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Review Article

Gamma irradiation for dried fish preservation: Safety, nutrition and export potential

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ABSTRACT

Dried fish, a traditional seafood, contributing to dietary protein, food security, and the livelihoods of coastal communities. Conventional sun drying is susceptible to microbiological contamination, insect infestations, pesticide misapplication, and poor storage methods, all of which limits product safety and quality. This review offers an in-depth discussion of gamma irradiation as a controlled non-thermal preservation strategy for enhancing the microbiological safety, quality parameters, and market potential of dried fish products. The available literature was carried out to assess irradiation mechanisms, microbial inactivation performance, nutritional preservation, sensory properties, regulatory frameworks, and emerging preservation approaches, while highlighting knowledge gaps and future research priorities. From previous studies indicates that gamma irradiation doses ranging from 1.5 to 5 kGy can substantially reduce foodborne pathogens, including *Salmonella*, *Vibrio*, and *Staphylococcus aureus*, depending on product characteristics and processing conditions. Low to moderate irradiation doses generally preserve protein, amino acid, and fatty acid profiles, although lipid oxidation and sensory alterations remain important considerations. The combination of irradiation and chitosan-based coatings, cutting edge microbial detection methodologies, superior packaging solutions, and molecular tactics may further increase preservation effectiveness and regulatory quality. This review highlights the potential role of gamma irradiation as an integrated preservation strategy for reducing post-harvest losses, improving food safety, and enhancing the export readiness of Bangladesh's dried fish sector.

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INTRODUCTION

Dried fish serves as a significant traditional seafood in Bangladesh, playing a crucial role in nutritional security, economical advancement, and the nutrition of coastal populations. The industry primarily relies on traditional open-air sun-drying methods, which provide a cost-effective source of superior protein (52–73% dry weight) and vital micronutrients for at-risk communities (Jamil *et al*., 2017; Mandal, 2021; Rasul *et al*., 2020). Unregulated drying conditions subject items to microbiological contamination, insect invasion, pesticide remnants, and physicochemical degradation, therefore jeopardizing food safety, shelf life, and adherence to international trade standards. Gamma irradiation is non-thermal preservation method capable of improving microbiological safety, reduce insect infestations, storage longevity, and maintaining nutritional qualities while reducing thermal damage. Prior studies have examined the impact of irradiation on the decontamination and quality preservation of seafood; however, a thorough assessment that encompasses microbial safety, nutritional integrity, sensory acceptability, regulatory frameworks, consumer perception, and technological constraints in dried fish systems is insufficient. This review critically assesses the current advancements, challenges, and future prospects of gamma irradiation for dried fish preservation. It highlights existing knowledge gaps and evaluates emerging synergistic approaches, including chitosan-based antimicrobial coatings, molecular microbial characterization, and advanced packaging technologies, to establish sustainable and export-oriented preservation strategies.

POST-HARVEST CHALLENGES

Fish exposed to airborne dust, bird droppings, rodents, and insects during open-air sun-drying offer substantial food safety risks (Gbegudu *et al.*, 2022; Verma *et al.*, 2024). Commercial products often have moisture content of 12% to 23%, above the 15–16% threshold needed to suppress microbial and enzymatic activity (Table 1) (Al Banna *et al.*, 2022; Dey *et al.*, 2017). Multiple market studies found Salmonella in traditionally dried species, which had total viable bacterial counts of 7.50–8.56 log CFU/g, significantly above the permissible limit for fish products of 7 log CFU/g (Rasul *et al.*, 2020). According to studies comparing processing methods, traditionally dried products had aerobic plate counts of 7.72 $\times$ 10^7 CFU/g. In contrast, enhanced dried products had 4.32 $\times$ 10^4 CFU/g. Insect infestation causes 30–40% weight loss and renders 60% of infested products unsafe for consumption (Paul *et al.*, 2018; Rasul *et al.*, 2020).

Table 1. Post-harvest challenges in Bangladesh's dried fish industry.

Challenge	Major Causes	Documented Effects	Source
Traditional Drying Methods	Open-air exposure, high monsoon humidity, poor sanitation	Moisture 12–23% (target <15–16%); contamination from dust, birds, insects	(Al Banna et al., 2022; Dey et al., 2017)
Microbial Spoilage	Inadequate drying, moisture reabsorption, poor hygiene	Bacterial loads 7.50–8.56 log CFU/g (exceeds 7 log limit); Salmonella presence	(Rasul et al.- , 2020)
Insect Infestation	Blow flies, beetles, mites; inadequate storage; humid conditions	30–40% weight loss; 60% of contaminated products unfit for consumption	(Paul et al., 2018)
Pesticide Contamination	Illegal use of DDT and Nogos by processors to combat infestation	DDT residues up to 875 ppb (limit: 50 ppb); long-term health risks	(Mehedi et al., 2020)

The pesticide dilemma

Even though the Stockholm Convention (2007) prohibits the use of organochlorine insecticides such as DDT and heptachlor, many processors have continued to use them to control pest populations. Market studies found DDT concentrations ranging from 3.04 to 875.0 ppb in dried Bombay duck, ribbon fish, and shrimp, above the 50 ppb maximum residual limit for DDT and <10 ppb for heptachlor (Rasul *et al.*, 2020). DDT, which poses a chronic disease risk for decades after its last application, bioaccumulates in animal tissue and persists in soils and sediments for at least 15 years. Researchers also suggested commercially safe alternatives such as turmeric, neem, and chilli; acid spray (especially organic acids); nitrite treatment; and phenolic compounds, but with limited evidence of commercial efficacy (Paul *et al.*, 2018).

Role of nuclear technology in dried fish preservation

The Bangladesh Atomic Energy Commission (BAEC) has operated a 50,000-curie ^{60}Co gamma source at its Institute of Food and Radiation Biology (IFRB) since 1979 for food irradiation research and modest pilot studies (Hossain, 1984). Bangladesh Institute of Nuclear Agriculture (BINA), a national institute, uses nuclear and radiation technology for agricultural research. BINA has a 10 kCi gamma source and plans to use a 500 kCi ^{60}Co facility to contribute to food radiation technology for agricultural products. Ionizing radiation reduces spoilage microorganisms and slows deterioration without altering protein denaturation or palatability, distinguishing it from thermal processing methods such as heating, smoking, or drying (Rasul *et al.*, 2020) and therefore provides a means to preserve fish (Figure 1). Irradiating items in their final packaging is beneficial because gamma rays penetrate most barrier materials (Hossain, 1984). Hilsa found that 2 kGy gamma irradiation plus potassium sorbate maintained shelf life at 0°C for 35 days, compared to 21 days for untreated controls (Sheuty *et al.*, 2018). About 2–7 kGy deactivates Salmonella, Listeria, Vibrio, Pseudomonadaceae, and Enterobacteriaceae pathogens (Al-Kuraieef, 2021), while 3.0 kGy may strike a balance between sensory quality and microbial safety for some fish species. While 3.0 kGy may strike a balance between sensory quality and microbial safety for some fish species. Irradiated chitosan coatings produced in Bangladesh may also prevent blowfly infestation and fungal contamination during open-sun drying without the use of pesticides (Rahman *et al.*, 2021).

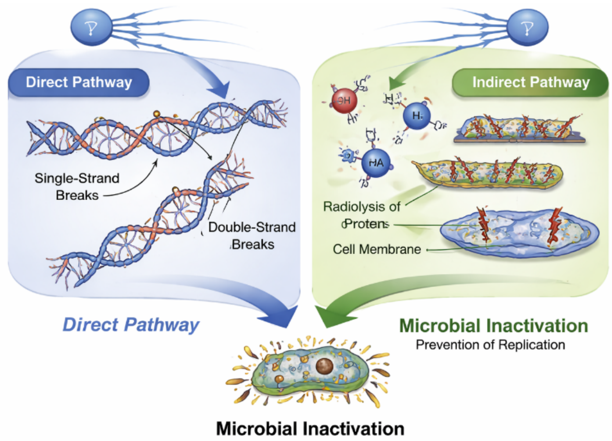

Figure 1. *Schematic flowchart of the integrated processing, dehydration, barrier-packaging, and ionizing irradiation framework for dried fish preservation.*

FUNDAMENTALS OF GAMMA IRRADIATION IN FOOD PROCESSING

Radiation sources: Cobalt-60 vs. Cesium-137

Industrial food irradiation mostly uses gamma rays from ^{60}Co and ^{137}Cs. Nuclear reactors blast stable ^{59}Co to produce double-encapsulated solid metallic slugs or pellets of ^{60}Co (Djezzar, 2018). ^{137}Cs is a fission byproduct recovered during nuclear fuel reprocessing and is usually manufactured as caesium chloride salt in a metal shell (Calado *et al.*, 2014). These sources differ in gamma energy output: ^{60}Co produces two photons at 1.17 and 1.33 MeV (mean 1.25 MeV), while ^{137}Cs emits at around 0.66 MeV (Eissa, 2012). ^{137}Cs has half the penetration depth of ^{60}Co, making it less efficient for treating dried fish trade bulk packaging (Makarov & Ponomarev, 2018). The 30 year half-life of ^{137}Cs reducing the replacement frequency, ^{60}Co accounts for 80% of global gamma irradiation capacity (Almayahi, 2019). The ^{60}Co is the common source for dried fish because of its greater penetrating capability, homogeneous dosage distribution, and physical durability, resulting in lower dispersion risk than caesium chloride salt (Calado *et al.*, 2014).

Direct effects

Ionizing photons interact directly with DNA, proteins, and phospholipids in the cell membrane. Ionization of atoms and chemical bond rupture due to this energy, causes structural damage during transmission, such as single or double-strand DNA breakdown (Figure 2). These direct impacts are especially critical in low-moisture or cold situations where molecular movement is limited (Calado *et al.*, 2014).

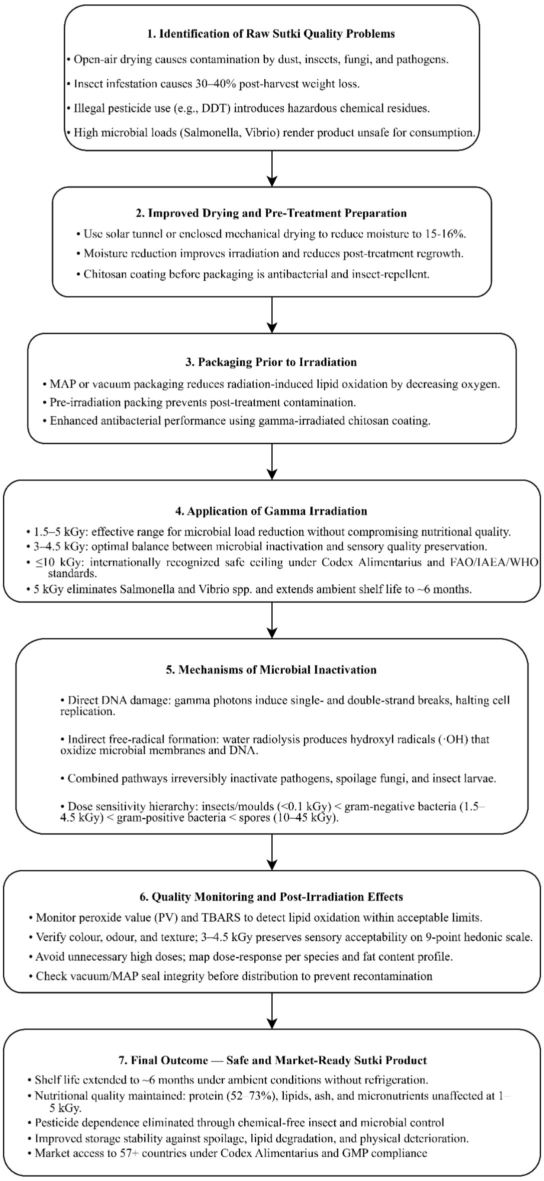

Figure 2. *Dual mechanisms of microbial inactivation in food irradiation: Direct and Indirect pathways .*

Indirect effects

Hydrogen atom, hydroxyl radical (•OH), and hydrated electron (e^-_{aq}) are highly reactive species generated by radiation-induced water radiolysis. Radiolysis of water takes about 10^{-6} seconds. Radiolytic chemicals, especially the strong hydroxyl radical, cross the cellular matrix within nanoseconds to chemically attack sensitive biological sites and disrupt the genomic stability of contaminating organisms. The combined effects irreversibly inactivate pathogenic bacteria, rotten fungi, and insects by preventing DNA repair and metabolic processes (Table 2) (Calado *et al.*, 2014).

Dosimetry and international regulatory standards

Safe and effective food irradiation requires dosimetry, the accurate measurement of ionizing radiation energy absorbed by a food product in Gray (Gy, equivalent to J/kg). Regulatory requirements specify that every part of the product receive a dose within a specified range. Dosimetry systems must be traceable to national or international standards and have statistical process control and extensive calibration processes to ensure reproducibility at laboratory, pilot, and commercial scales (Eichholz, 2003; Nasreddine, 2020). Through collaboration, the WHO, FAO, IAEA, and Codex Alimentarius Commission created the international food irradiation regulatory framework. In 1980, the Joint FAO/IAEA/WHO expert committee found that irradiating any food at an average dose of up to 10 kGy poses no toxicological risk and requires no further study (Andrews *et al*., 1998). The Codex General Standard for Irradiated Foods adopted this 10 kGy criterion in 1983. According to FAO/IAEA/WHO Study Group (1997), foods irradiated with doses exceeding 10 kGy are safe and nutritious (FAO, 1999). The 2003 Codex General Standard allows doses above 10 kGy for legitimate technological purposes, such as spice sterilization, but irradiation must complement hygiene controls and Good Manufacturing Practice (Nasreddine, 2020; Rahman *et al*., 2018).

MICROBIOLOGICAL IMPACT: A BIOTECHNOLOGICAL PERSPECTIVE

Microbial inactivation mechanisms under gamma irradiation

Gamma irradiation damages microorganisms' cellular structures through direct and indirect mechanisms, including DNA strand breaks and mutations that inhibit replication, water radiolysis in food, and the generation of reactive oxygen species (such as hydroxyl radicals) (Setia & Jadhav, 2025). Photon induced single and double stranded DNA breaks and radiolysis products (hydroxyl radicals) inactivate microorganisms directly and indirectly (Albert *et al*., 2021). Water undergoes radiolysis in approximately 10-6 seconds, producing highly reactive radiolytic compounds that interact strongly with other chemicals (Calado *et al*., 2014). Hydroxyl radicals, hydrated electrons, and hydrogen atoms can travel short distances through the cellular matrix to chemically attack sensitive biological targets and disrupt the genomic integrity. Complex life forms with large DNA molecules can be inactivated by less than 0.1 kGy, while bacteria and spores require 1.5–4.5 kGy and 10–45 kGy, respectively. Gram-negative bacteria are more vulnerable to irradiation than Gram-positive bacteria, yet *E. coli* and Salmonella exhibit differences in serotypes and serovars (Table 3) (Albert *et al*., 2021). Foodborne infections are prevented by irradiating fresh and frozen foods with 3–7 kGy to inactivate bacteria such as Salmonella. Ionizing radiation disrupts phosphodiester and hydrogen bonds in DNA strands, suppressing microbial growth in food at 0.5–30 kGy (Asghar *et al*., 2022). Irradiation directly breaks chemical bonds in DNA and indirectly affects microbial cell membranes and chromosomes through reactive oxygen and water radiolysis. Salmonella is more resistant to irradiation than *E. coli*, and strains and species differ in sensitivity, depending on cell size and DNA structure (Hadi *et al*., 2023).

Table 2. Comparison of direct and indirect effects of ionizing radiation in food systems.

Mechanism	Primary Targets	Predominant Medium	Reactive Species	Major Outcomes
Direct Effect	DNA, Proteins, Lipids	Low-moisture/Frozen systems	Ionizing photons	Immediate bond breakage; single/double-strand DNA lesions
Indirect Effect	Cellular water, DNA	High-moisture systems	•OH, e-aq, •H radicals	Radical-mediated oxidation; cellular membrane disruption; cell death

Table 3. Microbial inactivation doses for different organisms.

Organism Type	Dose Range for Inactivation	Key Characteristics	Reference
Complex life forms	< 0.1 kGy	Large DNA molecules, high sensitivity	(Albert *et al*., 2021)
Gram-negative bacteria	1.5–4.5 kGy	More sensitive than gram-positive	(Albert *et al*., 2021)
Gram-positive bacteria	1.5–4.5 kGy	More resistant than gram-negative	(Albert *et al*., 2021)
Salmonella spp.	3–7 kGy	Pathogenic, serovar variations in sensitivity	(Hadi *et al*., 2023)
Bacterial spores	10–45 kGy	Small DNA, high resistance	(Albert *et al*., 2021)

Decontamination of the dried fish microbiome

Gamma irradiation dose-dependently inactivates microbiological contamination in dried and smoked fish. Using 5 kGy of irradiation reduced microbial populations in sun-dried fish such *as C. malabaricus*, *S. lysan*, *S. acutipinnis*, *L. dussumieri*, *L. platypterus*, *L. rubrioperculatus*, and *A. thazard*, preserving overall bacterial counts for six months. Irradiated samples had low fungal counts, while non-irradiated samples had Salmonella and Vibrio (Prakash *et al*., 2014). In smoked and sun-dried anchovies (*Engraulis encrasicolus*), irradiation significantly reduced total viable count. Sun-dried and smoked samples reduced *Staphylococcus aureus* levels, with smoked samples falling from 4.502 to 1.158 CFU/g at 5 kGy (Stella *et al*., 2018). Total aerobic bacteria, faecal streptococci, *Staphylococcus aureus*, yeasts, and moulds decreased in bolti fish and smoked herring from 1.5 to 4.5 kGy (Al-Kuraieef, 2021). Irradiation at 5 kGy can eliminate aerobic plate counts in treated fish samples without altering protein, lipid, or carbohydrate content (Mohamed *et al.*, 2023). Gamma irradiation also inhibited fungal contamination, with filamentous fungal and yeast counts dropping substantially at 5, 10, and 25 kGy, reaching 98–99% at higher doses (Ibrahim *et al.*, 2024). Gamma irradiation prevents microbiological growth and preserves the quality of dried fish.

Effect of gamma irradiation on mycotoxins

Gamma irradiation degrades mycotoxins, especially aflatoxins, whereas fungal inactivation does not. Electron, gamma, and ultraviolet radiation are frequently employed to degrade aflatoxins in food and feed. Electron beam irradiation is less effective than gamma irradiation for aflatoxin destruction. However, it has dose control, fast processing time, minimal heat generation, low equipment cost, and versatility for in-line processing. Electron beam irradiation reduced aflatoxin B1 (AFB1) in Brazil nuts by 53.3% at 5 kGy and 65.7% at 10 kGy, whereas gamma irradiation achieved higher reductions of 70.6% and 84.2% at the same doses (Pandey, 2022). Chemical oxidants boost gamma irradiation. In 5% H_2O_2, 1 kGy eliminated 50 μg of AFB1, 4 kGy eliminated 100 μg, and all AFB1 mutagenicity in the Ames test with *S. typhimurium* TA100 was eliminated. AFB1 levels in contaminated groundnuts reduced from 14 to 3 μg/g and from 6.3 to 1.7 μg/g. Gamma irradiation of AFB1 solutions yielded 20 radiolytic products, seven of which were tentatively identified. Six were projected to be less hazardous because they lost the aflatoxin-toxic terminal furan-ring double bond (Calado *et al.*, 2014). However, gamma irradiation may not eliminate mycotoxins. In almonds, 15 kGy lowered AFB1 by 19.25%, AFB2 by 10.99%, AFG1 by 21.11%, AFG2 by 16.62%, and ochratoxin A by 23.90%. Doses of 0.5–15 kGy lowered aflatoxin in feed but did not remove it or ochratoxin A. Irradiation is most effective before mould creates toxins, and FAO/IAEA/WHO considers 10 kGy toxicologically safe (Su, 2020; Vita *et al.*, 2014; Wang *et al.*, 2023).

Biochemical and nutritional integrity

Stability of proximate composition in irradiated dried fish

Gamma irradiation at 1–5 kGy rarely alters fish protein, fat, moisture, ash, or carbs (Mohamed *et al.*, 2023). Dried fish products need this to maintain nutritional quality. Major components of Antarctic krill show low fluctuations up to 10 kGy, indicating compositional stability (Figure 3) (Ali-Nehari *et al.*, 2024). Very high doses (30–50 kGy) may marginally impact lipid and carbohydrate content, while protein and ash remain mostly intact due to non-thermal irradiation (Hadi *et al.*, 2023). Gamma irradiation conserves nutrients and protects microbes (Hadi *et al.*, 2023; Mohamed *et al.*, 2023).

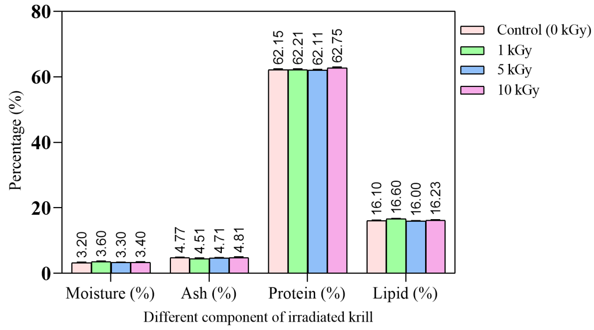

Figure 3. *Proximate composition stability in irradiated krill at different doses (Ali-Nehari et al., 2024).*

Lipid peroxidation and oxidative stability

Gamma irradiation generates free radicals that peroxidize polyunsaturated fatty acids, making lipid oxidation a quality issue in irradiated fish. It increases primary and secondary lipid oxidation products, peroxide value (PV) and thiobarbituric acid reactive substances (TBARS) (Table 4). Irradiation dose, packing, storage temperature, and antioxidant use significantly influence lipid oxidation. Irradiated fish maintain PV and TBARS below acceptable quality levels at low to moderate doses, notably 1–3 kGy, indicating that oxidation can be managed without significantly affecting edibility (Al-Kuraieef, 2021; Jeyakumari *et al.*, 2023). Fish are naturally oxidized due to their high polyunsaturated fatty acid content. However, vacuum packaging, modified-atmosphere packaging, freezing, chitosan-based coatings, and antioxidants such as rosemary, grape seed extract, and turmeric can minimize this. In irradiation, Hilsa, good packing, and low temperature decreased oxidative degradation, while 1.5- 3 kGy-irradiated fish stored at −18°C preserved TBARS below 1.0 mg MDA/kg for up to 6 months. Lipid oxidation during irradiation is manageable at optimal doses ($\leq$3 kGy) and with appropriate storage and antioxidant techniques (Xiao *et al.*, 2011; Arshad *et al.*, 2019; Rima *et al.*, 2019; Giannakourou *et al.*, 2023).

Table 4. Acceptable limits and control strategies for lipid oxidation in irradiated fish.

Aspect	Main information	Reference
PV acceptable limit	$\leq$10 meq O_2/kg fat is considered conservative; up to 20 meq O_2/kg fat may be permissible depending on product and storage condition	(Raj *et al.*, 2025)
TBARS acceptable limit	<1.0 mg MDA/kg indicates good oxidative stability; up to 5 mg MDA/kg is generally acceptable for fish/seafood	(Salari & Khatami, 2025)
Freezing storage	Irradiation combined with −18°C storage can maintain low PV and TBARS and extend shelf life up to 6 months	(Salari & Khatami, 2025)
Chitosan coating with antioxidants	Acts as an oxygen barrier and may reduce PV and TBARS by 30–50%	(Dini *et al.*, 2020)

Stability of amino acid and fatty acid profiles

Low to moderate gamma irradiation maintains fish amino acid and fatty acid profiles without producing undesirable compounds. Nutrient-rich polyunsaturated fatty acids (PUFAs) are preserved in rainbow trout, horse mackerel, and sea bass (Al-Kuraieef, 2021). Major fatty acids in mullet fillets are constant between irradiated and control samples, indicating lipid quality (Abd El-Ghafour *et al.*, 2018). Long-chain ω-3 fatty acids such as EPA and DHA are stable; however, DHA may decrease during storage due to its susceptibility to oxidation (Akintola *et al.*, 2013; Fidalgo *et al.*, 2021). Essential amino acids in krill and other food systems remain stable over irradiation dosages

(Ali-Nehari *et al*., 2024; Aquino & Ktia, 2012). Irradiation preserves important amino acids and fatty acids in fish, assuring quality and health (Abd El-Ghafour *et al*., 2018; Akintola *et al*., 2013; Ali-Nehari *et al*., 2024; Al-Kuraieef, 2021; Aquino & Ktia, 2012; Fidalgo *et al*., 2021).

Physical and sensory quality assessment

Organoleptic properties

The taste of irradiated dried fish depends on dose, species, packaging, and storage (Table 5). Higher irradiation doses may impair sensory qualities but enhance microbiological safety (Al-Kuraieef, 2021). Color changes are mainly due to oxidation of myoglobin into metmyoglobin, leading to browning, especially at higher doses (Asmarani *et al*., 2024; Dvořák *et al*., 2005; Wahyono *et al*., 2024). Irradiation can soften proteins and collagen in high doses, but it can also delay autolytic degradation, maintaining firmness during storage (Dvořák *et al*., 2005; Kim *et al*., 2024; Wahyono *et al*., 2024). Volatile sulfur compounds generated by lipid oxidation and radiolysis, irradiation significantly affects flavour and odour (Akyar, 2012). These effects may be temporary in some species but can intensify in fatty fish and at higher doses (Asmarani *et al*., 2024; Gong *et al*., 2026; Linko, 1970). Although fish products tolerate varying doses, 3-4 kGy maintains sensory characteristics and controls microbial growth (Al-Kuraieef, 2021; Debbarma *et al*., 2025).

Reconstitution properties

The quality of dried fish depends on the rehydration ratio and water-holding capacity (WHC). Gamma irradiation preserves the microstructure and prevents protein hardening, thereby keeping the structure porous for water absorption (Asghar *et al*., 2022; Wahyono *et al*., 2024). At doses up to 10 kGy, moisture and structure remain constant (Hadi *et al*., 2023). Oxidative changes, packing, and irradiation dose affect reconstitution. Protein cross-linking reduces WHC during storage, but vacuum packaging preserves texture and moisture (Hashemabad *et al*., 2018; Jeyakumari *et al*., 2023). High doses may reduce water intake due to protein denaturation, while moderate doses ($\leq$3 kGy) maintain texture and rehydration (Al-Kuraieef, 2021; Kim *et al*., 2024).

Shelf-life extension

Gamma irradiation reduces harmful organisms, by damaging DNA and inhibiting metabolic activity, thereby extending the shelf life of dried fish (Table 6) (Mohamed *et al*., 2023). At 5 kGy, dried fish can maintain appropriate bacterial levels for six months, and smoked items can significantly reduce total viable counts (Prakash *et al*., 2014; Stella *et al*., 2018). Low dosages (about 2 kGy) can significantly extend storage life in Hilsa species (Sheuty *et al*., 2018). A high dose may accelerate lipid oxidation, limiting shelf life based on sensory quality rather than microbiological safety (Jeyakumari *et al*., 2023). To balance safety, shelf life, and product quality, optimized dosages (3–4.5 kGy) are recommended (Al-Kuraieef, 2021; Debbarma *et al*., 2025).

Table 5. Effects of gamma irradiation on sensory attributes of fish.

Quality Parameter	Effect of Irradiation	Key Findings	References
Color	Browning at higher doses	Formation of metmyoglobin due to oxidation	(Asmarani *et al*., 2024; Dvořák *et al*., 2005; Wahyono *et al*., 2024)
Texture	Softening or firmness	Protein and collagen modification; delayed autolysis	(Dvořák *et al*., 2005; Y.-J. Kim *et al*., 2024; Wahyono *et al*., 2024)
Flavor & Odor	Off-odors formation	Sulfur compounds and lipid oxidation products	(Akyar, 2012; Gong *et al*., 2026; Linko, 1970)
Dose Optimization	Optimal at 3–4 kGy	Balances safety and sensory quality	(Al-Kuraieef, 2021; Debbarma *et al*., 2025)

Table 6. Reconstitution and texture stability indicators in irradiated fish systems.

Fish Product	Irradiation Dose (kGy)	Texture/Moisture Metric	Outcome	Reference
Antarctic Krill	1–10 kGy	Humidity/Moisture %	Stable (3.3% to 3.6%) across all doses	(Ali-Nehari *et al*., 2024)
Dried Fish	10 kGy	Structural Integrity	Nutritional profile and ash remain stable	(Hadi *et al*., 2023)
Fresh Bolti Fish	3.0 kGy	Sensory Texture Score	8.3/10	(Al-Kuraieef, 2021)
Tilapia Chunks	2.0–4.0 kGy	Water-Holding Capacity	Preserved through vacuum packaging	(Jeyakumari *et al*., 2023)
Dried Seafood	0.5–30 kGy	DNA/Protein Integrity	Effective disinfestation without quality loss	(Asghar *et al*., 2022)

Advanced biotechnological frontiers

Metagenomics for safety verification

Irradiated dried fish microbial communities can be profiled in culture independently using amplicon-based 16S rRNA sequencing to reveal diversity, taxonomic changes, and safety. Gamma-irradiated lettuce (1.0 kGy) exhibited a 30% decrease in Proteobacteria, a 26% increase in Firmicutes, and reductions in Pseudomonas, Escherichia, and Yersinia, but spore-forming Clostridiaceae (Dharmarha *et al*., 2019). Gamma irradiation at 5 kGy killed aerobic bacteria, Salmonella, and Vibrio in dried fish and low-moisture seafood (Mohamed *et al*., 2023; Prakash *et al.*, 2014). Baseline microbiome profiling of dried seafood found 56.9% shared Pseudomonas, Vibrio, Photobacterium, and Acinetobacter species (Kim *et al.*, 2024; Siddhnath *et al.*, 2024; Yu *et al.*, 2023). Sequencing 16S rRNA assesses relative abundance and detects early community shifts, but it cannot discriminate viable from non-viable cells or resolve species-level/pathotype information (Daly *et al.*, 2024; Sekse *et al.*, 2017). For radiation-resistant taxa such as Bacillus and Clostridium, 16S profiling, culture-based viability tests, and shotgun metagenomics provide a complete safety assessment (Dharmarha *et al.*, 2019; McHugh *et al.*, 2017; Walsh *et al.*, 2018).

Irradiated chitosan coatings

Radiation-induced structural changes in chitosan coatings improve antibacterial activity and storage stability in dried fish. Gamma irradiation decreases chitosan molecular weight (1.16 $\times$ 10^5 $\rightarrow$ 8.23 $\times$ 10^2 Da) while preserving functional groups, degree of deacetylation, solubility, water and fat binding, and antibacterial activity (Aktar *et al.*, 2017; Rosspertiwi *et al.*, 2024). Electrostatic interactions between protonated NH_3^+ groups and microbial cell surfaces cause membrane rupture and leakage, leading to antimicrobial activity (Perinelli *et al.*, 2018; Xing *et al.*, 2015). By reducing pH, K value, and volatile compounds, chitosan coatings extend oyster shelf life from 8–9 to 14–15 days, extend vacuum-packed sea bass shelf life to 25–30 days, and extend salmon fillet shelf life by 3 days. Chitosan replaces pesticides for insect contamination, uneven drying, and deterioration in dried fish like Bombay duck (Abenaim & Conti, 2023; Jeyakumari *et al.*, 2024; Rahman *et al.*, 2021); however, limited industrial-scale validation, moisture sensitivity, high water vapour permeability, and acidic dissolution are drawbacks (Bingol *et al.*, 2015; Luangapai *et al.*, 2019; Shi *et al.*, 2024). However, irradiation-treated chitosan coatings valorize crustacean shell waste, improve hygiene, and minimize pesticide dependence in Bangladesh's dried fish business.

Molecular markers

Irradiation in foods is detected using established "fingerprint" technologies that identify radiation-induced physical, chemical, or biological changes to support labelling and regulatory compliance (Guzik & Michalik, 2021). Thermal luminescence and electron spin resonance (ESR/EPR) are physical approaches. ESR can detect fish bones and mollusc shells; however, matrix dependence and high moisture limit detection (Sanyal *et al.*, 2019; Timakova *et al.*, 2016). A reliable method for measuring luminescence from silicates, TL (EN, 1788), applies to plants, nuts, and minerals. Chemicals target radiolytic compounds in fat-containing diets. Hydrocarbon analysis and 2-alkylcyclobutanones (2-ACBs) indicate the presence of fatty fish, such as dried shrimp, in irradiated triglycerides (Kim *et al.*, 2004; Tsutsumi *et al.*, 2011). Photo stimulated luminescence and DNA-based assays screen, while TL, ESR, and 2-ACBs verify (Nam *et al.*, 2022). Possible limitations include matrix dependence, low-dose false negatives, and difficulty measuring absorbed dose. ESR (bones, shells), hydrocarbon/2-ACB (fatty species), TL (mineral-contaminated products) Regulatory compliance, trade access and customer confidence Dried fish (Guzik & Michalik, 2021; Timakova *et al.*, 2016).

FOOD SAFETY, REGULATIONS, AND CONSUMER PERCEPTION

Wholesomeness and toxicology

International authorities and research have proven that irradiated fish products are safe and non-radioactive under approved processing settings (Almayahi, 2019; Lima *et al.*, 2018; Whitten & Mahon, 2021). Approved radiation sources are gamma rays from 60Co or 137Cs, and electrons or X-rays with energy limits (10 MeV electrons, 5 MeV X-rays) Click or tap here to enter text.. Proteins, lipids, and carbohydrates are stable at doses up to 10 kGy (Lima *et al.*, 2018). International committees have endorsed the wholesomeness of irradiated foods, including fish, with no microbiological, nutritional, or toxicological issues at doses below 10 kGy (Ehlermann, 2016; Elias, 1980). High-dose applications up to 60 kGy, such as sterilization of medical or space foods, have also been deemed safe. Evidence from FAO, WHO, IAEA, and FDA shows that approved food irradiation is a safe, controlled process that ensures microbiological safety without introducing radioactivity (Ravindran & Jaiswal, 2019; Sultana *et al.*, 2021). Consumer concerns about radioactivity are mostly unfounded.

The Bangladesh perspective

Bangladesh's food irradiation framework is led by the Bangladesh Atomic Energy Commission (BAEC), which conducts research, development, and pilot-scale irradiation through its 50,000-curie ^{60}Co gamma source at IFRB and the Institute of Radiation & Polymer Technology (Hossain, 1984; Sattar, 2016). BAEC is distinct from the Bangladesh Atomic Energy Regulatory Authority (BAERA), which licenses radiation activities for safety (Rahman *et al.*, 2016). The broader food safety system is supported by the Bangladesh Pure Food Ordinance (1959), Pure Food Rules (1967), Radiation Protection Act (1987), Food Safety Act (2013), Fish and Fish Product Rules (1997), and BSTI quality control mechanisms (Mohiuddin, 2019; Noor & Feroz, 2017). In addition, the Bangladesh Institute of Nuclear Agriculture (BINA) is expanding national irradiation capacity through a food/agricultural irradiation facility in Gazipur, aimed at reducing post-harvest losses and improving the export readiness of agricultural products (Arefin *et al.*, 2025). Recent reports also indicate that BINA's planned gamma irradiation facility is designed for food treatment, quarantine support, shelf-life extension, and product safety improvement. However, wider adoption remains constrained by limited facilities, high compliance costs, traceability gaps, low public awareness, and safety concerns in sectors such as dried fish, where sun drying and pesticide use remain common (Hobbs *et al.*, 2023; Rahman *et al.*, 2021). Overall, BAEC, BAERA, and BINA together provide an institutional foundation for expanding food irradiation to enhance food safety, preserve quality, and support agricultural export growth.

Consumer acceptance

Radiation fears, and labelling issues reduce consumer acceptability of irradiated product (Eissa, 2012; Sádecká, 2007). Only 20–29% of customers has positive thought about irradiated product, while creating awareness and knowledge sharing activities improve willingness to buy by 60–90% (Buczkowska *et al.*, 2023; Orynbekov *et al.*, 2025; Ravindran & Jaiswal, 2019). Irradiated goods were refused by 22-41% of Bangladeshi consumers, particularly women, older persons and people with limited incomes (Arefin *et al.*, 2025). Trust in technology, regulators, and brands substantially influences acceptance, whereas unfavorable perceptions of nuclear energy diminish willingness to pay (Dobó *et al.*, 2023; D'Souza *et al.*, 2021).

The aim of mandatory labeling with the "Radura sign" and the word "irradiated" is to encourage openness, however most customers do not know it and the terminology of radiation can be negative (Eissa, 2012; Rahman *et al*., 2018; Ravindran & Jaiswal, 2019). Export compliance demands clear labelling and additional expenditures for dried fish, which face price sensitivity, limited education, and domestic market attitudes (Rai *et al*., 2023). Awareness programs and science-based communication make irradiation acceptable for dried fish safety and shelf-life extension (Buczkowska *et al*., 2023; Orynbekov *et al*., 2025).

SOCIO-ECONOMIC IMPACT AND EXPORT POTENTIAL

Reducing post-harvest loss

Gamma irradiation has reduced post-harvest losses by controlling microbial contamination, insect infestation, and quality deterioration. Traditional sun-drying is vulnerable to *Dermestes* spp. and blowfly infestations, causing weight loss, reduced market value, and depends on hazardous pesticides (Table 7) (Mohiuddin, 2019; Rahman *et al*., 2021). A dose of 5 kGy can reduce aerobic microbial and inactivate pathogens such as *Salmonella* and *Vibrio*, helping conserve product safety and quality (Prakash *et al*., 2014). Radiation may help recover 25–30% of lost production (Arefin *et al*., 2025; Hossain, 1984). It may also support with international sanitary standards, because fishery exports remain less than 1% of total exports in Bangladesh (Hobbs *et al*., 2023). Combining irradiation with specialized coatings can improve dried fish quality and reconstitution, particularly for species such as Bombay duck, thereby supporting livelihoods and export potential (Jeyakumari *et al*., 2024; Mohamed *et al*., 2023; Zahid *et al*., 2022).

Table 7. Economic drivers of irradiation in food preservation systems.

Loss Mitigation Factor	Economic/Market Effect	Estimated Benefit	Evidence Base
Pathogen Control	Reduction in foodborne illness and product recalls	Enhanced future export prospects	(Asghar *et al*., 2022)
Safety Validation	Increased consumer trust and market access	Wholesomeness established by WHO/FAO	(Ravindran & Jaiswal, 2019)
Trade Standards	Regulatory compliance for international labeling	Global acceptance of irradiated commodities	(Medina-Hernández *et al*., 2023)
Sensory Stability	Maintenance of color, texture, and flavor profiles	Retention of high premium market prices	(Sultana *et al*., 2021)

International trade compliance

For exporting irradiated dried fish need to follow the EU and U.S. irradiation rules. In the EU, food irradiation is governed by the Framework Directive 1999/2/EC and the Implementing Directive 1999/3/EC. While EU-wide authorization currently limited to dried herbs, spices, and seasonings at $\leq$10 kGy (Calado *et al*., 2014; Farkas & Mohácsi-Farkas, 2011). Dried fish is not on the EU-approved list currently and market access remains limited. Some members of EU states accept temporary national authorizations. EU law also requires irradiation at approved facilities, validated detection methods, and labelling as "irradiated" or "treated with ionizing radiation" (Dobó *et al*., 2023; Ravindran & Jaiswal, 2019). In the U.S., FDA regulations require the Radura symbol and labelling approved doses for molluscan shellfish ($\leq$5.5 kGy) and crustaceans (6.0 kGy) (Harder *et al*., 2017; Mares, 2017; Szczawinska, 2017). Bangladesh must strengthen HACCP-based safety controls, traceability, documentation, supplier verification, and consumer transparent labelling to overcome fragmented supply chains and expand exports of irradiated dried fish (Hobbs *et al*., 2023; Koonse, 2016; Rahman *et al*., 2018).

Cost-benefit analysis

Industrial scale irradiation of dried fish in Bangladesh is not possible due to high investment, operating expenses and logistics. There is no commercial irradiation facility in the coastal manufacturing centers such as Cox's Bazar and Chattogram (Hosan, 2017; Hossain, 1984). X-ray facilities cost $1.95–5.8 million and fully automated high-power sterilizing machines cost $50 million or more, but gamma operating costs of $5.10/ton at a throughput of 22,500 tons/year, but capital costs are still significant (Meissner *et al*., 2025; Zimek, 2020). Irradiation can reduce the microbial load, extend shelf life by up to 6 months, and support sanitary compliance in over 57 countries (Islam *et al*., 2024; Prakash *et al*., 2014).

CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Species dependent dose requirement for industrial irradiation as a consequence of changes in lipid content, fatty acid composition, water activity and muscle structure affecting radiolytic and oxidative sensitivity (Qadr & Salih, 2025; Wahyono *et al*., 2024). Fish tissues are more prone to oxidation than other meats, in the order fish > turkey > chicken > pork (Wahyono *et al*., 2024). Not all fish can handle the same amount of radiation. Fresh Bolti needs a low dose (under 3 kGy) to remain fresh-tasting, whereas smoked herring can withstand up to 4.5 kGy. Indian mackerel becomes microbe-free at 4 kGy, but a higher dose of 6 kGy changes its natural fats (Al-Kuraieef, 2021; Debbarma *et al*., 2025). Multi-hurdle systems using irradiation, vacuum packaging, MAP, UV-C, essential oils, low-temperature storage, and solar tunnel drying can enhance microbial control, reduce oxidation, and preserve sensory quality (Hassoun & Emir Çoban, 2017; Mahmud *et al*., 2018; Pal *et al*., 2021). Vacuum packaging with 3–5 kGy gamma irradiation has extended storage life to up to 6 months in Phassya Shidal, while irradiation with refrigeration extended chub mackerel shelf life to 14 days (Kakati *et al*., 2020; Mbarki *et al*., 2009). Solar tunnel drying can reduce moisture by 66–75%, improving hygiene before irradiation (Haftom *et al*., 2017). However, some reported outcomes, such as a 66.6% extension with UV-C/vacuum sealing or a reduction in weight loss from 4.4% to 2.7% under irradiation-MAP, are from related food matrices and require validation for dried fish (Damdam *et al.*, 2023; Zhang *et al.*, 2021). Automation could improve future dried fish irradiation by strengthening quality control, traceability, and processing efficiency. Industry 4.0 tools such as IoT, AI, machine vision, robotics, smart dosimetry, blockchain, digital twins, and automated conveyors can support sorting, defect detection, dose monitoring, lot tracking, and export documentation (Meissner *et al.*, 2025; Pavlov & Bystrov, 2025; Qian *et al.*, 2022; Zimek, 2020). Machine vision technologies may achieve up to 98% sorting accuracy, robotic handling can reduce manual exposure and improve throughput (Chen & Yu, 2022; Drogalis *et al.*, 2023; Song *et al.*, 2025). For Bangladesh, adoption should be phased because high capital costs, decentralized production, limited electricity and internet infrastructure, cybersecurity risks, and skill gaps remain major barriers (Ismail *et al.*, 2019; Rashed *et al.*, 2025).

Table 8. Comparative status of global food irradiation adoption.

Country	Region	Income Category	Major Food Types Irradiated	Facility/ Use Status	Employment/Economic Significance	References
China	East Asia	Upper-Middle	Meat, Spices, Garlic, Health foods	Commercial (>200 facilities)	550,000 tons processed; large-scale industrial employment	(Eissa, 2012; Kume & Todoriki, 2019; Medina-Hernández *et al.*, 2023)
Vietnam	SE Asia	Lower-Middle	Frozen seafood, Fruits, Spices	Commercial	110,000 tons processed; critical for sea food value chain	(Kume & Todoriki, 2013, 2019; Medina-Hernández *et al.*, 2023)
USA	N. America	High	Spices, Mangoes, Fresh produce	Commercial	31,000 tons imported; logistics and phytosanitary handling	(Fazio *et al.*, 2019; Kume & Todoriki, 2019; Medina-Hernández *et al.*, 2023)
India	South Asia	Lower-Middle	Spices, Dried fish, Onions, Mangoes	Commercial	Supports US export compliance; value chain stabilization	(Kume & Todoriki, 2013; Medina-Hernández *et al.*, 2023)
Thailand	SE Asia	Upper-Middle	Fruits, Herbs, Fermented sausage	Commercial	High consumer acceptance; supports niche export markets	(Kume & Todoriki, 2013; Medina-Hernández *et al.*, 2023)
Bangladesh	South Asia	Lower-Middle	Spices, Grains, Dried fish	Commercial/ Pilot	Facilitates export growth; potential for coastal employment growth	(Arefin *et al.*, 2025; Zahid *et al.*, 2022)

Global adoption of food irradiation

Food irradiation is approved in over 60 countries, and industrial scale use is concentrated in about 33 nations, mainly where trade, food safety, and post-harvest loss reduction create economic demand (Da Vinha & Sousa e Silva, 2022; Eissa, 2012). Adoption of food irradiation varies by a country's income level and market structure. In the U.S. primarily relies on privately owned ^{60}Co facilities for spice sterilization and phytosanitary treatment, importing approximately 31,000 tons of irradiated food each year. China operates more than 200 irradiation facilities and processes about 550,000 tons annually (Table 8) (Fazio *et al.*, 2019; Kume & Todoriki, 2019). Vietnam also demonstrates strong commercial use, processing about 110,000 tons of seafood and fruits. In contrast, India applies irradiation to dried fish, seafood, and spices through public and private facilities to support trade and reduce post-harvest losses (Eissa, 2012; Kume & Todoriki, 2013). Bangladesh is still moving from research-scale irradiation toward commercial application, and BAEC, BINA, and coastal facilities in Cox's Bazar and Chattogram could improve dried fish safety, export compliance, value addition, and employment across logistics, packaging, maintenance, and quality-control systems (Arefin *et al.*, 2025; Rashed *et al.*, 2025; Zahid *et al.*, 2022).

Conclusion

Gamma irradiation enhanced preservation of dried fish, particularly in Bangladesh where microbiological contamination and insect infestations result in large post-harvest losses. Gamma rays inhibit spoilage bacteria and pests, extend shelf life and improve food safety while maintaining nutritional content. In addition, irradiation decreases the need of hazardous pesticides in conventional drying processes. This technology complies with the global food safety regulations and can improve the export of dried fish in Bangladesh. Future research on the combination between irradiation and other preservation techniques may improve the economy and export market access of Bangladesh's dried fish sector.

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