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Review

Effect of Gamma Irradiation on the Microbial Load and Quality of Foods

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A B S T R A C T

Foodborne pathogenic microorganisms pose a significant public health issue worldwide, while post-harvest food losses are also considered one of the leading causes of hunger and malnutrition globally. In the food industry, irradiation technology, particularly used as an alternative to thermal processes and regarded as an environmentally friendly method, plays a crucial role in addressing food insecurity and foodborne diseases worldwide. Food irradiation is a non-thermal, technical process in which food is exposed to ionizing or non-ionizing radiation (such as UV, visible light, infrared, radio waves) at specific doses. The irradiation process, which does not involve high temperatures, preserves the food's nutritional value, freshness, and sensory properties (texture, colour, taste, and flavour) because it does not damage the structure of food components. The basic principle is that when the irradiation source hits the food, excitation and ionization occur, which inhibits DNA synthesis in living organisms. This effect is primarily used to inhibit the growth of pathogenic microorganisms. Gamma irradiation technology is effective in inhibiting both important foodborne pathogens (e.g. *Escherichia coli* O157, *Campylobacter jejuni*, *Listeria monocytogenes*, *Staphylococcus aureus* and *Salmonella* spp.), and microorganisms reducing food quality. Even low doses (up to 10 kGy, the safe dose limit) affect target groups of microorganisms. This review discusses the role and applicability of irradiation technology in ensuring the microbiological quality of foods.

Keywords: *Food irradiation, food safety, gamma irradiation*

Gama Işınlama Yönteminin Gıdaların Mikrobiyal Yükü ve Kalitesi Üzerine Etkisi

Ö Z E T

Gıda kaynaklı patojen mikroorganizmalar dünya çapında önemli bir halk sağlığı sorunu oluştururken, hasat sonrası meydana gelen gıda kayıpları da dünya çapında açlığın ve yetersiz beslenmenin önde gelen nedeni olarak değerlendirilmektedir. Gıda endüstrisinde özellikle ısıl işlemlere alternatif olarak kullanılan ve çevre dostu yöntem olarak kabul edilen ışınlama teknolojisi dünyadaki gıda güvensizliği ve gıda kaynaklı hastalık sorunlarının çözümünde önemli bir rol oynamaktadır. Gıda ışınlaması, gıdanın iyonlaştırıcı özelliği olan veya olmayan radyasyonlara (UV, görünür ışık, kızılötesi, radyo dalgaları gibi) belirli dozlarda maruz bırakılmasıyla gerçekleşen, ısıl olmayan teknik bir işlemdir. Yüksek sıcaklık uygulaması içermeyen ışınlama işlemi, gıda bileşenlerinin yapısına zarar vermediği için, gıdaların besleyiciliğini, tazeliğini ve duyusal özelliklerini (doku, renk, tat ve aroma) koruyabilmektedir. Temel prensip olarak, ışınlama kaynağının gıda maddesine çarpmasıyla uyarım ve iyonlaşma meydana gelmekte ve bu durum canlılarda DNA sentezini engellemektedir. Bu etki özellikle patojenik mikroorganizmaların gelişmesini engellemek için kullanılmaktadır. Gama ışınlama teknolojisi, *Escherichia coli* O157*, Campylobacter jejuni, Listeria monocytogenes, Staphylococcus aureus* ve *Salmonella* spp. gibi tehlikeli hastalıklara neden olan ve gıdaların kalitesine zarar veren mikroorganizmaları/patojenleri inhibe edebilen bir teknoloji olup, düşük dozları bile (10 kGy güvenli doz limiti) hedef mikroorganizma gruplarını etkilemektedir. Bu derlemede, ışınlama teknolojisinin gıdaların mikrobiyolojik kalitesini sağlamadaki rolü ve uygulanabilirliği ele alınmıştır.

Anahtar kelimeler: *Gıda* ışınlama*, gıda güvenliği, gama* ışınlama

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Introduction

Food safety is a critical issue for human health, encompassing the entire process from farm to fork, including foodborne diseases. Foodborne diseases pose a threat to human health all over the World, and cause problems in even in developed countries with modern food processing and distribution systems (Arapcheska et al., 2020). Despite the implementation of safety practices such as modern technologies, good manufacturing practices, risk assessments, quality control, and hygiene management, there is still an increase in the number of foodborne diseases and poisonings as of today. Especially in recent years, with the significant and remarkable developments in technology and globalization in the food market, new preservation methods such as irradiation, ozonation, cold plasma, high pressure applications to minimize the risk of microbiological contamination in unprocessed or processed products are constantly being investigated (Prokopov and Tanchev, 2007; Amit et al., 2017). Irradiation, one of the comparably new food preservation methods, is a technique used for various purposes such as extending the shelf life of fresh or processed foods, preserving ready-to-eat meat products when appropriate additives are not used, reducing losses caused by chemical or microbiological spoilage, preventing post-harvest damage, protecting fruits, vegetables, grains and legumes from insect infestations during storage, preventing sprouting in tuber vegetables as potatoes, eliminating pathogenic microorganisms in meat, fish, poultry, seafood and spices. It is also called cold pasteurization as it does not involve heat treatment (Pillai and Pillai, 2021).

Types of Radiation Used in Food Preservation

In food preservation, gamma rays, accelerated electron beams, and X-rays can be used. Among these, the most commonly used in the food industry are the gamma rays. Gamma rays are generated by sources such as Cobalt-60 (Co-60) and Cesium-137 (Cs-137). Cs-137 is not recommended for food irradiation due to its high solubility in water, which may cause environmental damage. Co-60, on the other hand, is widely used in food irradiation since it is insoluble in water and has almost no harm to the environment (Ravindran and Jaiswal, 2019). Accelerated electron beams are not favoured in food applications because of their low penetration depth, and strong effect on atoms and molecules, such as breaking of double helix structures, and formation of highly reactive free radicals (Edae, 2023; Mshelia et al., 2023). X-rays have high penetration and dose rates, enabling shorter irradiation periods for foods. X-rays, with a penetration depth of 25 cm, are commonly used to irradiate packaged food products. The minimal environmental impact of X-rays, their effectiveness, and the possibility of direct installation on commercial processing lines have proven their applicability in microbial control (Mshelia et al., 2023).

Gamma Irradiation Application

In gamma irradiation, chromosomes (DNA), the carrier of the genetic code is targeted. Gamma irradiation affects macro and micromolecules in microorganisms, leading to various chemical changes (Eugster et al., 2018). The primary lesions caused by ionizing radiation in intracellular DNA are chemical damages to purine and pyrimidine bases, as well as to the deoxyribose sugar. In general, double strand breaks are formed at a rate of 5-10% of the single strand break rate induced by ionizing radiation. However, most microorganisms can repair their single strand breaks. To survive, microorganisms must be able to repair DNA damage quickly. Therefore, some microorganisms have different repair mechanisms that involve a variety of enzymes. If there are too many lesions in the DNA molecule for the microorganism to handle, replication is halted (Ajibola, 2020).

There are three terms, which have been introduced into the terminology for microbial inactivation: radurization, radicidation, and radappertization. Radurization (low dose) involves the application of a radiation dose ranging from 0.1 to 1 kGy, which reduces microbial or insect load that cause food spoilage, inhibits respiration in fruits and vegetables, delays ripening, and extends the quality and shelf life of food products. Radicidation (medium dose) refers to a radiation dose in the range of 1-10 kGy. Through radicidation, the number of pathogens such as *Salmonella* spp. and *L. monocytogenes* in foods can be reduced or they can be totally eliminated. Radappertization (high dose) is a radiation treatment applied at doses above 10 kGy to kill almost all microorganisms present in food. Radappertization is used to eliminate resistant bacteria and spores (Indiarto et al., 2023). The doses applied and the food products treated are summarized in Table 1 (Arapcheska et al., 2020). The use of gamma irradiation for meat, seafood, poultry, spices, and vegetable seasonings has been approved by the Food and Drug Administration (FDA). According to the World Health Organization (WHO), exposure of food to doses up to 10 kGy is generally considered safe and does not pose a microbiological or toxicological hazard to human health. However, radiation doses above 10 kGy may cause deterioration in sensory properties such as colour, texture, and taste of the foods (Jeong et al., 2020).

There is a negligible temperature increase after irradiation as 0.36°C at a dose of 1 kGy. The absorption of the maximum permissible dose for food irradiation (10 kGy) results in a temperature increase of only 2.4°C on the food. Irradiation at doses below 10 kGy results in less chemical modification than processes such as heating (Arvanitoyannis et al., 2009; Bashir et al., 2021).

The Effect of Irradiation on Microorganisms

The resistance of microorganisms to gamma radiation depends on the ability of their DNA repair enzymes to repair single strand breaks. Strains lacking this ability are more radiosensitive than others. There is considerable variability in radiation resistance of microorganisms. For example, yeasts are more resistant to radiation than molds. Single stranded DNA viruses are more sensitive to

Table 1. Irradiation at various doses and its applications (Arapcheska et al., 2020)

Dose Level	Purpose	Food Products
Low Dose (<1 kGy)	Prevention of sprouting killing insects and larvae in wheat, flour, fruits, and vegetables after harvest, slowing down the ripening process, and the elimination of certain harmful parasites associated with food.	Potatoes, onions, garlic, ginger, bananas, mangoes and non-citrus fruits, cereals and legumes, dried vegetables, dried fish and meat, fresh pork
Medium Dose (1-10 kGy)	Significant reduction or elimination of specific microorganisms and parasites that cause food spoilage, and reduction or elimination of many pathogenic microorganisms.	Strawberry, grapes, dried vegetables, fresh or frozen seafood, fish, raw or frozen poultry and meat
High Dose (>10 kGy)	Sterilization of food for special uses, such as meals for immunocompromised patients, elimination of certain viruses that cause diseases.	Sterilized food for immunocompromised patients

radiation than double stranded DNA viruses. The higher radiation resistance of Gram-positive bacteria compared to Gram-negative bacteria highlights the importance of peptidoglycan in bacterial resistance to gamma radiation (Harrell et al., 2018). Environmental factors, such as moisture content, temperature during irradiation, presence or absence of oxygen, and whether the food is fresh or frozen, also influence microbial resistance to irradiation (Gradini et al., 2019). Additionally, bacterial sensitivity to irradiation depends on the growth phase. In general, cells in the exponential growth phase are more sensitive to ionizing radiation compared to microbial cells in the latent or stationary phase (Arapcheska et al., 2020). Certain spore-forming and toxin-producing bacteria, such as *Bacillus* spp. and *Clostridium* spp., are more resistant to irradiation than non-spore-forming species. Therefore, radiation doses below 10 kGy can only reduce the number of spores. However, irradiation can be applied in combination with other preservation methods, such as freezing, to prevent spore formation (Mshelia et al., 2023).

The Effect of Irradiation on Meat and Meat Products

Irradiation of meat is an alternative food preservation method to traditional techniques such as salting, curing, smoking, drying, canning, cooking, cooling, freezing, modified atmosphere packaging, and high-pressure applications. This preservation method is advantageous because it causes minimal physical changes to the food, does not require the use of additives, and does not involve thermal processing. Studies have shown that while macro nutrients in meat are not significantly altered, some vitamin levels can be affected by irradiation. Meat contains water-soluble B vitamins such as thiamine, riboflavin, niacin, pyridoxine, biotin, cobalamin, choline, folic acid, and pantothenic acid. There are little fat-soluble vitamins in meat. Beef contains around 1 µg of vitamin A per gram of fat, negligible amounts of vitamins D, E and K. Fat-soluble vitamins are generally more stable under irradiation compared to water-soluble vitamins. For extending the shelf life of fresh or frozen red meat and poultry products, irradiation doses of 3.0 kGy are recommended, while 7.0 kGy doses are advised to reduce pathogenic microorganisms. Studies have shown that irradiation with 3.0 kGy gamma rays reduces the growth of mesophilic bacteria, coliforms, and *Staphylococcus aureus* in beef (Jayathilakan et al., 2015; Indiarto et al., 2023). According to the Food Irradiation Regulation in Türkiye, maximum irradiation dose for poultry, red meat, and their products (fresh or frozen) is set at 7.0 kGy (FIR, 2019). Poultry meat and products can be contaminated with pathogens such as *Campylobacter*, *Salmonella* spp., and *E. coli* O157. Low-dose irradiation can inactivate over 90% of the bacteria present in meat. The microbiological quality of poultry is significantly improved with irradiation doses of 1.0 to 2.0 kGy (Singh and Singh, 2020).

Rahimi et al. (2013) studied the effects of irradiation at doses of 2, 5, 7 and 10 kGy on ground beef, showing that gamma irradiation reduced the number of microorganisms in all irradiated ground beef samples (20 samples, up to day 10) at 2, 5, 7 and 10 kGy, which also extended the shelf life of the products. They reported that irradiation at high doses (more than 7 kGy) has a negative effect on some organoleptic properties such as color, as well as on parameters affecting meat quality such as flavor and fat oxidation. Therefore, they recommended the use of low doses (less than 5 kGy) to reduce the microbial load of minced meat. In another study, the effects of gamma irradiation and frozen storage on improving the shelf life of turkey breast meat were evaluated, irradiation was applied at doses of 0.5, 2 and 4 kGy, and it was reported that the number of mesophilic bacteria decreased by about 5 log units and Salmonella was not detected in samples irradiated at 4 kGy (Jouki, 2013). Zhao et al. (2017) applied irradiation at various doses (0.5, 1.5, 3, 4, 6 and 8 kGy) for pasteurization of beef jerky and reported that 4 kGy is an appropriate dose for pasteurization of jerky. It was reported that deterioration in color, taste and texture occurred with the increase in dose and these deteriorations were associated with the increase in free radicals. In a study comparing the effect of irradiation on sporulating bacteria with the addition of nitrite, cooked hams were irradiated at doses of 1.5, 3, 4.5 and 6 kGy. It was reported in the study that the level of nitrite required to inhibit *Clostridium sporogenes* spores was equivalent to a gamma ray dose of 3 kGy. With 3 kGy irradiation dose, it has been shown that microbiological safety can be ensured and the sensory quality of the product can be improved while inhibition is achieved (Silva et al., 2020).

Akhter et al. (2021) investigated the synergistic effect of low dose (1 kGy) gamma irradiation combined with natural antimicrobial (nisin and sodium nitrate) and antioxidant agents (rosemary and BHT) on the quality of sheep meat, in this study it was reported that rosemary extract and nisin application along with low dose irradiation were the most effective natural alternatives to maintain the quality of meat emulsions. In another study investigating the effect of irradiation on various bacteria, 2, 4 and 6 kGy doses of irradiation were applied to ostrich meat and the reduction in the number and inhibition of some bacteria were observed. The results of the study showed that the irradiation dose of 4 kGy was effective in the inhibition of bacteria and the number of mesophilic bacteria, coliform bacteria, *S.aureus* and psychrophilic bacteria decreased at this dose. At the same time, *Salmonella* spp. and *E. coli* were eliminated at this dose (Mashak and Abbasi, 2023).

Effect of Irradiation on Spices

Spices and herb seasonings are among the most irradiated food products for microbial decontamination on commercial scale. Spices are prone to microbial contamination during harvesting, processing, and storage. Spices that are often dried in outdoor are susceptible to contamination by pathogenic microorganisms such as *Salmonella* spp., *Clostridium perfringens*, *Bacillus cereus*, as well as molds and insects. Irradiation of spices with doses ranging from 3.0 to 10.0 kGy has been established as a reliable method to enhance microbiological safety. Irradiation of spices is practiced on a commercial scale in over 20 countries such as USA, Mexico, Vietnam, Thailand, India, Australia, New Zealand, Pakistan, South Africa, Malaysia, Indonesia. Irradiation of potatoes, onions and spices were the first food items approved for domestic marketing by health authorities of India in 1994 (Roberts, 2016; Kyung et al., 2019; Singh and Singh, 2020).

Cruz-Zaragoza et al. (2011) examined the effects of low doses of irradiation on the total number of mesophilic bacteria and showed that 0.5 kGy dose irradiation on coriander led to a 99.9% reduction in the total number of mesophilic bacteria. In a study on the effect of microbial load in red pepper, gamma irradiation was used at doses of 2, 4 and 6 kGy and D_{10} values of total mesophilic bacteria were determined as 2.66 kGy in gamma irradiation. At 6 kGy irradiation, it was reported that the bacterial population decreased, yeast, mold and coliform bacteria were completely inhibited and sensory properties were also preserved at this irradiation dose (Jung et al., 2015). Sadecka et al. (2018) conducted a similar study on black pepper and reported that 5 kGy irradiation dose was sufficient to control total microbial load. When they examined the irradiation dose in terms of organoleptic properties and essential oil components, it was reported that no physical and chemical problems occurred up to 10 kGy. In a study that also tested irradiation doses above 10 kGy on spices with high bacterial load, fennel and cinnamon were irradiated at doses of 2.5, 5, 7.5, 10 and 15 kGy and the change in microbial load was observed. Proving again that doses of 10 kGy and above are sufficient to reduce bacterial load, the study also reported that a dose of 5 kGy is sufficient to eliminate mold and yeast growth. 7.5 kGy dose of irradiation can be considered as a suitable dose for decontamination and microbial protection of these spices, as well as for increasing their antioxidant capacity (Ahmed and Hassan, 2023).

Labelling of Irradiated Foods

The Radura symbol, shown in Figure 1, is derived from the word 'radurization', which is a combination of the words 'radiation' and 'durus', the Latin term for permanent (Mshelia et al., 2023). The Radura symbol is typically green and resembles a plant within a circle, with the upper half of the circle is dashed. In the symbol, the central dot represents the radiation source, while the two segments (the leaves) represent the biological shield provided to protect workers and the environment (Ehlerman, 2009 ; Gonçalves et al., 2011).

Figure 1. Radura Symbol (Mshelia et al., 2023)

Conclusion

The development of new technologies is crucial for ensuring consumers access to healthy and nutritionally rich functional foods, which are increasingly in demand. Technologies such as irradiation, which do not require thermal processing or the use of chemical substances to obtain safer products, are also considered environmentally friendly methods. Understanding the principles of these technologies, inactivating not only vegetative cells but also spores, and optimizing production conditions are crucial, which makes ongoing research essential. Using different radiation sources, and dose levels according to the type and composition of foods minimizes potential negative effects on food quality. Irradiation, with its ability to reduce numbers of or eliminate food-borne pathogens, can be combined with other food preservation methods both to improve hygiene conditions, and to ensure higher quality and safer end products. The possibility to apply irradiation to packaged products eliminates the contamination risks that may arise post-processing, giving it a significant advantage over other preservation techniques. However, the acceptance of irradiated foods by consumers has not yet reached the desired level yet. The main reason for this is consumer bias and suspect that irradiated foods may be radioactive. In addition to lack of consumers awareness, high cost of gamma irradiation applications is one of the main reasons why this method found limited application in food products. Still, irradiation is gaining increasing acceptance each year despite consumer concerns about irradiated foods.

Author contribution statement

All authors accepted responsibility for the entire content of this review and approved its submission. The concept of the review was made by all authors. This review was written by HD. HD conducted the literature search of the review. Critical reading of the article was conducted by DB. DB performed the interpretation of this review.

Conflict of interest

The authors declare that they have no conflict of interest in this study.

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