Review on the Impact of Gamma Irradiation on the Phytochemical and Proximate Composition of Different Food Products: Mechanisms, Dose–Response Dynamics, and Nutritional Implications

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***Abstract*—Gamma irradiation is a widely accepted non-thermal preservation technique that reduces post-harvest losses, delays spoilage, prevents sprouting, and enhances microbial safety. Its impact on nutritional and phytochemical integrity, however, is still subject to scientific assessment, despite its well-established microbiological efficacy. This review critically summarises research on the effects of gamma irradiation on phytochemicals (phenolics, flavonoids, carotenoids, vitamins, and antioxidant capacity) and proximate composition (moisture, protein, lipid, ash, fibre, and carbohydrate) in cereals, legumes, fruits, vegetables, spices, and oilseeds from 2015 to 2025. It reveals that proximate macronutrients are generally stable at doses below 10 kGy, but at higher exposures, lipid oxidation and mild protein denaturation may occur. Phytochemicals exhibit dose-dependent dual behaviour: moderate doses (1–5 kGy) frequently increase extractable phenolics and antioxidant activity due to cell wall disruption, while higher doses (>10 kGy) may degrade vitamin C, carotenoids, and some flavonoids by radiolytic oxidation. The food matrix, moisture content, oxygen availability, packaging environment, and storage conditions all have a significant impact on the outcome. Gamma irradiation is generally safe for nutrition at recommended dosages; however, product-specific optimisation is required to protect sensitive bioactive materials.**

***Keywords*—Gamma Irradiation; Phytochemicals; Proximate Composition; Dose–Response; Antioxidant Activity; Food Preservation**

I. Introduction

FAO, IAEA, and WHO have approved food irradiation as a safe food preservation technique, especially when using gamma rays from Cobalt-60 (IAEA, 2015; WHO, 2018). It is frequently used for quarantine treatment, sprout inhibition, and microbial decontamination. Usually released from Cobalt-60, gamma rays interact with food matrices by forming free radicals and ionising them. Nutritional quality may be impacted by these interactions' effects on macronutrients and bioactive phytochemicals. Optimising radiation doses that guarantee microbial safety while maintaining nutritional integrity requires an understanding of these effects.

In the twenty-first century, food security and nutritional sustainability continue to be significant worldwide issues. Microbial spoilage, enzymatic degradation, insect infestation, and physiological deterioration cause a substantial amount of food produced globally to be lost during post-harvest handling, storage, and distribution (FAO, 2022). According to estimates, almost one-third of the food produced worldwide is lost before it is consumed, especially in developing nations with limited post-harvest preservation technologies (Aghdam et al., 2018). In order to guarantee food availability and minimise financial losses, cutting-edge preservation technologies that can increase shelf life while preserving nutritional and sensory quality are crucial.

Nonetheless, worries about potential nutrient and phytochemical degradation continue. Therefore, the key to irradiation research is striking a balance between nutritional preservation and microbial safety (Bhatnagar et al., 2022; Radi et al., 2017). Microbial contamination and post-harvest losses continue to be significant obstacles to global food security, especially in developing nations.

Food irradiation, especially gamma irradiation, has drawn a lot of attention among new non-thermal preservation technologies because it can enhance food safety, lower microbial contamination, postpone ripening, prevent sprouting, and prolong storage life without appreciably raising temperatures or seriously damaging food structures (Fan & Sokorai, 2015; Bhatnagar et al., 2022). Gamma irradiation is the process of inactivating microorganisms and pests through ionisation processes that harm nucleic acids and cellular structures using high-energy electromagnetic radiation, which is typically released from radioisotopes like Cobalt-60 (^{60}Co) or Cesium-137 (^{137}Cs) (IAEA, 2015). Because irradiation works at ambient or low temperatures, it maintains many of the sensory and nutritional qualities of food, unlike thermal processing.

International regulatory bodies, such as the Food and Agriculture Organization (FAO), the World Health Organization (WHO), and the International Atomic Energy Agency (IAEA), have assessed the safety of food irradiation and determined that doses up to 10 kGy do not present toxicological or nutritional risks to consumers (WHO, 2018). Because of this, irradiation of a variety of food commodities, including spices, grains, fruits, vegetables, meat, and seafood, is currently permitted in more than 60 countries (Mostafavi et al., 2020). Food-borne pathogens, such as *Salmonella, Escherichia coli,* and *Listeria monocytogenes*, which are the cause of many food safety outbreaks globally, have been particularly successfully controlled by the technology (Fan & Sokorai, 2015). Despite its benefits, there are still worries about how ionising radiation might affect food's nutritional value, especially in relation to proximate composition and bioactive phytochemicals. Proteins, lipids, carbohydrates, moisture, ash, and crude fibre are examples of proximate components that are crucial markers of food products' overall nutritional value. Because of their antioxidant, anti-inflammatory, antimicrobial, and anticancer qualities, phytochemicals such as phenolic compounds, flavonoids, carotenoids, vitamins, and other antioxidant molecules are becoming more widely acknowledged for their important roles in human health (Ognyanov et al., 2022). Any Foods' functional and nutritional qualities may be impacted by preservation methods that change these compounds.

Gamma irradiation can influence food components through both direct and indirect mechanisms. When biomolecules like proteins, lipids, or carbohydrates are directly ionised by ionising radiation, structural changes or fragmentation result. Highly reactive species like hydroxyl radicals (-OH), hydrogen radicals (+H), and hydrated electrons ($e^{-}aq$) are produced through indirect interactions, which are more prevalent in foods with high moisture content. Following a reaction with biomolecules, these reactive species may oxidise, polymerise, or degrade nutrients and phytochemicals (Mostafavi et al., 2020). Radiation dose, food composition, moisture content, oxygen availability, packaging conditions, and storage time are some of the variables that affect how much of these reactions occur.

Different effects of gamma irradiation on proximate composition have been reported in earlier studiesMacronutrients frequently hold steady at low and moderate radiation doses, especially below 10 kGy (Bhatnagar et al., 2022). However, due to improved extractability or structural changes of macromolecules, some studies have found modest increases in crude protein or carbohydrate content (Siddhuraju et al., 2018). Lipids are often more susceptible to irradiation-induced oxidation because of the presence of unsaturated fatty acids, which may undergo peroxidation under the influence of free radicals generated during irradiation (Al-Bachir, 2016). Flavour, shelf life, and nutritional quality can all be impacted by these lipid changes.

The reactions of phytochemicals to radiation are more intricate. By rupturing cellular matrices and releasing bound phytochemicals, moderate doses of gamma radiation have been demonstrated to improve the extractability of phenolic compounds and flavonoids in specific plant foods (Ali et al., 2019). Consequently, irradiated fruits, vegetables, and legumes have been shown to have higher levels of antioxidant activity. On the other hand, oxidative reactions may cause sensitive substances like vitamin C, carotenoids, and some polyphenols to break down at higher radiation doses (Radi et al., 2017; Jabin et al., 2023). The dose-dependent behaviour seen in many irradiated food systems is influenced by the equilibrium between enhanced extractability and degradation.

Additionally, the effects of gamma irradiation differ depending on the food group. Because of their higher moisture content and metabolic activity, fruits and vegetables may show more variation in vitamin and antioxidant levels following radiation, while cereals and legumes typically show relatively stable macronutrient profiles (Fan & Sokorai, 2015). According to Balakrishnan et al. (2021), irradiation is also beneficial for spices and herbs because it effectively removes microbiological contaminants while retaining volatile compounds that give them flavour and aroma. Optimising irradiation treatments requires an understanding of these food-specific reactions.

Long-term quality is largely determined by post-irradiation storage conditions in addition to immediate changes in nutritional composition. Sensitive nutrients and phytochemicals may gradually deteriorate during storage due to oxidative reactions started during irradiation, particularly when oxygen is present (Mostafavi et al., 2020). Therefore, when assessing the technology's nutritional impact, the combined effects of irradiation dose, packaging atmosphere, and storage environment must be taken into account.

A thorough synthesis of the most recent scientific data on the effects of gamma irradiation on the nutritional and phytochemical characteristics of foods is required, given the growing interest in non-thermal food preservation technologies around the world. Individual commodities have been the subject of numerous experimental investigations, but comparative studies between various food categories are still scarce finding broad patterns, dose-response correlations, and research gaps that need more study can be aided by a thorough analysis of the body of existing literature.

Thus, this review's goal is to critically assess current research on how gamma irradiation affects the proximate composition and phytochemical components of a variety of food items, such as cereals, legumes, fruits, vegetables, spices, and oilseeds. The review also discusses factors influencing irradiation outcomes, highlights dose-dependent patterns found across studies, and investigates the underlying mechanisms responsible for nutrient modification. The review also highlights research gaps and offers suggestions for improving irradiation treatments to preserve nutritional quality while attaining microbiological safety and extending shelf life.

II. Mechanism of Gamma Radiation Interaction with Food Components

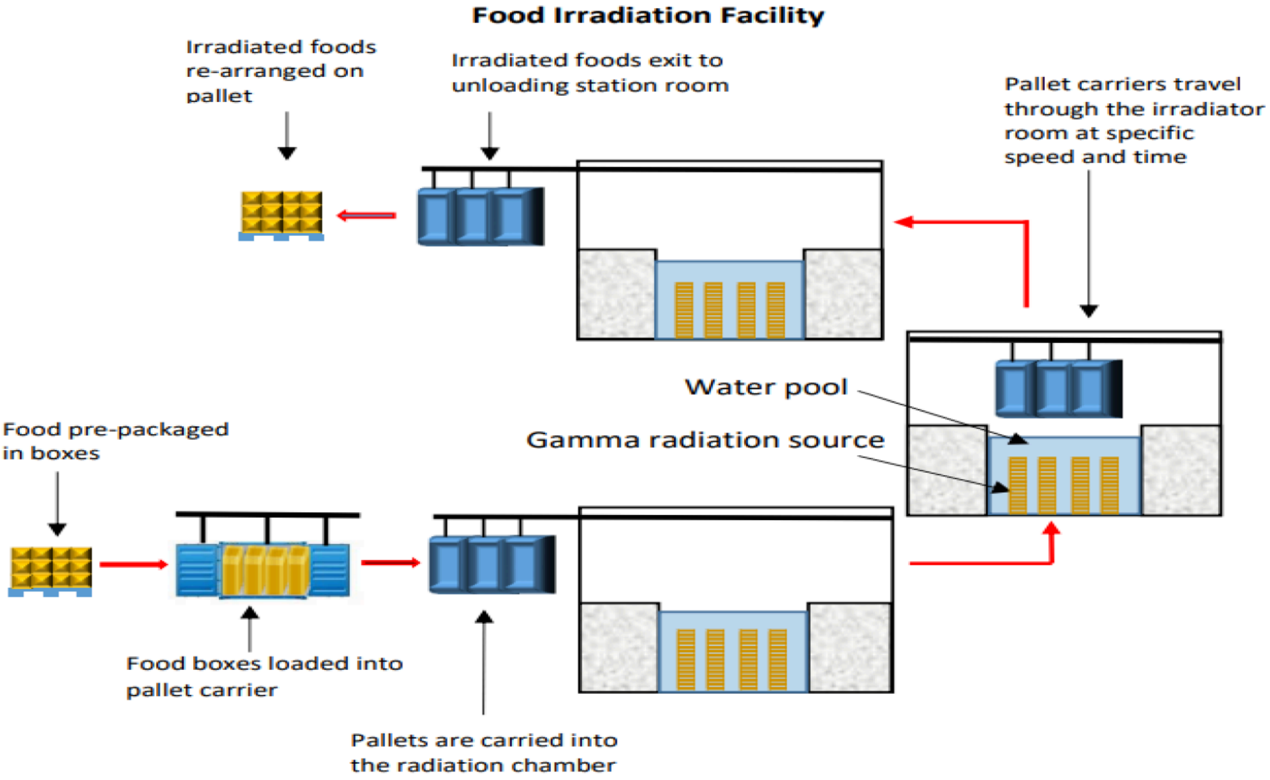

Figure 1: Mechanism of Gamma Radiation Interaction with Food Components ()

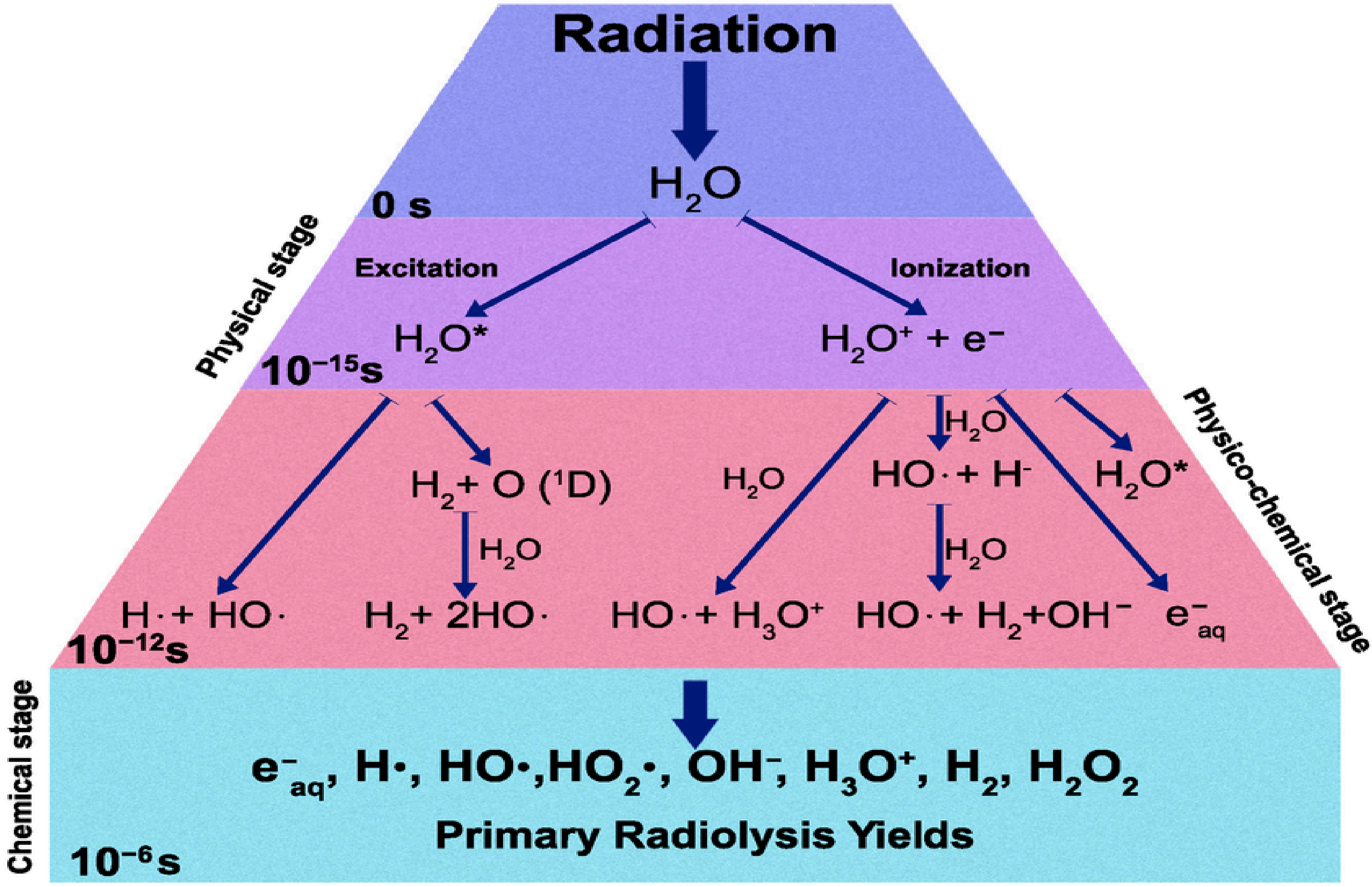

Figure 2: Decomposition of Water Molecules by Ionizing Radiation (Hall & Giaccia, 2012)

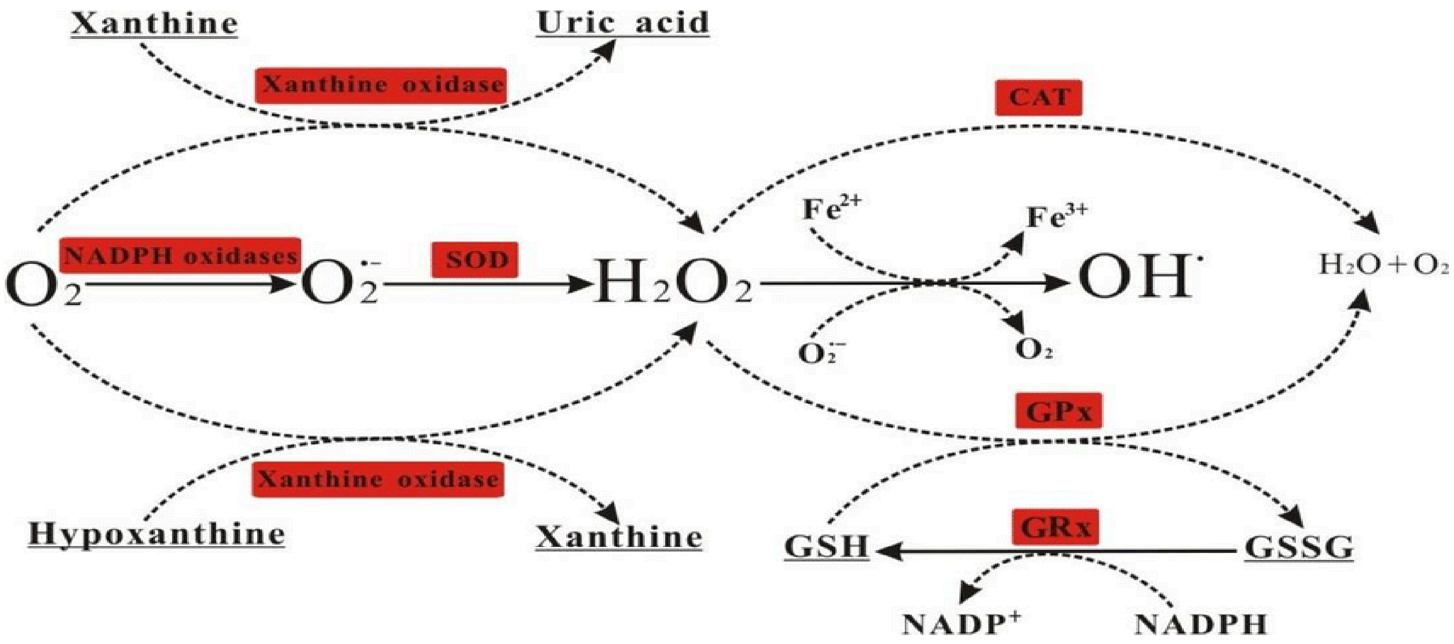

Figure 3: Decomposition of Water Molecules by Ionizing Radiation (Hall & Giaccia, 2012)

2.1 Direct Effects

Ionization of biomolecules:

- Protein backbone cleavage
- Lipid peroxidation
- Carbohydrate depolymerization

2.1 Indirect Effects (Dominant in High-Moisture Foods)

Radiolysis of water generates: $^{-}$OH (hydroxyl radical), $^{+}$H (hydrogen radical) and e^{-}aq (hydrated electron)

These reactive species oxidize:

[1] Ascorbic acid

[2] Unsaturated fatty acids

[3] Phenolic compounds

(Bhatnagar et al., 2022 ; Fan & Sokorai, 2015 ; Mostafavi et al., 2020)

III. Effects on Proximate Composition

3.1 Protein

Across legumes (cowpea, chickpea, lentils), crude protein generally remains stable at ≤10 kGy (Ali et al., 2019 ; Bamidele et al., 2021). Some studies report slight increases due to enhanced nitrogen extractability (Siddhuraju et al., 2018). At higher doses (>15 kGy), protein denaturation and reduced solubility may occur (Khan et al., 2017). Several studies report either stability or slight increases in crude protein following irradiation. In *Vigna unguiculata*, crude protein increased at doses up to 25 kGy (Soris Tresina & Mohan, 2011). Similarly, irradiation of legume seeds improved protein digestibility (Ali et al., 2019). However, cocoa beans irradiated at 7 kGy showed no significant protein alteration (Apaydın, 2024).

The apparent increases may result from enhanced nitrogen extractability rather than true protein synthesis.

3.2 Lipids and Fatty Acids

Lipids are most sensitive due to unsaturated bonds, like Increased peroxide value in oilseeds (peanut, sesame) above 10 kGy (Al-Bachir, 2016; Arvanitoyannis et al., 2018). Minor fatty acid profile changes at ≤5 kGy (Apaydın, 2024) and enhanced oxidative stability under vacuum packaging (Santos et al., 2019). Lipids are particularly susceptible to oxidative reactions. Cocoa beans exposed to gamma radiation exhibited reduced fat content and altered fatty acid profiles (Apaydın, 2024).

Low-moisture foods generally show minimal lipid degradation at doses below 10 kGy (Bhatnagar et al., 2022).

3.3 Carbohydrates and Fiber

Irradiation may cause partial depolymerization of polysaccharides (partial hydrolysis), leading to slight increases in measurable carbohydrate content (Soris Tresina & Mohan, 2011) and Increased reducing sugars in cereals (Fan & Sokorai, 2015). Fiber content may decrease due to breakdown of complex structural carbohydrates (Siddhuraju et al., 2018)

3.4 Moisture and Ash

Moisture content remains largely unchanged immediately after irradiation (WHO, 2018). Minerals (ash) are radiation resistant and remain unaffected. Moisture content generally remains stable immediately after irradiation but may vary during storage (Bhatnagar et al., 2022).

IV. Effects on Phytochemical Composition

4.1 Total Phenolic Content (TPC)

Gamma irradiation often enhances total phenolic content at moderate doses (≤5 kGy) by releasing bound phenolics from cell wall complexes (Ali et al., 2019). However, higher doses can degrade phenolic structures due to oxidative stress (Ognyanov et al., 2022). Moderate doses of 1–5 kGy Increased TPC in faba beans and lentils (Ali et al., 2019; Al-Bachir, 2016) and Increased extractability due to cell wall disruption. High doses (>10 kGy) causes degradation via oxidation (Mostafavi et al., 2020).

4.2 Flavonoids

Flavonoid content may increase due to improved extractability or decrease at high doses. Cocoa bean epicatechin significantly declined following irradiation (Apaydın, 2024). Dose-dependent behaviour Increased flavonoids at 2–5 kGy in legumes and decreased epicatechin in cocoa at 7 kGy (Apaydın, 2024)

4.3 Vitamin C

Ascorbic acid is particularly sensitive to irradiation. Decreases have been observed in legumes and fruits at higher doses (Soris Tresina & Mohan, 2011; Jabin et al., 2023). The degradation mechanism involves oxidation via hydroxyl radicals. Consistently sensitive and so 10–30% loss at 5–10 kGy in fruits (Fan & Sokorai, 2015) and also greater losses during storage (Jabin et al., 2023)

4.4 Carotenoids

Carotenoids may be moderately stable at low doses but degrade at higher exposure levels. Some fruits show improved extractability at moderate doses. Stable at low doses; degradation begin at >7 kGy. Tomato lycopene shows moderate reduction beyond 10 kGy (Radi et al., 2017).

4.5 Antioxidant Activity

Antioxidant capacity often increases when phenolics increase but declines when sensitive compounds degrade. Effects depend on food matrix and storage conditions (Ognyanov et al., 2022).

Table 1: Dose-Dependent Patterns

Dose Range	Observed Effects
1–5 kGy	Minimal proximate changes; possible increase in phenolics
5–10 kGy	Stable macronutrients; moderate vitamin loss

Dose Range	Observed Effects
>10 kGy	Greater phytochemical degradation; lipid oxidation risk

Generalized Dose–Response Trend in Nutritional Components

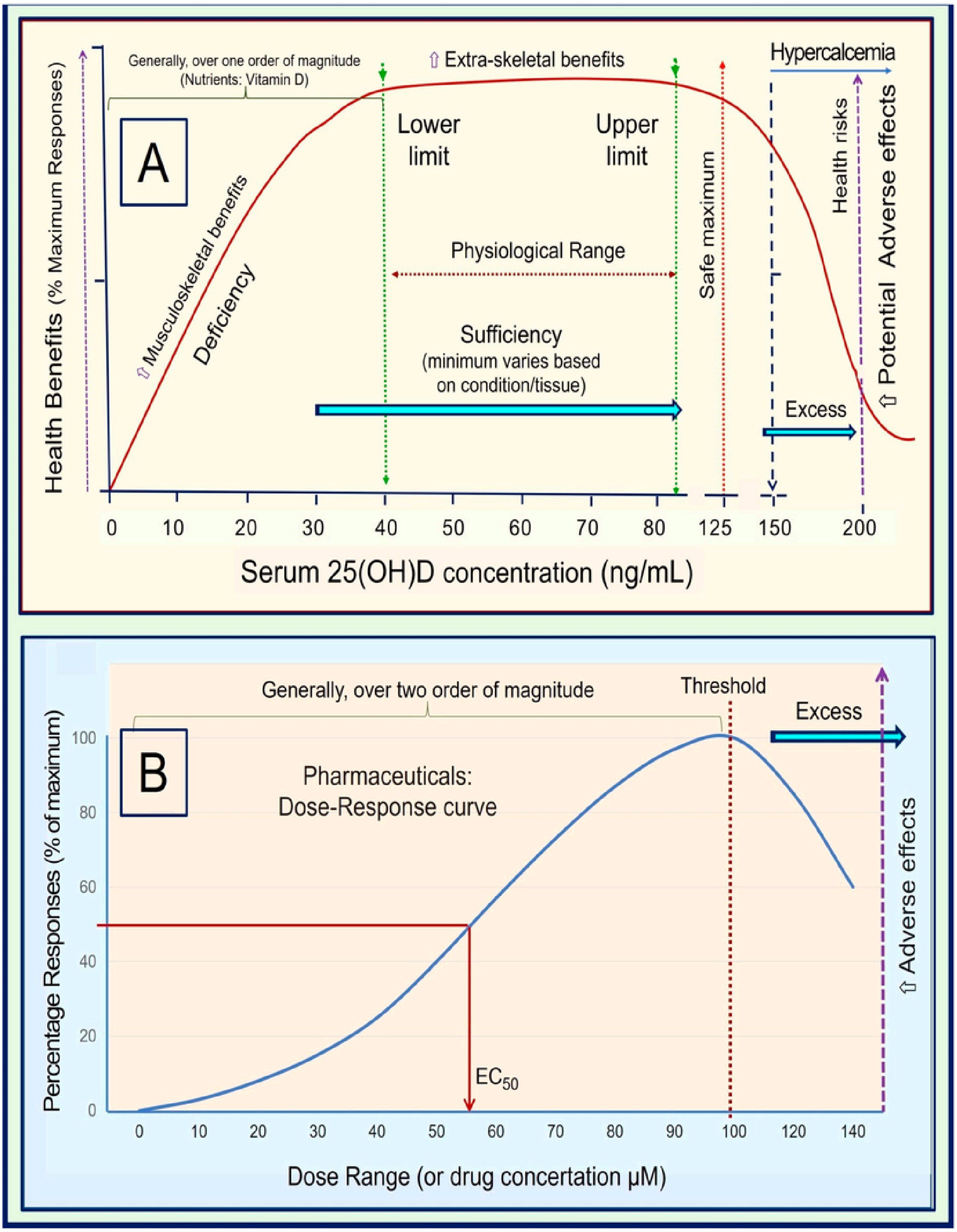

Figure 4: Generalized Dose–Response Trend in Nutritional Components

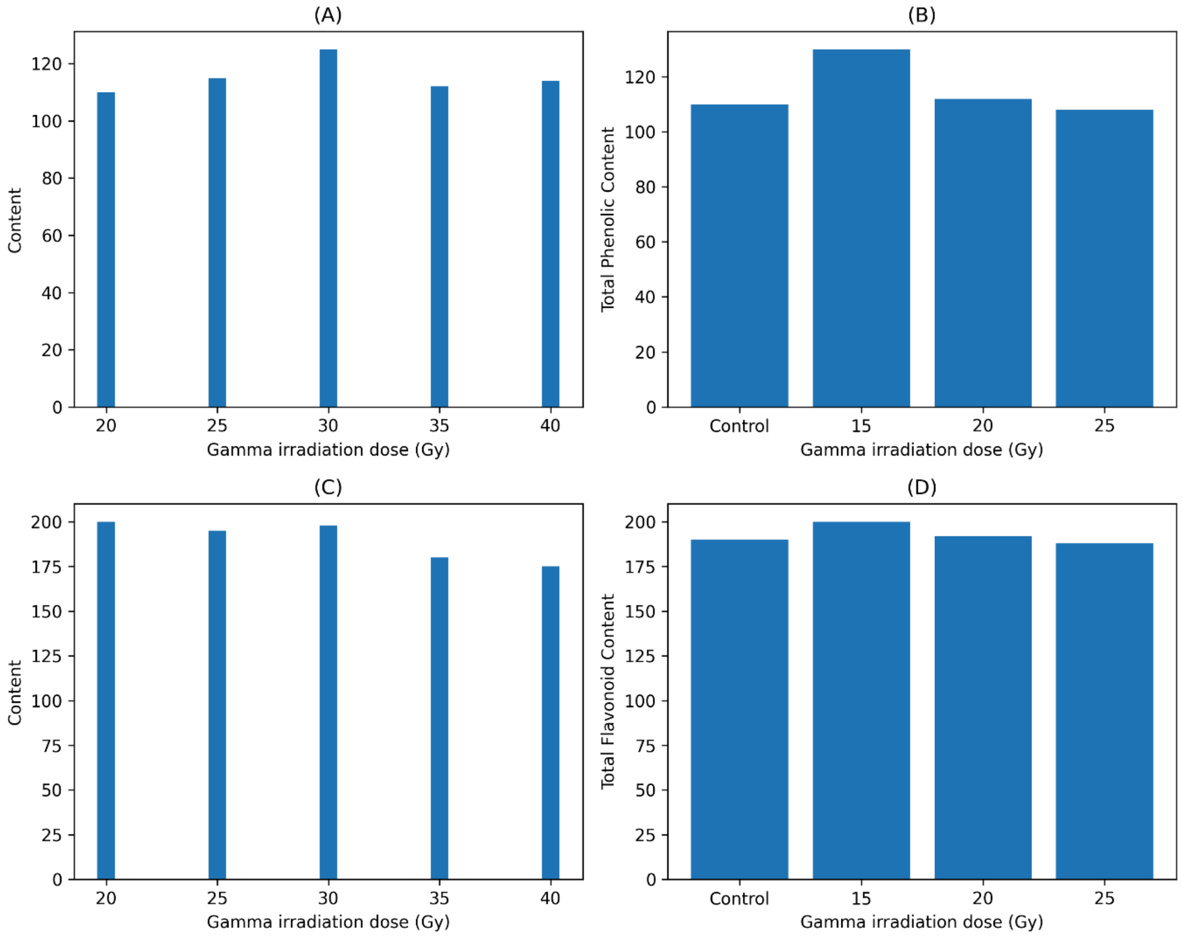

Figure 5: Pictorial representation of Gamma Irradiation dose against Phytochemical component

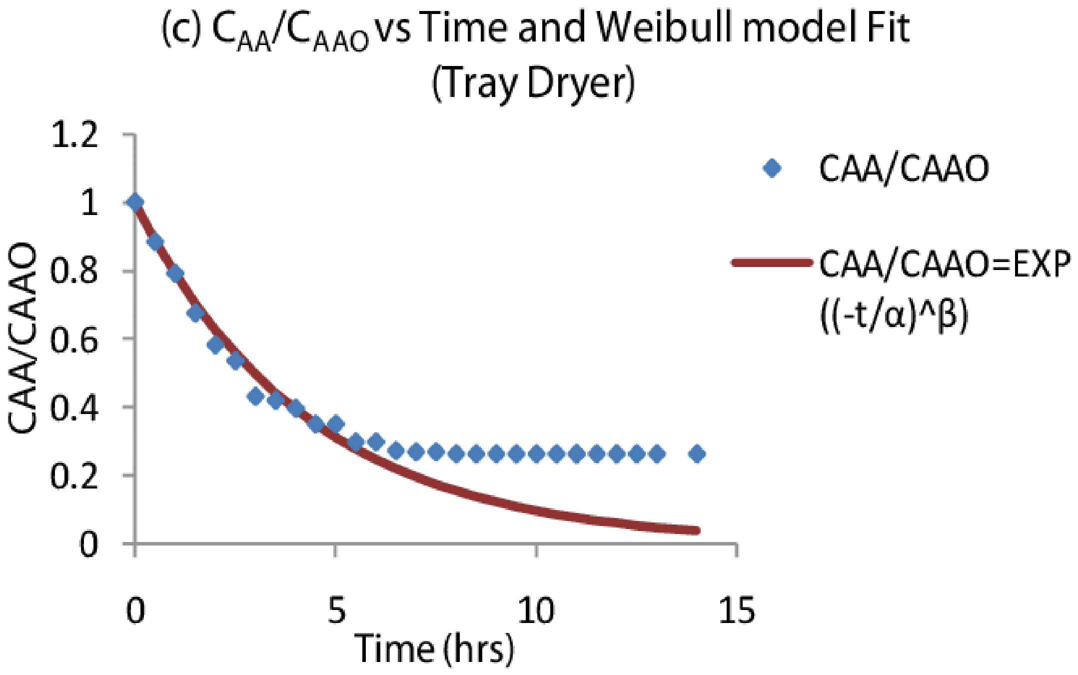

Figure 6: Graph of Time Rate and Weibull Model Fit

Table 2: Observed Pattern

Dose (kGy)	**Proximate Composition**	**Phenolics**	**Vitamin C**
1–3	Stable	↑ Slight	Minimal loss
5–7	Stable	↑ Moderate	10–20% loss
10–15	Slight changes	↓	20–40% loss
>15	Structural damage	Significant ↓	Major degradation

Table 3: Comprehensive Summary Table on Effects of Gamma Irradiation on Phytochemical and Proximate Composition of Food Products

Food Product	Dose (kGy)	Proximate Composition Effects	Phytochemical Effects	Key Findings	Citation
Cowpea (*Vigna unguiculata*)	2–25	Protein ↑; fiber ↓; ash ↓	Phenolics ↑; tannins ↑; Vitamin C ↓	Increased protein extractability; antioxidant enhancement at moderate dose	(Soris Tresina & Mohan, 2011)
Faba bean (*Vicia faba*)	1–10	No significant change	Phenolics ↑; flavonoids ↑	Enhanced antioxidant activity due to release of bound compounds	(Ali et al., 2019)
Chickpea (*Cicer arietinum*)	2–8	Protein stable; lipid slight ↓	Phenolics ↑	Improved digestibility and antioxidant capacity	(Siddhuraju et al., 2018)
Lentil (*Lens culinaris*)	1–6	Minimal changes	Phenolics ↑; flavonoids ↑	Improved bioavailability of phytochemicals	(Al-Bachir, 2016)
Cocoa beans	5–7	Fat ↓; protein stable	Epicatechin ↓; total phenolics ↓	Oxidative degradation of flavonoids at higher doses	(Apaydın, 2024)
Rice (pigmented)	2–10	Carbohydrates ↑; protein stable	Antioxidants ↑; phenolics ↑	Improved antioxidant activity at moderate doses	(Smita et al., 2023)
Wheat grains	1–5	Moisture stable; protein stable	Minor phytochemical changes	Suitable for storage without major nutritional loss	(Fan & Sokorai,2015)
Maize	2–10	Protein stable; lipid ↓ slight	Phenolics ↑	Enhanced shelf life and antioxidant potential	(Mohamed et al., 2009)
Tomato	1–10	Moisture slight ↓; TSS ↑	Lycopene stable ≤7 kGy; ↓ at higher doses	Shelflife extension with minimal nutrient loss	(Radi et al., 2017)
Mango peel	2–8	Stable	Vitamin C ↓; phenolics ↑	Increased antioxidant activity despite vitamin loss	(Jabin et al., 2023)

Food Product	Dose (kGy)	Proximate Composition Effects	Phytochemical Effects	Key Findings	Citation
Apple	1–5	Minimal change	Polyphenols ↑	Enhanced phytochemical extractability	(Fan & Sokorai, 2015)
Potato	0.5–1	No major changes	Minor phytochemical changes	Effective sprout inhibition	(IAEA, 2015)
Onion	0.5–1	Stable	Flavonoids stable	Sprout inhibition without nutrient loss	(WHO, 2018)
Peanut	2–10	Lipid oxidation ↑ at high dose	Phenolics slight ↑	Oxidative stability affected by dose	(Nguyen et al., 2022)
Sesame seeds	5–15	Lipid oxidation ↑; fat ↓	Minor phytochemical changes	Unsaturated fats sensitive to irradiation	(Al-Bachir, 2016)
Soybean	2–10	Protein stable; lipid slight ↓	Isoflavones ↑	Improved functional properties	(Bhatnagar et al., 2022)
Spices (chili, pepper)	5–10	Stable	Capsaicinoids stable; antioxidants ↑	Effective decontamination without quality loss	(Balakrishnan et al., 2021)
Rose hip	1–10	Stable	Phenolics stable; antioxidants stable	Minimal degradation due to low moisture	(Ognyanov et al., 2022)
Cucumber	1–6	Moisture ↓ slight	Vitamin C ↓	Storage-dependent degradation	(Khalili et al., 2017)
Seafood	2–7	Protein stable; lipidoxidation ↑ slight	Antioxidant activity ↓	Shelf-life extended with minor oxidation	(Uikey et al., 2025)

4.6 Factors Influencing Nutritional Outcomes

- Oxygen availability
- Packaging atmosphere
- Moisture level
- Food matrix complexity
- Storage duration
- Radiation source energy

(Santos et al., 2019 ; Mostafavi et al., 2020)

4.7 Nutritional Safety and Regulatory Perspective

International agencies confirm no significant nutritional hazards at ≤10 kGy (WHO, 2018; IAEA, 2015). Protein quality, amino acid integrity, and mineral bioavailability remain within acceptable ranges.

4.8 Research Gaps (2015–2025)

1. Limited long-term storage interaction studies
2. Insufficient meta-analysis on antioxidant capacity
3. Understudied tropical indigenous crops
4. Lack of molecular-level phytochemical degradation mapping
5. Limited combined irradiation + packaging studies

4.9 Implications for Food Security and Post-Harvest Loss Reduction

Gamma irradiation offers significant potential for reducing microbial spoilage and extending shelf life while maintaining nutritional quality when properly optimized. This is particularly relevant for tropical fruits and legumes in Africa (Onoja et al, 2025).

V. Conclusion

This review critically evaluated the impact of gamma irradiation on the proximate composition and phytochemical profile of diverse food products, including cereals, legumes, fruits, vegetables, spices, and oilseeds. The synthesis of recent literature (2015–2025) demonstrates that gamma irradiation is a robust, non-thermal preservation technology capable of enhancing food safety and extending shelf life while largely preserving nutritional quality when applied within recommended dose limits.

A key finding of this review is that the proximate composition of foods remains relatively stable under low to moderate irradiation doses (≤10 kGy). Macronutrients such as proteins, carbohydrates, and ash exhibit minimal or no significant changes, indicating that gamma irradiation does not substantially compromise the fundamental nutritional value of food products. However, lipids are comparatively more susceptible to oxidative degradation, particularly at higher doses, due to the radiolytic formation of free radicals that initiate lipid peroxidation reactions (Bhatnagar et al., 2022; Mostafavi et al., 2020). These findings highlight the importance of dose optimization and protective strategies such as vacuum packaging to mitigate oxidative damage. In contrast, phytochemical constituents exhibit a complex, dose-dependent response to gamma irradiation. Moderate irradiation doses (typically 1–5 kGy) often result in an increase in total phenolic content, flavonoids, and antioxidant activity, primarily due to the disruption of plant cell wall matrices and the release of bound bioactive compounds (Ali et al., 2019; Ognyanov et al., 2022). This enhancement suggests that controlled irradiation can improve the functional quality of certain foods. However, higher doses (>10 kGy) tend to induce degradation of sensitive phytochemicals, including vitamin C, carotenoids, and some polyphenols, through oxidative mechanisms driven by reactive oxygen species generated during radiolysis (Fan & Sokorai, 2015; Radi et al., 2017). Thus, the dual effect of irradiation underscores the need for carefully calibrated treatment conditions.

The review further reveals that the extent of irradiation-induced changes is strongly influenced by intrinsic and extrinsic factors, including food matrix composition, moisture content, oxygen availability, packaging conditions, and storage duration. High-moisture foods such as fruits and vegetables are more prone to indirect oxidative reactions due to water radiolysis, whereas low-moisture foods such as grains and spices exhibit greater stability. Additionally, post-irradiation storage conditions can amplify or mitigate nutrient degradation, indicating that irradiation should be considered as part of an integrated preservation system rather than a standalone treatment (Mostafavi et al., 2020). From a safety and regulatory perspective, the evidence consistently supports the conclusion that gamma irradiation is nutritionally safe at doses approved by international agencies, with no significant adverse effects on protein quality, mineral composition, or overall dietary value (WHO, 2018). This reinforces its suitability for large-scale application in food preservation, particularly in regions facing high post-harvest losses and food insecurity. Despite the substantial progress in this field, several research gaps remain. There is a need for more comprehensive, long-term studies evaluating the combined effects of irradiation and storage, particularly under different packaging atmospheres. Furthermore, limited data exist on the molecular mechanisms of phytochemical transformation and the bioavailability of irradiated nutrients in human systems. Emerging research should also explore the application of gamma irradiation to underutilized indigenous crops like Cocoyam and Yellow yam, especially in developing countries, to enhance food security and nutritional outcomes.

Gamma irradiation represents a scientifically validated and nutritionally acceptable technology for food preservation. While proximate composition is largely retained, phytochemical responses are dose-dependent and require optimization to balance enhanced bioactive availability with the prevention of nutrient degradation. Future advancements in irradiation technology, combined with improved packaging and storage strategies, will further strengthen its role in sustainable food systems and global food security.

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