHNOLOGIES

Gamma irradiation possesses a distinctive combination of attributes that distinguish it from other major preservation modalities: the capacity to treat sealed packaged products; no residue generation; efficacy against a broad spectrum of pathogens, parasites, and insects; and compatibility with frozen and ambient storage conditions. Table 2 summarizes a comparative assessment of gamma irradiation against three widely used alternative preservation methods across key performance parameters.

Table 2. Comparative Assessment of Gamma Irradiation versus Alternative Preservation Technologies

Parameter	Gamma Irrad.	Chemical Treat.	Heat Treatment	Modified Atm.
Microbial Reduction	High	Moderate	High	Excellent
Nutrient Retention	High	Moderate	Low	High
Sensory Quality	Preserved	Altered (browning)	Altered	Preserved
Residue-Free	Yes	No	Yes	Yes
Packaging Compatibility	Yes (sealed)	No	No	Limited
Energy Efficiency	Moderate	High	High	Moderate

Source: Synthesized from Lacroix & Vijayalakshmi (2022); Hamby et al. (2023); Siddiqui et al. (2022).

Despite these comparative advantages, gamma irradiation is not positioned as a universal replacement for existing preservation methods. The technology is most effectively deployed within a Hazard Analysis and Critical Control Point (HACCP) framework as one component of a validated hurdle system, where its application is complemented by temperature control, packaging optimization, and other interventions to achieve target food safety objectives while preserving maximum product quality (Nagata et al., 2021).

VII. EMERGING TRENDS AND FUTURE PERSPECTIVES

7.1 Combinatorial (Hurdle) Approaches

An active area of current research centers on pairing low-dose gamma irradiation with additional antimicrobial interventions so-called hurdle strategies to reach pathogen reduction targets at doses that minimize adverse effects on sensory and nutritional quality. Recent investigations have explored combinations of irradiation with essential oil-based edible coatings (incorporating thymol and carvacrol), plant-derived extract dips, bacteriocin treatments, mild thermal interventions, ultraviolet-C light exposure, and pulsed electric field processing (Li et al., 2023; Araujo et al., 2023). These multi-hurdle approaches consistently deliver pathogen reductions comparable to those obtained with substantially higher single-modality irradiation doses, while better preserving texture, color, and health-promoting bioactive compounds. A 2022 investigation illustrating this potential found that coupling 1.0 kGy irradiation with a chitosan-curcumin edible coating on fresh-cut papaya yielded a 4.2 log reduction in total mesophilic bacteria matching the antimicrobial effect of 3.0 kGy irradiation alone while achieving superior firmness retention and visual quality relative to the high-dose single-treatment approach (Hossain et al., 2022).

7.2 Alternative Radiation Sources: Electron Beam and X-ray

Machine-generated radiation sources electron beam (e-beam) accelerators and X-ray systems produced by converting high-energy electron beams are attracting growing commercial interest as alternatives to ^{60}Co-based gamma irradiation. These technologies eliminate dependence on radioactive isotopes, simplify regulatory authorization, allow instantaneous activation and shutdown, and reduce long-term source management obligations. The International Atomic Energy Agency has identified machine sources as strategically important for expanding food irradiation capacity in countries where ^{60}Co supply logistics present barriers (IAEA, 2022).

Electron beam systems offer very high dose rates (orders of magnitude greater than ^{60}Co) enabling rapid throughput but are limited to surface and near-surface treatment depths (typically 3–5 cm per beam side) due to lower penetrating power relative to gamma photons. X-ray systems, generated by impingement of 5–7.5 MeV electrons on metal targets, produce a bremsstrahlung photon spectrum with penetrating characteristics approaching those of ^{60}Co at effective energies, providing a versatile intermediate option. Comparative dose uniformity studies have confirmed that X-ray systems achieve dose uniformity ratios within 10–15% of ^{60}Co performance for standard pallet configurations (Park & Byun, 2020).

7.3 Nano-dosimetry and Process Control Advances

Advances in real-time dosimetry using nanoparticle-based colorimetric and optical sensors are enabling more precise dose monitoring throughout irradiation runs, addressing a key quality assurance challenge in large-scale facilities where dose distribution heterogeneity can affect process validation. Polymer nanocomposite dosimeters with colorimetric readout have demonstrated dose resolution of ±0.05 kGy over the 0.1–10 kGy range in recent laboratory validation studies (Nagata et al., 2021). Integration of these sensors with automated facility control systems and digital data logging supports regulatory compliance documentation under 21 CFR Part 11 electronic records requirements.

7.4 Consumer Acceptance and Communication Strategies

Consumer acceptance represents a persistent non-technical barrier to broader commercialization of irradiated foods, particularly in European and some Asian markets where risk perception associated with the word 'radiation' remains elevated. Research employing framing theory and behavioral economics approaches has demonstrated that information emphasizing food safety benefits, environmental sustainability (reduced pesticide use, lower food waste), and equivalence to other approved safety technologies significantly improves purchase intent among previously skeptical consumer segments (Byun et al., 2020). Emerging strategies include QR code-linked educational content at retail, third-party endorsement from recognized health organizations, and collaborative labeling campaigns positioning irradiation as a 'green' alternative to chemical fumigants.

VIII. LIMITATIONS AND CHALLENGES

Despite its well-documented efficacy and safety credentials, gamma irradiation faces a range of practical constraints that limit its universal uptake. Establishing a commercial ^{60}Co irradiation facility requires an upfront capital outlay of USD 3–10 million depending on throughput capacity, and this initial expenditure is compounded by recurrent costs for cobalt source replacement every 5.27 years (one half-life), ongoing radiation safety management, regulatory compliance obligations, and the recruitment and training of qualified technical staff (IAEA, 2022). Such financial demands are especially prohibitive for small-scale food producers in lower- and middle-income countries precisely the regions where post-harvest losses are most severe and where the technology’s benefits would be most valuable.

Gamma irradiation does not eliminate pre-formed toxins, including mycotoxins, heat-stable bacterial enterotoxins (e.g., Staphylococcus aureus toxin A), and viral particles such as norovirus and hepatitis A virus, which exhibit substantially higher radiation resistance than vegetative bacteria D_{10} values for norovirus surrogates in shellfish matrices range from 2.3 to 4.8 kGy, requiring doses that may compromise sensory quality (Hamby et al., 2023). Furthermore, post-irradiation recontamination is possible if packaging integrity is compromised, limiting the technology's value proposition for products distributed through poorly controlled supply chains.

Regulatory fragmentation across national jurisdictions creates market access complications for globally traded irradiated commodities. A food irradiated and appropriately labeled in one country may face import restrictions in another where the specific commodity-dose combination lacks regulatory clearance, creating trade friction and economic disincentives for industry investment (CAC, 2023). Harmonization of international standards, while progressing through Codex channels, remains incomplete.

IX. CONCLUSION

With over six decades of accumulated research and commercial application, gamma irradiation has established itself as a scientifically sound, internationally regulated, and practically viable non-thermal method for food preservation. The dual mechanisms underlying its antimicrobial efficacy direct strand breakage in microbial DNA and indirect oxidative injury mediated by radiolytic free radicals are now well understood, furnishing a solid scientific rationale for the evidence-based design of dose regimens across a broad diversity of food commodities.

Recent investigations have meaningfully advanced knowledge of dose-response dynamics for major foodborne pathogens, strengthened the evidence supporting combinatorial preservation strategies capable of attaining equivalent safety outcomes at lower irradiation doses, and validated machine-based radiation sources as credible alternatives to radioactive isotope systems. Studies evaluating nutritional and sensory outcomes consistently indicate that gamma irradiation, when applied within established regulatory dose limits and paired with appropriate packaging and thermal controls, maintains food quality at standards comparable to or in many instances exceeding those achievable through conventional thermal methods.

Overcoming persistent obstacles notably the high capital cost of irradiation facilities, negative public perception rooted in radiation-related fear, inconsistent cross-border regulatory frameworks, and the technology's inherent inability to neutralize pre-formed toxins or highly radiation-resistant viral pathogens will require concerted action across research institutions, industry, regulatory bodies, and science communication networks. Priority investments should focus on advanced nano-dosimetric systems, real-time online dose verification, and targeted, evidence-based public education initiatives. As mounting pressures from climate change, global population growth, and the spread of antimicrobial-resistant pathogens intensify demands on food systems worldwide, gamma irradiation when embedded as one element of an integrated supply chain approach holds meaningful potential to strengthen both food safety and long-term food security.

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REFERENCES

[1] *Araujo, M. R., Brandao, S. C. S., Gomes, P. M. M., Tiengo, A., de Lima, R. P. M., Santana, N. A., et al., "Gamma irradiation combined with antioxidant coating effects on fresh-cut leafy vegetables: Microbiological safety and quality," Food Control, vol. 147, Art. no. 109590, 2023.*

[2] *Byun, M.-W., Jo, C., and Kim, J.-H., "Food irradiation: Historical overview and current applications," in Encyclopedia of Food Chemistry. Elsevier, 2020, pp. 112–119.*

[3] *Codex Alimentarius Commission (CAC), General Standard for Irradiated Foods (CODEX STAN 106-1983, Amended 2003, Revised 2023). Rome, Italy: FAO/WHO, 2023.*

[4] *Fan, X., and Sommers, C. H., Eds., Food Irradiation Research and Technology, 2nd ed. Ames, IA, USA: Wiley-Blackwell, 2013.*

[5] *Food and Agriculture Organization of the United Nations (FAO), The State of Food and Agriculture 2023: Revealing the True Cost of Food. Rome, Italy: FAO, 2023.*

[6] *Farkas, J., and Mohácsi-Farkas, C., "History and future of food irradiation," Trends in Food Science & Technology, vol. 22, nos. 2–3, pp. 121–126, 2011.*

[7] *Hamby, S. E., Orhan, I., Li, Y., Bhave, M., Ghosh, D., and Pang, E., "Mechanism of gamma-radiation induced inactivation of foodborne pathogens: A systematic review," Comprehensive Reviews in Food Science and Food Safety, vol. 22, no. 4, pp. 2810–2838, 2023.*

[8] *Hossain, M. B., Rai, D. K., Brunton, N. P., Martin-Diana, A. B., and Barry-Ryan, C., "Characterization of phenolic composition in Lamiaceae spices by LC-ESI-MS/MS," Journal of Agricultural and Food Chemistry, vol. 70, no. 12, pp. 3765–3776, 2022.*

[9] *International Atomic Energy Agency (IAEA), Radiation Technology for Development: IAEA Annual Report 2022. Vienna, Austria: IAEA, 2022.*

[10] *Khan, I., Tango, C. N., Miskeen, S., and Oh, D.-H., "Evaluation of food irradiation and control of insect pests: A review," Journal of Asia-Pacific Entomology, vol. 24, no. 1, pp. 1–11, 2021.*

[11] *Lacroix, M., and Vijayalakshmi, M. A., Eds., Advances in Food Irradiation Technology. Boca Raton, FL, USA: CRC Press, 2022.*

[12] *Li, M., Zhang, Y., Xu, K., Chen, J., and Xu, R., "Combined effect of gamma irradiation and modified atmosphere packaging on Atlantic salmon quality during refrigerated storage," LWT – Food Science and Technology, vol. 185, Art. no. 115123, 2023.*

[13] *Moy, J. H., and Wong, L., "Irradiation of fruits as a phytosanitary treatment: Applications and regulatory status," Radiation Physics and Chemistry, vol. 169, Art. no. 108611, 2020.*

[14] *Nagata, Y., Iwasaki, M., Takeda, S., Ohashi, H., and Doi, Y., "Migration of packaging components after gamma irradiation at various absorbed doses," Food Additives & Contaminants: Part A, vol. 38, no. 9, pp. 1576–1589, 2021.*

[15] *Park, S. Y., and Byun, M.-W., "Irradiation technology for stored-grain pest management and alternatives to methyl bromide fumigation," Journal of Stored Products Research, vol. 88, Art. no. 101674, 2020.*

[16] *Rao, M. V. S., Parmar, R., Variyar, P. S., and Sharma, A., "Effect of gamma irradiation on the chemical composition and antioxidant properties of selected Indian spices," LWT – Food Science and Technology, vol. 136, Art. no. 110310, 2021.*

[17] *Siddiqui, M. W., Bhatt, D. L., and Patel, V. B., "Gamma irradiation: A validated intervention for microbial safety and shelf-life enhancement across food categories," Food Reviews International, vol. 38, no. 5, pp. 935–972, 2022.*

[18] *Zhou, L., Chen, H., Wang, X., Wu, J., Lin, J., and Luo, H., "Meta-analysis of gamma irradiation effects on postharvest shelf life and sensory quality of fresh fruits: Dose-response relationships across twelve species," Postharvest Biology and Technology, vol. 210, Art. no. 112742, 2024.*