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# Beyond Preservation: a Systematic Review on the Impact of Ionizing Radiation on Food Functionality

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**Irradiation stands out as a prominent technology for eliminating potentially hazardous organisms from food items and extending shelf life. Beyond its traditional role, there is a growing interest in its capacity to enhance the nutritional quality and functionality of food. Despite various research endeavors in this domain, a systematic literature synthesis has been notably absent. Thus, following the PRISMA guidelines, we conducted a systematic review to bridge the knowledge gap by comparing existing studies on the usage of ionizing radiation in connection to food functionality. A set of quality criteria were applied to assess the studies and identified 144 high-quality studies. Analysis of data during the present work revealed that gamma radiation was the most used type of radiation for irradiating functional food, and the most common enhancement mechanism exhibited by irradiated functional food was the elevation of bioactive compounds, particularly antioxidants. Cancer and allergies were the most frequently targeted diseases associated with irradiated food. Our findings provide valuable insights into the potential benefits and applications of food irradiation in the functional food sector and may inform future R&D in the field.**

Keywords: bioactive compounds, food irradiation, food preservation, functional foods, ionizing radiation, nutraceuticals, PRISMA guidelines

## INTRODUCTION

Food irradiation employs non-thermal techniques, utilizing specific doses of non-ionizing or ionizing radiations to eliminate harmful pathogens in food or agricultural commodities (Bisht *et al.* 2021). This process extends the shelf life of the food while preserving its nutritive parameters (Maherani *et al.* 2016). By eliminating microbes, food irradiation effectively ensures food safety, preventing food poisoning and reducing post-harvest losses of food products. Furthermore, it can control insects and delay sprouting and ripening – making it an increasingly recognized solution to meet quarantine requirements, enhance exports, and guarantee the hygienic quality of foods (Roberts 2016).

Ionizing radiation is a type of energy characterized by extremely short wavelengths and high intensity capable of removing electrons from atoms to generate ions without rendering the exposed substance radioactive (Maherani *et al.* 2016). Examples of ionizing radiation encompass X-rays, gamma rays, and electron beams, with gamma rays being the most commonly employed for sterilizing packaged goods. Both the FDA and the International Standards for Food Irradiation have authorized two

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types of gamma sources for use in food irradiation: $^{60}$Co and $^{137}$Cs (Nam *et al.* 2016). These types of radiation have common impacts on pathogens and product quality through direct and indirect effects. In the direct effect, components of cells or food products are directly damaged by radiation. Meanwhile, in the indirect effect, free radicals and reactive species from the radiolysis of water such as hydroxyl radicals (OH•), hydrogen radicals (H•), and hydrated electrons ($e_{aq}$) interact with the food materials. Given the high water content of biological materials, the indirect effect is the main mechanism of ionizing irradiation.

The beneficial effects of food irradiation are well-documented. In comparison to alternative physical processes applied to food, irradiation offers several practical advantages by demonstrating versatility for food safety, security, and trade. It is highly effective and efficient against all non-sporing bacteria, insects, and many other pests. Being a cold process, food irradiation does not denature or alter the sensorial properties of food. Furthermore, its penetrating nature allows for the treatment of foods in their final packaging, unaffected by package shape or position, thereby ensuring treatment consistency. Solid, raw foods can also be treated, and the process does not involve chemicals or chemical residues. The ease of control in the process, usually dependent only on conveyor speed and the power/activity of the radiation source, allows irradiated food to be immediately distributed into the food supply chain (Satin 2020).

The technology is particularly useful in preventing foodborne outbreaks caused by post-harvest losses and microbial contamination, which remains a significant challenge for the food industry. Irradiation, by extending the shelf life of food products, also facilitates their availability during off-seasons for future consumption (Roberts 2014; Gallo *et al.* 2020). Yet despite these advantages, food irradiation is still underutilized at large scale. In recent years, this technology has also been found to enhance the medicinal properties of foods by increasing their antioxidant content and reducing harmful bacteria and fungi while extending their shelf life for consumer convenience. With the increasing demand for healthier food options, irradiation has the potential to play a significant role in the production of functional foods and nutraceuticals in the future.

While the global food irradiation industry has experienced gradual growth in recent years, its adoption in Europe appears to be proceeding at a slower pace. The food irradiation market is expected to grow significantly in the coming years, reaching a value of USD 276.7 million by 2026, growing at a compound annual growth rate (CAGR) of 5.7% from 2021–2026, according to the AI-driven market intelligence platform Report Linker (2022). The United States (US) maintains a 30.5% share of the worldwide food irradiation industry, with a 2021 worth of USD 69.9 million. China, as the world's second-largest economy, is expected to reach a market size of USD 132.8 million by 2026, with a CAGR of 4.5%. Other important markets include Japan and Canada, with projected growth rates of 2.6 and 3.4%, respectively. Germany stands out as Europe's largest market, poised for a 1.9% CAGR growth, whereas the rest of the European market is expected to reach USD 138.1 million by the end of the analysis period. The Asia-Pacific region leads the food irradiation market for several reasons, including increased public acceptance and favorable legislation on irradiated food consumption in various countries across the region. Despite the growing trend, it is crucial to acknowledge that irradiated food still accounts for a small fraction of global food production and consumption. Nevertheless, food irradiation is projected to gain broader appeal in the worldwide market driven by the increasing demand for safe and long-lasting food options.

In response to the growing need for healthier food choices, irradiation may play a role in the future production of functional foods and nutraceuticals, that may facilitate access to overlooked market segments. While both traditional and functional foods are important for health and disease prevention, this study specifically focuses on functional foods. Distinct from nutraceuticals, functional foods are whole foods or fortified foods that provide health benefits beyond basic nutrition. In contrast, nutraceuticals are bioactive compounds or substances extracted from foods that have physiological benefits, conferring protection against several chronic diseases (El-Sohaimy 2012). Additionally, functional foods are consumed as part of the regular diet, whereas nutraceuticals are typically consumed in supplement form such as capsules or tablets (Hasler 2002).

Mounting research indicates that irradiation can positively impact food functionality. For instance, the immunomodulatory effect of *Astragalus* polysaccharides was enhanced through irradiation (Li *et al.* 2018). Gupta and co-authors (2011) found that as yeasts, molds, and coliforms were eliminated in *Terminalia chebula* (myrobalan), *Curcuma longa* (turmeric), *Syzygium aromaticum* (clove), and *Mentha piperita* (peppermint) after irradiation at a dose of 2.5 kGy, the total extraction yield of bioactives increased. In another study, Kim *et al.* (2000) reported that 5–10 kGy of gamma irradiation was sufficient to inactivate microorganisms, and at 10 kGy, the total extraction yield of bioactives was increased by 5–25% in 15 Korean medicinal herbs. Irradiation of *saengshik*, a Korean cereal meal of plant and animal origin, improved its antioxidant activity due to a higher total phenolic content after irradiation (Kim *et al.* 2020). Notably, irradiation of honey reduced moisture and quantities of vitamin E and 5-hydroxymethylfurfural

– a genotoxic molecule generated by honey's reducing sugars, enhanced color intensity, and even raised vitamin C content. Nevertheless, it had no discernable effect on the physicochemical qualities or mineral content of honey (Hussein *et al.* 2014).

Despite an expanding body of research on the benefits of irradiation on food that go beyond safety and shelf-life extension, the phrase "food irradiation" is still synonymously linked with food sterilization and phytosanitary treatment. This limited view overlooks the potential of irradiation to enhance the medicinal properties and functionality of food. To address this gap in knowledge, a systematic review was conducted to synthesize the findings on the enhancement of functional foods through irradiation. Specifically, the review aimed to profile irradiated functional food products from 2001–2021, analyze the radiation treatments performed, identify target diseases for functional foods, and investigate mechanisms for enhancing food functionality through radiation treatment.

## METHODOLOGY

### Search Strategy

The selection of studies followed the PRISMA 2020 flow diagram (Figure 1), whereas the PRISMA 2020 checklist was used as a guide to ensure that this systematic review contained the contents that needed to be addressed in each section. The search strategy followed those of Gadioli *et al.* (2018) and Tawfik *et al.* (2019) with modification. Relevant journal articles published in English were obtained from the following electronic databases: PubMed, Scopus, and ScienceDirect. The search terms used by the authors include “radiation,” “irradiation,” “gamma,” “cobalt 60,” “cesium 137,” “electron beam,” “X-ray,” “fruits,” “leaves,” “seeds,” “roots,” “bark,“ “stem,” “spice,” “natural products,”“secondary metabolites,” “compounds,” “concoction,” “extract,” “extraction,” “isolation,” “sterilization,” “characterization,” “herbs,” “herbal,” “traditional,” “medicine,” “medicinal,” “healing,” “properties,” “functional food,” “dietary,” “supplement,” “phytomedicine,” “ethnomedicine,” and other synonyms, related keywords, and wildcard terms (see Appendix A for the detailed search strategy). Searches of studies were modified according to the filter settings available on each database. Aside from using Boolean keywords, other works of recurring authors were also explored to find relevant studies. All records were collated in the Mendeley library to remove duplicate entries and exported into a Microsoft Excel spreadsheet. The information obtained were the authors’ names, publication year, journal, DOI or URL link, and abstract.

### Screening and Categorization of the Studies

The following inclusion criteria were applied to select relevant studies for this systematic review: [1] use radiation to enhance the functionality of food and [2] not be restricted by country. Exclusion criteria encompassed studies where [1] only non-ionizing radiation was employed, [2] publication fell outside the 2001–2021 timeframe, [3] the language was other than English, or [4] they constituted opinion-based, case reports, or systematic reviews, as indicated by Tawfik *et al*. (2019). Two independent reviewers performed the initial screening of the articles by analyzing the titles and abstracts to exclude the studies that did not meet the inclusion criteria. Duplicate articles were removed prior to the screening. The data of interest, including the study's main objective and outcomes, were extracted from the articles' titles and abstracts.

After obtaining the abstracts, the articles were evaluated according to the Critical Appraisal Checklist for Systematic Reviews and Research Syntheses by Joanna Briggs Institute (Aromataris *et al.* 2015; Gadioli *et al.* 2018). The assessment involved addressing the following inquiries:

[1] Does the study mention the irradiated functional food products?

[2] Does the study report on the type of irradiation process used on functional food?

[3] Does the study specify the radiation doses or levels used for treatment?

[4] Does the study mention the diseases targeted by enhanced functional foods?

[5] Does the study elaborate on the mechanism/s of enhancement?

For each question, a "yes," "no," "unclear," or "not applicable" response was assigned. Studies with at least 70% frequency of "yes" were considered of good quality and automatically added to the list of studies from which data was extracted. Articles with a frequency between 50–69% were of moderate quality, whereas those below 50% were of bad quality and subjected to scrutiny. Any discrepancies were resolved through discussion to determine the inclusion status of particular articles.

The selected studies were organized and tabulated in an Excel sheet containing information about the functional food category, functional food product, radiation type, radiation dose, effect or mechanism of enhancement, and targeted disease if mentioned. The functional foods were classified according to Crowe and Francis (2013) distinguising between conventional foods, modified foods, and synthesized ingredients. Moreover, conventional foods were further categorized into vegetables, fruits, protein, grains, and others based on the healthy eating plate (Harvard School of Public Health 2011).

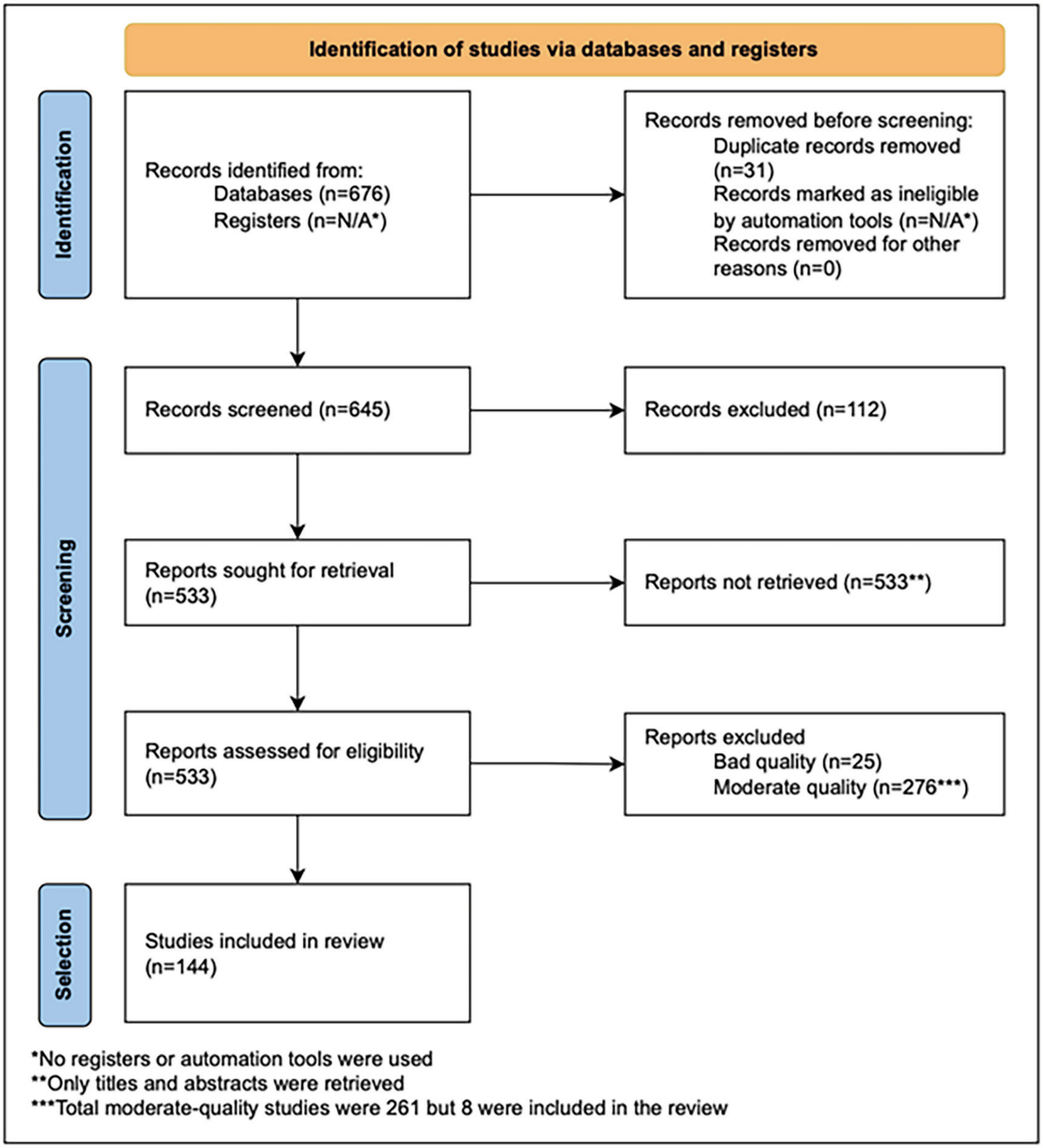


**Figure 1.** 2020 PRISMA flow diagram for selecting journal articles.

**Data Analysis**

Various data visualization tools were used to analyze the selected studies. A cluster bar graph was created to display the frequency of usage of each type of radiation from 2001–2021. The frequencies of target diseases per functional food category were also recorded using the same program and a chord diagram was generated using the Circlize package of RStudio. Only studies with target diseases mentioned in their abstract were included and if a study mentioned more than one disease, these were treated as separate variables. Studies were also categorized based on whether they had a positive, negative, or no effect on the functional food product, and only studies with positive effects were used to generate a heatmap. It should be noted that studies that did not state their results in the abstract were not included in the analysis. Finally, to create the word cloud, the title and keywords of each study were retrieved. Greek letters such as "β" and "γ" were also Romanized into "beta" and "gamma" since the word cloud generation software cannot read non-Roman letters. After removing frequently used words and polishing the resulting words, the word cloud was generated using Wordle (https://makewordcloud.com/wordle-generator). Words with the same or similar meaning were treated as distinct words due to the limitations of the software.

## RESULTS AND DISCUSSION

Initially, a total of 676 studies were initially retrieved from three research databases – Scopus, ScienceDirect, and PubMed – based on the inclusion criteria. After removing duplicates, 645 unique studies were identified. Critical evaluation of abstracts resulted in the exclusion of 112 studies, hence leaving 533 studies. Further screening resulted in the selection of 144 good-quality journal articles. In addition, eight moderate-quality studies were added to the final list after review and discussion among the reviewers (Figure 1). The inclusion criteria for the studies required the authors to mention the effect of ionizing irradiation on the functional properties of certain functional foods and provide a general conclusion of whether there was an effect. Although some studies only partially met these criteria, they were still included if they fulfilled the other requirements of the study. The list of good-quality articles and extracted data can be found in Appendix A.

### Comparison of Use of Gamma Rays, Electron Beam, and X-rays

The food irradiation compendium of research and development (R&D) can be segmented based on the source of radiation, which includes gamma rays, X-rays (≤ 7.5 MeV in some countries and ≤ 5 MeV in others), and electron beams (≤ 10 MeV). Radionuclides such as $^{60}$Co and $^{137}$Cs are used to produce gamma radiation. $^{60}$Co gamma irradiation has energy levels ranging from 1.17–1.33 MeV. $^{137}$Cs gamma irradiation has a gamma energy of 0.662 MeV. However, because of the solubility in water, the use of $^{137}$Cs in food preparation is strongly discouraged. Electron beam and X-ray technologies are two alternatives to gamma irradiation in the field of ionizing radiation technology. In contrast to gamma irradiation, which depends on radioactive source materials, electron beam and X-ray technologies are powered by commercial electricity in a linear accelerator, rendering the operator switch the process on and off. Electron beams are generated by a high-energy stream of electrons from an electron accelerator and have similar effectiveness for sterilization but are more acceptable to consumers compared to gamma rays (Maherani *et al.* 2016). Electron beam accelerators have energy ranging from 0.15–10 MeV. The industry typically employs accelerators with beam power between 5–100 kW, with some recent applications requiring even more powerful accelerators exceeding 400 kW. Low-energy accelerators (0.15–0.5 MeV) are usually self-shielded and utilized for surface treatment, coating, and irradiation of thin materials. Medium-energy accelerators produce electrons within the energy range of 0.5–5 MeV and use up to 300–350 kW of power. High-energy accelerators generate electron beams with 5–10 MeV energies and typically employ linear accelerators with pulsed beams of up to 50 kW (Fan and Niemira 2020). Finally, X-rays are generated through the collision of high-energy electrons with materials of very high atomic mass, *i.e.* gold and tungsten. X-ray photons share similarities with gamma irradiation in terms of penetration capabilities but differ in their energy levels. X-rays exhibit higher energy levels, ranging from 5–7.5 MeV, as opposed to gamma irradiation. Moreover, the dose rate of X-ray photons is considerably higher, typically around 100 Gy/s, in contrast to gamma photons, which typically operate at around 100 Gy/min (Nam *et al.* 2016; Pillai and Shayanfar 2017).

The data in Figure 2 is based on selected literature from 2001–2021 and shows a continuous growth in publications referencing gamma radiation, with a peak in 2015 for functional food processing. From 2001–2015, the trend for electron beam processing was generally flat, but there was a significant rise in interest recorded from 2017–2021, which appears to correlate with the global marketing of electron beam facilities. According to Future Market Insights (2021), gamma rays are currently the most widely used source of radiation in the food irradiation market, accounting for more than 70% of the market share, whereas electron beams are expected to grow at the fastest rate during the forecast period, owing to their safety and efficiency advantages over the former.

It is noteworthy that the vast majority of high-activity radiological sources used in commercial applications are radioactive sources, accounting for more than 99% of Category 1 and 2 sources. Nonetheless, these sources represent potential targets for terrorists, giving rise to a considerable security concern for national security. Moreover, the storage and utilization of high-activity sources, even those that have been spent, present a significant security challenge, especially in facilities lacking robust security measures. Such sources are also susceptible to theft, creating a scenario where malicious actors could potentially manufacture a dirty bomb or a radiological dispersal device. To address these problems, international organizations such as the International Atomic Energy Agency (IAEA) and the US Defense

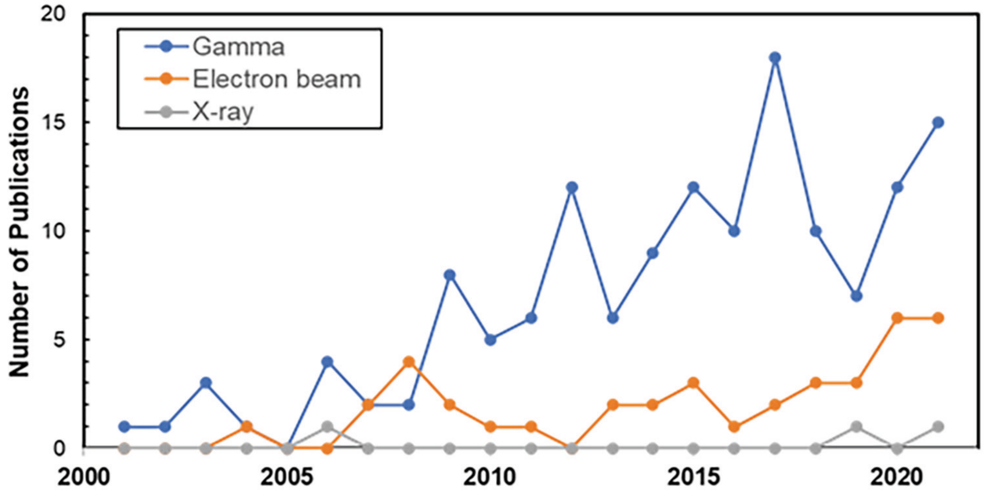


**Figure 2.** The number of publications referencing the use of ionizing radiation on functional food in chosen literature from 2001–2021. Shown are the trends for gamma radiation (blue line), electron beam (orange line), and X-ray (gray line).

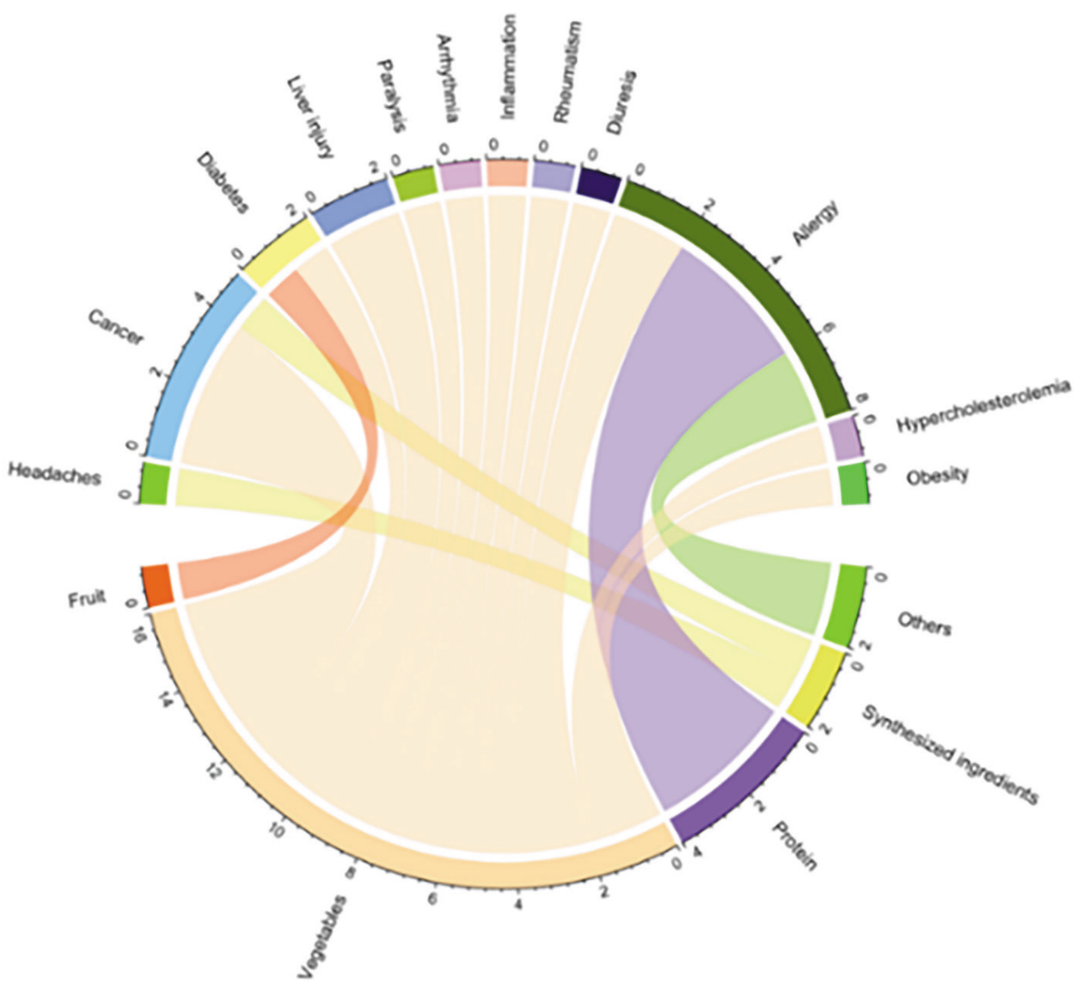


**Figure 3.** Chord diagram of functional food types and their targeted diseases.

Threat Reduction Agency have been working to replace isotope-based technologies with electron beam and X-ray technology. These technologies are generated from commercial electricity and are less susceptible to theft (US National Research Council 2008). In contrast to gamma radiation and electron beam processing, X-rays have not yet been explored extensively for functional foods, as indicated by the trend in Figure 2.

**Functional Food and Disease Targets**

A considerable portion of the literature discussing irradiated functional foods has highlighted potential benefits in preventing cancer and mitigating allergic reactions to specific foods (Figure 3). The association with cancer prevention is primarily linked to the heightened antioxidant activity observed in irradiated functional foods. One suggested mechanism involves the increased synthesis of compounds with antioxidative properties. Notably, in the case of *Moringa oleifera*, gamma irradiation was identified as a factor inducing the biosynthesis of glucomoringin. This molecule, as reported by Ramabulana *et al.* (2015, 2017), has been recognized for its ability to regulate antioxidant processes in mammals. Another possible mechanism of antioxidative improvement of irradiated functional food is through a change in the structure or conformation of these antioxidant compounds. For instance, the antioxidant activity of β-D-glucan in barley is associated with the presence of multiple anomeric hydrogen atoms. It was found that after gamma irradiation, β-D-glucan had increased scavenging activity, which could be explained by depolymerization of the polysaccharide to low molecular weight subunits, exposing its hydroxyl groups and decreasing intramolecular hydrogen bonding (Shah *et al.* 2015). Another study employed gamma irradiation to synthesize pectin-oligosaccharides from citrus fruits, which were reported to suppress cell growth in lung, skin, and colon cancer cell lines (Kang *et al.* 2006). A comparable phenomenon was noted in gamma-irradiated banaba (*Lagerstroemia speciosa* Linn.) leaves. These leaves exhibited an enhancement in hypoglycemic activities, as observed through *in vivo* assays conducted on alloxan-treated diabetic mice, upon administration of ethanol extracts (Deocaris *et al*. 2005).

The prevention of allergic reactions through food irradiation primarily involves altering the structure and conformation of allergens present in the food product. For instance, shellfish allergies – often triggered by tropomyosin – exhibit changes when subjected to gamma and electron beam irradiation. This process induces secondary and tertiary structural modifications in the protein, resulting in a more disordered configuration. Such changes are attributed to the oxidation of sulfhydryl groups that form disulfide bonds leading to protein cross-linking and polymerization (Mei *et al*. 2020). Allergies to soybeans are also quite common and are usually attributed to the soybean trypsin inhibitor (STI). Similar to tropomyosin, it has been reported that gamma irradiation can disrupt the tertiary structure of STI *via* two mechanisms. For moist samples, the indirect mode of radiation effect is predominant where free radicals are formed from the radiolysis of water damaging the structure of the protein and forming insoluble aggregates. In dry samples, radiation can impart energy along its tracks through linear energy transfer and directly damage the protein (Mallikarjunan *et al.* 2012). In a study on porcine serum albumin (PSA), the major allergen in pork, Zhu *et al.* (2018) found a reduction in IgE-binding of PSA after gamma irradiation. Changes in the allergen structure can mitigate allergenicity by reducing its affinity for IgE binding, a key factor in allergic reactions. Structural alterations may involve modifying the conformational epitopes recognized by IgE antibodies, making them less accessible or recognizable (Pomés *et al*. 2020). These changes may offer a promising avenue for developing “hypoallergenic” food variants through radiation technology that could potentially reduce the risk and severity of allergic reactions in susceptible individuals.

**Radiation Enhancement of Food Functionality**

Radiation enhancement of food functionality across various food types is summarized in the heat map shown in Figure 4. In general, radiation-induced structural changes in food constituents may play a role in the enhancement of food functionality, encompassing the reduction of antinutritional factors – chemical compounds inherent in natural food and feed components that impede optimal nutrition. For example, degradation of the protein structure in gamma-irradiated finger millet flours was hypothesized to have caused the observed dose-dependent decrease in total tannin content (Gowthamraj *et al.* 2021). In lotus (*Nelumbo nucifera*) seeds, reactive oxygen species generated during electron beam-irradiation at 2.5–30 kGy are believed to induce the formation of inositol and inositol phosphates, a consequence of the disruption of a bond in the phytic acid structure. The degradation of the antinutritional factor phytic acid, as demonstrated in studies by de Boland *et al*. [1975, cited by Bhat and Sridhar (2008); Bhat *et al*. (2009)], rendered it undetectable at a dose of 5 kGy (Bhat and Sridhar 2008). In defatted soybean (*Vicia faba* L.) flour exposed to 2.5–5 kGy of gamma radiation, a proposed breakdown in the structure of trypsin inhibitor is posited to account for the observed dose-dependent reduction in trypsin inhibitor activity (Al-Kaisey *et al.* 2003).

Increased antioxidant activity has also been attributed to structural changes in food constituents. For instance, the depolymerization by radiolysis of β-D-glucan from

| | Increased levels of bioactives | Changed in polymer structure | Reduced anti-nutritionals | Reduced toxicity and allergenicity | Growth of beneficial microbes | Preservation of bioactive compounds |
|---|---|---|---|---|---|---|
| Grains | 8 | 0 | 0 | 0 | 0 | 0 |
| Meat/fish | 1 | 2 | 0 | 1 | 0 | 0 |
| Poultry/dairy | 1 | 3 | 0 | 0 | 0 | 0 |
| Beans/nuts | 5 | 1 | 1 | 0 | 0 | 0 |
| Leafy | 3 | 0 | 0 | 0 | 0 | 0 |
| Non-leafy | 16 | 3 | 0 | 0 | 0 | 0 |
| Herbs/spices | 13 | 0 | 0 | 0 | 0 | 0 |
| Fruits | 5 | 0 | 0 | 0 | 1 | 1 |
| Fortified or enriched food | 0 | 0 | 0 | 0 | 0 | 0 |
| Synthesized ingredients | 1 | 1 | 0 | 0 | 0 | 0 |
| Others | 20 | 2 | 1 | 0 | 0 | 1 |

Higher — Lower
Frequency

**Figure 4.** Heat map of the mechanisms of food enhancement for each functional food type.

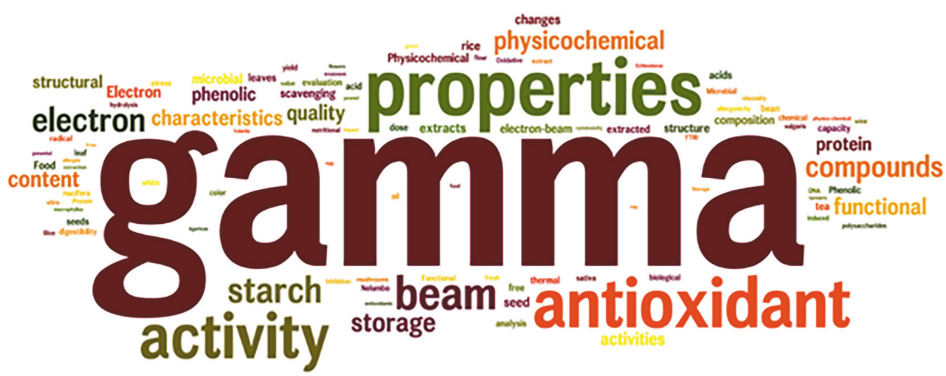


**Figure 5.** Word cloud showing the relative frequency of single words from the title and keywords of papers on food irradiation of functional foods from 2001–2021.

barley (*Hordeum vulgare*) resulted in the exposure of the hydroxyl groups and decreased intramolecular hydrogen bonding in the polysaccharide (Xing *et al.* 2005). This is suspected to have contributed to an increased antioxidant activity (Shah *et al.* 2015). Similarly, increased or sustained antioxidant activity was observed in irradiated tamarind juice (Lee *et al.* 2009), attributed to the generation of Maillard reaction products that scavenged hydroxyl and superoxide anion radicals (Chawla *et al.* 2007). The breakdown of pectin from free radicals yielded lower molecular weight oligomers at 37 kDa compared to 500 kDa in non-irradiated samples. This is hypothesized to result in enhanced antioxidant activity, although the precise mechanism remains unknown. Additionally, the depolymerization resulted in reduced viscosity at radiation doses ranging from 2.5–10 kGy (Kang *et al.* 2005). Interestingly, electron beam-treated pectin and pectin derivatives subjected to doses of 3–250 kGy exhibited enhanced prebiotic potential. Although the mechanism underlying this outcome is yet to be elucidated, it was observed that radiation-treated pectin and its derivatives resulted in the proliferation of selected gut microorganisms, including lactic acid bacteria and short-chain fatty acid-producing bacteria but not of pathogenic bacteria (Gamonpilas *et al.* 2021).

## CONCLUSION

This systematic review aims to address the knowledge gap concerning the enhancement of functional foods through irradiation. By synthesizing existing evidence and analyzing 154 selected studies, this study offers valuable insights into the potential benefits and applications of irradiation in improving food functionality. Gamma radiation is the most used type of radiation for processing functional, and the predominant mechanism of enhancement observed in irradiated functional foods is the increased levels of bioactive compounds. Moreover, the target diseases most frequently tackled by irradiated functional foods are cancer and allergies. To sum up the role of radiation in functional food R&D, the author indexed keywords and presented a word cloud that represents the general above-mentioned findings (Figure 5).

This systematic review holds significant implications. We have highlighted the promise of food irradiation in contributing to the production and enhancement of functional foods and nutraceuticals, thereby addressing the growing demand for healthier food options. Future studies could delve into the specific mechanisms by which irradiation enhances food functionality, providing valuable insights into optimization strategies of food processing or production. Moreover, research efforts can be directed toward broadening the spectrum of target diseases and exploring the potential of irradiation in the development of novel, indigenous functional food products.

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# APPENDIX A

## The Detailed Search Strategy Employed in the Systematic Review

**SEARCH STRATEGY**

**Online** databases
PubMed (https://www.ncbi.nlm.nih.gov/pubmed/)
Scopus (https://www.scopus.com/search/form.uri#basic)
ScienceDirect (https://www.sciencedirect.com/)

**Boolean keywords/search terms**

1. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND fruits
2. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND leaves
3. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND flower
4. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND seeds
5. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND roots
6. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND bark
7. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND stem
8. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND spice
9. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND natural products
10. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND secondary metabolites
11. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND compounds
12. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND concoction
13. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND extract OR extraction
14. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND isolation
15. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND sterilize OR sterilization.
16. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND characterization
17. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND herbs OR herbal
18. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND traditional
19. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND medicine OR medicinal
20. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND healing
21. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND properties
22. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND food
23. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND dietary
24. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND supplement
25. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND functional AND food
26. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND phytomedicine
27. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND ethnomedicine
28. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND plant OR plants
29. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND crop OR crops
30. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND nutraceutical
31. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND cosmeceuticals
32. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND bioactive peptides
33. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND probiotics
34. radiation OR irradiation OR gamma OR cobalt 60 OR cesium 137 OR electron beam OR X-ray AND antioxidants