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Review

Food irradiation technology: Prospects and future applications

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Abstract Food irradiation technology (FIT) is a non-thermal processing that covers all significant aspects of food processing and preservation such as shelf-life extension, natural flavour maintenance, chemical-free preservation, and pathogen reduction. Excessive irradiation dosages can have negative consequences on food, which may include a reduction in functional and sensory qualities. On the other hand, the standard dose can have a positive influence, such as phytosanitary treatments, detoxifying aflatoxins, reducing pathogenic microorganism growth, reducing allergenicity of food allergens and increasing the product's shelf life. Consumer acceptance, prejudice, incorrect information, stringent legal and regulatory restrictions, and a subsequent unwillingness of food makers and the food trade to employ the latest technology are all impediments to FIT.

Keywords food irradiation, aflatoxins, consumer acceptance

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1. Introduction

The Codex general standard for irradiated food allows three forms of ionizing radiation to be employed in food irradiation: high-energy gamma rays (^{60}Co and ^{137}Cs), X-rays (energies up to 5 MeV and in some countries up to 7.5 MeV), and electron beam (energies up to 10 MeV) (Fan and Niemira, 2020). The inactivation of microorganisms by ionizing radiation is mostly due to direct or indirect damage to microbial nucleic acids (DNA) and enzymatic activity, which is caused by the reactive oxygen species and free radicals (Fig. 1). The most common application of irradiation is to decontaminate spices, herbs, and condiments (Prakash, 2020). Irradiation preserves food flavours and aromas that would otherwise be lost by other techniques of processing, such as cooking (Nawrot et al., 2019). It also avoids the application of chemical treatments to control bacteria and other pests. Food irradiation does not influence the nutritional value and essential macronutrients like carbohydrates, proteins, and fats, therefore the food remains fresh (Pedreschi and Mariotti-Celis, 2020).

FIT is a beneficial sterilizing technique because of its probable application in extending shelf life by preventing food-borne infections and spoilage (Indiarto and Qonit, 2020). However, previous research shows that irradiation treatment can alter

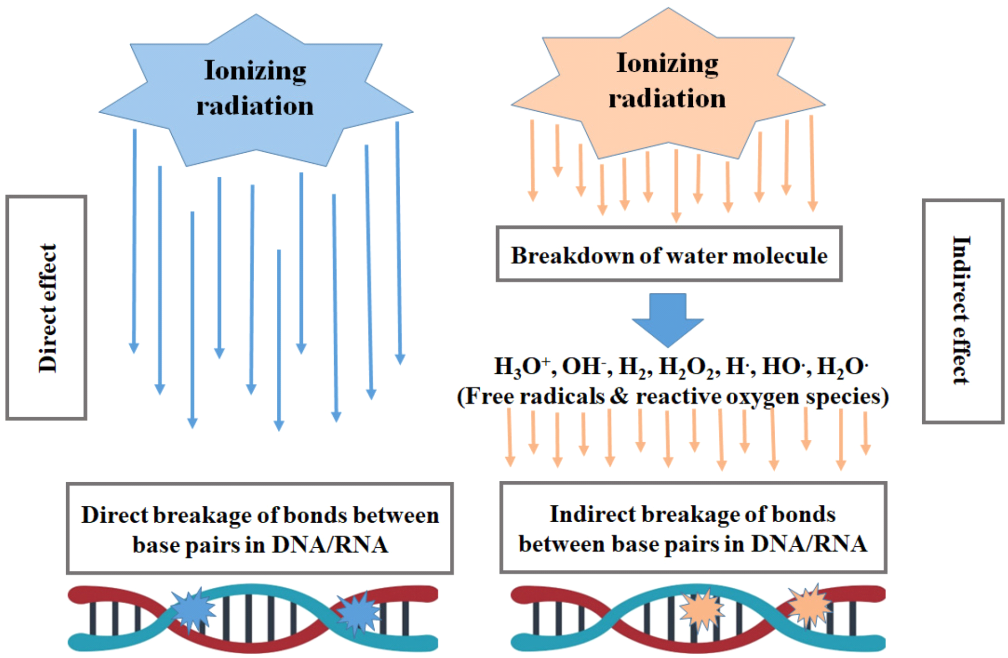

Fig. 1. Direct and indirect inactivations of microorganisms by ionizing radiation.

the colour of fresh meat and cause a distinct undesirable odour due to the myoglobin molecule and some polyunsaturated fatty acids' response to energy input and changes in the chemical environment, as well as influence the functional properties of food (Pedreschi and Mariotti-Celis, 2020). Some research studies have also used gamma irradiation in combination with several natural antibiotics (essential oil and nisin), to enhance the microbiological safety and quality of foods at low irradiation levels (Dini et al., 2020). The assumption that food irradiation is a nuclear technology has hampered the growth of FIT applications in the food business. Therefore, changing customer perceptions and encouraging them to purchase irradiated food, as well as developing safe and more durable apparatus and optimizing treatments, are all critical steps in the development of this technology.

The application of FIT is gaining popularity in various fields due to its high efficacy, simple operation, green and safe. FIT at high dosages has now been extended to ready-to-eat foods, hospital diets, and space food (Castell-Perez and Moreira, 2021).

The purpose of this review was to focus on applications of FIT in the last few years, covering almost all major unique aspects with rising trends in space foods, agricultural products, as phytosanitary treatment and reducing allergenicity and biogenic amines in foods etc. Moreover, the major drawback of FIT and its applicability to regional-specific products was also reviewed. The current review differs from previous reviews in several respects such as comprehensive recent applications of FIT, major concerns related to this technology, as well as applicable prospects.

2. FIT for space foods

It is one of NASA's most prevalent methods for sterilizing space food. Previously, NASA testing for

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irradiation technology on flour and bread revealed that a single dose of 50,000 rads does not affect the flour's functional quality and nutrients. Six months later, irradiated flour and bread functioned considerably better than untreated bread. Moreover, the least electron beam quantity needed for space food decontamination has been investigated, with results indicating that 15 kGy might satisfy the long-term safety and shelf-life targets obligatory for space food (Jiang et al., 2020). A ready-to-cook Korean traditional food (*bibimbap*) treated with 1% ascorbic acid followed by gamma irradiation at 25 kGy also revealed a better sensory score and improved shelf life with no pathogenic bacteria. The product was certified for use in the International Space Station (ISS) by the Russian Institute of Biomedical Problems (Long et al., 2020). Moreover, Chinese-style fried noodles sterilized with ^{60}Co irradiation at 5 or 10 kGy also revealed that ^{60}Co irradiation coupled with thermal treatment might preserve fried noodles, improve their sensory quality and maintain the protein content for one year (Jiang et al., 2020).

3. FIT for agricultural products

3.1. Detoxification of aflatoxins

The high amount of aflatoxin exposure has been associated with oedema, haemorrhage, liver damage, cancer, nutritional disorders and ultimately death (Guo et al., 2021). Grains are most susceptible to the aflatoxins that might contribute serious health effects, 40.1% degradation of aflatoxin B_1 and 33.3% degradation of aflatoxin B_2 (Fig. 2) was achieved in grains after gamma-irradiation application with a dose of 20 kGy. This treatment also increases the storage time (Khalil et al., 2021).

3.2. Reduction of pathogens

Various disinfectants such as chlorine, hypochlorite and hydrogen peroxide are being applied in the industry to combat the pathogens however, several health risks are also associated with these chemicals (Elias et al., 2020). As an alternative to these chemicals, irradiation technology can be used to manage microorganisms. Ionizing radiation can cause microbial growth suppression by disrupting phosphodiester and hydrogen bonds in DNA strands

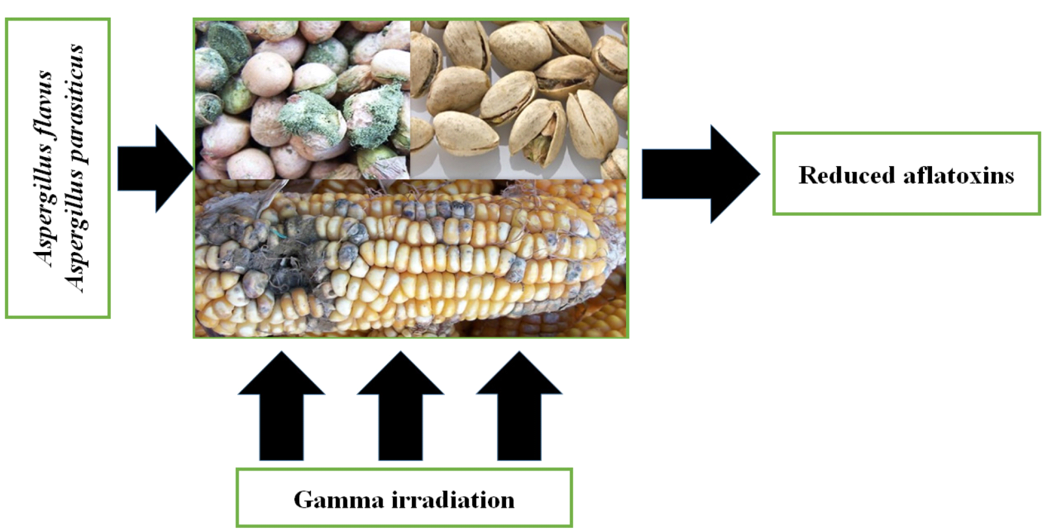

Fig. 2. Reduction in aflatoxins through gamma irradiation.

(Handayani and Permawati, 2017). To reduce the microbial content in food the dose range of 0.5-30 kGy ionizing radiation has been approved and the list of acceptable irradiated foods is also expanding (Begum et al., 2020).

The *E. coli* O157:H7 and *Salmonella typhimurium* were effectively reduced in peanut butter on treatment with 5 kGy gamma irradiation (Song et al., 2019). Moreover, the microbial population in smoked salmon can also be reduced using 3 kGy gamma radiation without altering the sensory attributes (Nawrot et al., 2019). To increase microbial reduction, irradiation approaches need to combine with other treatments (Pillai et al., 2017).

3.3. Increase in shelf life

It has been demonstrated that FIT can be used to prolong the shelf life of foods. According to Ricciardi et al. (2019) X-ray application in ricotta cheese at 2 kGy increased shelf-life up to 20 days as compared to the shelf life of 3 days in untreated samples. Moreover, gamma irradiation has exhibited the potential to prolong the shelf life of fresh pasta by 90 days and maintained its sensory properties (Cassares et al., 2020). The increase in shelf life could be because of the microbial reduction on applying irradiation.

4. Phytosanitary treatment

To prevent fruits and vegetables from pests, phytosanitary treatments are required. Since, the use of different chemicals, fumigants and thermal treatments have negative impacts on fruits and vegetables, therefore, irradiation has been opted as a suitable quarantine treatment against invasive species (Vinha and Silva, 2022). The exposure of bitter gourd to the gamma irradiation with a dose value of 1 kGy as phytosanitary treatment, has extended the shelf life up to 30 days. Moreover, it improves microbiological quality and sensory properties (More et al., 2022). As most countries are preferring irradiation as a quarantine treatment for fruits and vegetables, mangoes are one of the most cultivated fruits whose trade has been enhanced by adopting gamma irradiation as a phytosanitary treatment (Sultana et al., 2021).

5. Reduction in biogenic amines

Biogenic amines are the indicators of the food's freshness and are produced by the enzymatic decarboxylation of free amino acids in bacteria. However, these biogenic amines are resistant to high temperatures, therefore, gamma irradiations are most likely to be used for the killing of microbes producing biogenic amines and to destroy already produced biogenic amines (Mahmoudzadeh et al., 2022).

Food poisoning and cancers are some of the risks associated with the consumption of high amounts of biogenic amines hence, their reductions in fermented and protein-rich food are decisive (Jaguey-Hernández et al., 2021). Irradiation may reduce the number of biogenic amines in Ras cheese as irradiated cheese revealed greater rates of biogenic amine breakdown without any negative alterations in chemical composition over the storage of 6 months. Gamma irradiation at 10 kGy destroyed histamine, whereas 15 kGy eliminated tyramine. In addition, gamma irradiation maintained sensory properties and made it suitable and wholesome. Irradiated samples, together with proper storage, make cheese safe for human consumption (Nájera et al., 2021).

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6. Reduction in allergenicity of food allergens

FIT destroys the structure and epitope of allergen proteins by causing a chemical reaction between water-free radicals and amino acids. It also has high efficiency in reducing allergen sensitivity. It will be a hotspot in future food desensitization processing research. Multiple elements such as the food matrix the interaction between food ingredients triggered by irradiation, and other factors such as irradiation dose in the desensitization process have a critical effect on allergen immune activation. However, the majority of current radiation desensitization research is conducted in allergen-free solutions. To further enhance this technology, a basic study on complex food matrices is required (Pan et al., 2021). The gamma irradiation of 1, 10, or 100 kGy exhibited a promising potential in reducing the allergenicity of pistachio allergens in mice however, 100 kGy caused undesirable changes to the sensory quality, hence, sufficient dose to maintain the sensory quality is vital (Naei et al., 2019). Moreover, the application of >7 kGy electron beam radiation on fish also exhibited an effective reduction of allergenicity and significantly maintained the texture (Fu et al., 2019).

The study of the mechanism of food allergy elimination by radiation is still in its early stages. Because food allergens are largely biological macromolecules with complex spatial configurations, existing biological detection technology is limited in its ability to identify them. Irradiation causes allergen proteins to degrade but the cross-linked compounds are still difficult to identify. Spectroscopy is the only way to determine changes in protein structure. As a result, the mechanism of radiation desensitization is mostly speculative, and product safety studies of irradiated allergens are yet to be conducted. Hence, the challenges such as the creation and establishment of detection methods for irradiated allergen items, as well as product safety evaluation, must be addressed in the future irradiation desensitization technology (Pan et al., 2021). Some other potentially useful applications of FIT are shown in Table 1.

7. Acceptance and future prospects of FIT

To enhance the applicability of this technology on various regional-specific products globally, scientific research is still needed while the food irradiation community works on ways to improve the acceptability of customers for their products. Continuous research into improving the sensory quality of high-dose irradiated food and combining irradiation with other technologies is desirable

Table 1. **Other potentially useful applications of food irradiation technology**

Benefits	Products	Dose	References
Phytosanitation	Lemon, strawberry	1 kGy	Ramakrishnan et al., 2019; Yoon et al., 2020
Inactivation of microorganisms (bacteria and viruses)	Onion flakes, black pepper Raspberries	200 keV-300 keV 1-11 kGy	Gryczka et al., 2018; Pimenta et al., 2019
Mycotoxin degradation	Peanuts, soybean, flour, juice, corn, red pepper	9-50 kGy	Calado et al., 2018; Patil et al., 2019; Woldemariam et al., 2021; Zhang et al., 2018
Sprouting inhibition	Potatoes Garlic	0-1 kGy 0.25-1.25 kGy	Fouzia et al., 2021; Son et al., 2022

(Bearth et al., 2019). Irradiation is considered one of the best pathogen decontamination technologies for fresh fruits and vegetables; but, except for specific fruits, they are not commercially available, owing to processors' and consumers' lack of acceptance of the technology (Egolf et al., 2019). According to marketing trials, consumers are increasingly keen to purchase irradiated food if they are well-informed about the method and its impact on food (D'Souza et al., 2021). Feng et al. (2019) reported that the fear that customers will reject irradiated meat has been recognized as a major obstruction to its use. Experts suggest that trade organizations, government agencies, and university extension departments use digital and social media to endorse the use of less-known food technologies such as irradiation.

Greater effort is required to improve the technology's appeal as a food safety tool hence, processors, retailers, policymakers, regulators, and scientists must work together to develop effective ways to accomplish this (Pedreschi and Mariotti-Celis, 2020). The modern world of rapid knowledge and the rise of internet purchasing may provide an attractive platform for increasing consumer acceptance of irradiation foods as they become available. During global crises like the COVID-19 epidemic, the growing relevance of online commerce cannot be overstated. Food irradiation proponents, like everyone else, must establish action plans for online-only purchases.

The future of food irradiation depends on persuading food producers and retailers that the technique is not only valuable but also that customers will buy it. This could be aided by analysis and harmonization of labelling necessities. The food sector views labelling as an additional cost and, more significantly, as a focal point for residual resistance to food irradiation and consumer concerns (Zhang et al., 2019). An improved understanding of its potential role in eradicating foodborne infections and willingness to pay for food safety could prove handy in the FIT implementation (Pedreschi and Mariotti-Celis, 2020).

To promote the efficacy of global food chains and employment, as well as respond to global food safety challenges, legislation must be standardized and updated regularly. However, if not coordinated globally, it can add to the complexity and confusion. Moreover, consumer awareness is also critical to eradicating the layman's concepts of irradiated food being always expensive, less nutritive, cancerous and radioactive.

8. Conclusion

FIT can extend shelf life, reduce the allergenicity of food allergens, reduce the bacteria population, and detoxify the food. Using recommended safe dose of the irradiations has no substantial impact on the physicochemical properties, nutritional value, or sensory value of the food. Some people are against using this technology, but as long as it is being utilized as per the standards, human health and the environment will not be endangered. The irradiation processors and the food sector also need to work together to prevent food supply chain disruption. Moreover, labelling is a supplementary cost to the food trade and is a pivotal point of conflict with irradiated foods furthermore, the labelling regulations and their enforcement also require rationalization. Consumer awareness is also critical if irradiated foods must gain better market acceptability and growth.

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Conflict of interests

The authors declare no potential conflicts of interest.

Author contributions

Conceptualization: Khalid N. Writing - original draft: Asghar S, Ayub H. Writing - review & editing: Khalid N.

Ethics approval

This article does not require IRB/IACUC approval because there are no human and animal participants.

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