Overview of irradiation: advantages to foods of plant origin

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ABSTRACT
The technology of food irradiation is gaining more attention around the world. This method is recognized by using ionising radiation in order to control foodborne pathogens, reduce microbial load and insect infestation, inhibit the germination of root crops, extend the durable life of perishable produce, and reduce plant-derived allergens. According to the International Atomic Energy Agency (IAEA), more than 50 countries have approved the use of irradiation for about 50 different types of food, and 33 are using the technology commercially. Despite the fact that irradiation has been used for decades for food disinfection that satisfies quarantine requirements in trade, health concerns over the consumption of irradiated food continue to attract attention. This low-cost method has the advantage that the organoleptic properties of irradiated foods are not altered, allowing, however, to increase their bioactivity and nutritional quality. This review focuses on the advantages of irradiation applied to foods of plant origin. With proper application, irradiation can be an effective means of eliminating and/or reducing microbial and insect infestations along with the foodborne diseases they induce, thereby improving the safety of many foods as well as extending shelf life.

Keywords: irradiation, vegetable foods, security, food preservation.

1 INTRODUCTION

Food safety and food security are two accompaniment components for future sustainable food worldwide and ecological impact (Rojas et al., 2022). Nowadays, consumers are aware of the health benefits and risks associated with consumption of contaminated food or food allergens (Harder et al., 2017). Hence, food industry is assigning considerable resources and expertise to the production of wholesome and safe products (Amit et al., 2017). Thus, the food preservation becomes indispensable and fundamental based on the application of science-based knowledge through a variety of available technologies and procedures, to prevent deterioration and spoilage of food products and, consequently, extend their shelf-life, while assuring consumers a product free of pathogenic microorganisms (Kumar, 2019) and healthy foods for human (Dantas et al., 2021).

Food contamination can be prevented by scrutinizing materials entering the food chain, storing the food at chilling temperature, and reduction or destruction of microbial load by processing and preventing post-processing contamination. Of primary importance to ascertain safety and stability of foods, the unit operation aiming at microbial destruction is of primary importance (Abdolshahi & Yancheshmeh, 2020). Traditionally heat treatments are applied for foods preservation, however they can interfere in food sensory and nutritional qualities. That's why, food industry is seeking alternative technologies to maintain most of the fresh attributes, safety, and storage stability of different types of food, from the most to the least perishable ones.

Food irradiation is one of the recent food preservation technologies which may be used to address some of these problems. It is a physical process which has been thoroughly researched and is as well-understood as other methods of food processing, or more so. The potential of food irradiation processing to reduce postharvest losses of foods, to meet quarantine requirements, to increase exports and to ensure the hygienic quality of foods has been increasingly recognized by many countries. In fact, radiation reduces the biological processes that lead to decay and the ability to sprout. According to Kalyani & Manjula (2014) this technique is considered as a cold process, and it can be used to pasteurize and sterilize foods without causing changes in freshness and texture of food unlike heat. Application of ionising radiation on certain food can be used to reduce a potential risk to hygiene, to influence physiological processes, to control insects populations and also to increase the shelf-life of fresh food within in short time.

Irradiation is also an effective technique for eliminating food allergens (Jiménez-Saiz et al., 2015; Pan et al., 2021). Food allergenicity, which has been increasing in recent years, can be reduced by irradiating foods, both in animal (milk, egg, fish, shellfish) and vegetable (soy, peanut, wheat and tree nuts) origin. This non-thermal food treatment strategy allows for improved food quality and safety, helping to produce hypoallergenic foods. Irradiation can cause specific changes in food components, namely in proteins, which undergo denaturation, fragmentation, or aggregation. These structural changes may alter the overall IgE-binding profiles and, consequently, the immunogenic properties of food allergens (Byun et al., 2002; Jiménez-Saiz et al., 2015). The referred modifications undergone by food proteins make them more resistant to proteases and more stable at low pH, changing their resistance to digestion, and consequently increasing their allergenic potential. In general, plant protective proteins, which function as a defense system under stress conditions, have greater allergenic potential, as do pathogens-related proteins belonging to families 1, 2, 3, 4, 5, 8, 10 and 14 (Ebner et al., 2001; Sinha et al., 2014).

1.1 IRRADIATION

Irradiation is one of the few industrial technologies that can maintain food quality and address food safety and security problems without significantly affecting a food's sensory or nutritional attributes. In fact, the use of ionizing radiation for food preservation started to be used in the early 1920s. From that time onwards, the optimization of the intensity of radiation used in food started to be a prominent topic for the scientific and industrial community. For instance, Song et al. (2007) performed a sensorial analysis of irradiated and non-irradiated fresh vegetable juices (carrots and cabbage), based on the parameters of odor, color, flavor and global acceptance. They found that, immediately after irradiation, there were no significant differences between irradiated and non-irradiated samples, but the sensory quality of non-irradiated juices decreased with storage time, showing the importance of the irradiation as a food preservation methodology. Also Al-Bachir (2016) showed that sensorial properties of sesame seeds (color, texture, odor and flavor) immediately after irradiation (1, 2 and 3 kGy) did not change significantly. Irradiation of raw pistachios (1, 2 and 3 kGy) as a decontamination treatment did not cause significant changes in texture, odor, color nor flavor (Al-Bachir, 2015). Verde et al. (2013) contested that physicochemical and sensorial properties of non-irradiated and irradiated raspberries were quite similar during storage time, which is in agreement with Gaspar et al. (2019).

Irradiation possess the ability to slow ripening, inhibit sprouting in bulbs and tubers, control spoilage and food borne pathogenic microorganisms, prevent the spread of invasive insect pests and decrease food allergenic potential. The number and variety of foods that are irradiated are growing, mainly in Asian, American and European continents (Antonio et al., 2017). The industrial use of ionizing radiations, such as gamma and electron beam (e-beam) radiation, is regulated and authorized by international organizations (EU, EFSA, IAEA, FAO, WHO) for different purposes, including medical devices sterilization, materials modification (Chancellor et al., 2017), heritage preservation, microbial quality of pharmaceutical and cosmetic ingredients and, food decontamination (Kondziołka & Wilczyński, 2021). However, there is mistrust among the general public regarding food irradiation due to the wrong association with an induced radioactivity on the product. Therefore, several obstacles have to be overcome in order to promote food irradiation as a safe and useful application of ionizing radiations.

2 IMPORTANCE AND ADDED VALUE OF IRRADIATION

One of the current problems is related to the growth of the world population and the lack of food (Reisch et al., 2013; Battersby, 2016). Therefore it is imperative to prevent food losses. This has given rise to a greater interest in plant foods, recognized for their nutritional properties and health benefits, and in technologies that allow their conservation, destroying microorganisms and, at the same time, increasing their nutritional quality and food safety. One of the strategies to achieve these goals is irradiation, a process of exposing food to ionizing radiation (Arvanitoyannis et al., 2009).

2.1 FOOD PRESERVATION

Irradiation is an effective method to reduce post-harvest losses, controlle the stored product insects and microorganisms, and prolong the fruit and vegetable shelf life by 3-5 times (Arvanitoyannis et al., 2009). Moreover, irradiation for phytosanitary purposes is a physical and environmentally friendly treatment, often used for the disinfestation of insect pests in grains. Accordingly to Hammad et al. (2020) low doses of irradiation on eggs, larvae or pupae of *Callosobruchus maculatus* did not give rise to any emergent adult beetle, and the same result was observed when irradiating parental adults. The irradiation dose required for cowpea seed weevil disinfestation was 650 Gy, a dose that did not affect the physical and chemical characteristics of cowpea seeds, although it reduced their microbial load very slightly.

The risk of food becoming contaminated with aflatoxins during harvesting, transport and storage is common. However, gamma irradiation can eliminate / control the growth of fungi and inactivate mycotoxins, reducing the content of aflatoxin B1 in soybeans. This method, with a radiation dose of less than 20 kGy and for an incubation period of up to 30 days, does not cause significant changes in the quality of the soybean, in terms of moisture, protein, fat and ash content. However, there was an increase in the acid and peroxide values, and a decrease in the iodine content of the soybean oil, these alterations were not significant for radiation doses below 10 kGy (Zhang et al., 2018). The increase in peroxide value could be due to the liberation of free radicals, what is in agreement with Choi et al. (2021).

De Camargo et al. (2012) irradiated samples of peanuts and stored them for a year at room temperature. These authors found that a radiation dose of 5.2 kGy prevents the growth of mycotoxic fungi in bleached samples, and that the irradiation process was positively correlated with antioxidant activity in the case of shelled peanuts. They also showed that irradiation did not significantly alter the content of the samples in polyunsaturated fatty acids, nor in polyphenols.

According to Al-Bachir (2016) gamma irradiation reduced microorganisms from sesame seeds, with 3 kGy being enough to completely eliminate the fungi, but requiring 9 kGy to eradicate bacteria. In addition to the antimicrobial effect, the chemical and sensory properties of the seeds were also studied after gamma irradiation (3, 6 and 9 kGy), showing that radiation altered protein and sugar contents, total acidity and total volatile basic nitrogen, but had no significant effect on moisture, ash and fat content. The effect of gamma irradiation (doses up to 5 kGy) on the characteristics of mung bean (*Vigna radiata*) grains and starches, partially altered the structure of the starch, which started to present smaller molecules, as well as the morphology of the granules. Irradiation resulted in lower water holding capacity at 75 °C, lower apparent viscosity, but it accelerated hydration, and improved the cooking time of mung bean grains (Castanha et al., 2019).

Since fat-rich seeds are often contaminated with pathogenic microorganisms, their irradiation is widely used to improve seed-propagated crops. Seed irradiation is an effective process to improve their quality during storage. However, irradiation of other tissues, such as the reproductive organs of plants, also seems promising (Jo et al., 2021; Pan et al., 2021). Gamma irradiation can also be used with the aim of genetically altering a species in order to improve cultivation (Yasmin et al., 2020).

Song et al. (2021) investigated the hormesis effect of gamma-ray in quinoa. Plant height and biomass, as well as physiological parameters, increased in quinoa plants treated with a low dose of gamma radiation (50 Gy), which shows the benefits of this procedure. Gamma ray irradiation was also applied to quinoa, with the objective of causing genetic variations. Badran et al. (2019) cultivated quinoa seeds irradiated in saline stress conditions. These authors have obtained promising new genotypes of these seeds, capable of facing environmental stress. According to the study, 90 and 120 Gy allowed the best results in the production of desirable genetic variations.

The effects of gamma radiation on dry maize (*Zea mays*) seeds were studied. After their exposure to gamma radiation (0.1 to 1 kGy), it was observed that germination potential and physiological parameters of corn seedlings (root and shoot length) decreased with the increase of radiation intensity. In addition, the chlorophyll and carotenoid contents significantly decreased in plant leaves derived from irradiated seeds. The some authors also concluded that the relative concentration of radiation-induced free radicals linearly depends on the absorbed doses (Marcu et al., 2013), which was later attested in a work carried out byYasmin et al. (2020).

The use of low doses of gamma radiation appears to increase germination, initial growth and physiological activity of pumpkin seeds. The activity of antioxidant enzymes catalase and peroxidase of pumpkin also increased after irradiation with 2 Gy and 8 Gy, respectively (Kim et al., 2002). Similar results were obtained for black gram (*Vigna mungo* L. Hepper) seeds, in which gamma irradiation, in addition to rising the activity of catalase and peroxidase, increased that of superoxide dismutase. The enlargement in the activity of these antioxidant enzymes is related with the increase in free radicals, produced by the exposure of sedes to gamma irradiation (Yasmin et al., 2019). Sengupta and Raychaudhuri (2017) also reported that gamma irradiation induced oxidative damage in mung bean.

Gamma irradiation (100 and 130 Gy) of sunflower cultivars allowed an increase in fertility and antioxidant activity of the osunflower oil (Rajeev et al., 2022).

The choice of solvents for the extraction of phenolic compounds from seeds irradiated with gamma rays seems to influence the yield of the process. This conclusion was reached by Chierentin et al. (2021) when they used different solvents to extract polyphenolic compounds from irradiated chia seeds: a significant increase in extracted polyphenols was obtained with 50% methanol, with higher doses of radiation, but this process did not was affected when they used ethanol (100%, 70%, 50%) or methanol (100%, 70%) as extractors. It should also be noted that irradiation does not reduce the extraction yield in none of the systems tested.

2.2 ANTINUTRIENTS AND ALLERGENS CONTENT

Modern society has easy access to a extensive informational database. The pursuit of sustainable green and healthy lifestyle leads to a series of food choices. Therefore, it is of importance to provide reliable, comprehensive and up-to-date information about food content including both nutritional and antinutritional elements. Vegetables and cereals contain high amounts of macronutrients and micronutrients but also contain anti-nutritional compounds. Major anti-nutritional constituents including saponins, tannins, phytic acid, gossypol, lectins, protease inhibitors, amylase inhibitor, and goitrogens are described in vegetables, cereals and edible seeds. As is common knowledge, anti-nutrients can be combined with different compounds and act as the major concern because they can preventing nutrients bioavailability. Irradiation appears to be an effective method for reducing anti-nutritional factors such as phytic acid, trypsin inhibitors, tannins, saponins, among others. Antinutritional factors are compounds synthesized by plants as a way to defend themselves against pests, pathogenic bacteria and fungi. For instance, trypsin inhibitors inhibit the proteolytic activity of the digestive enzyme trypsin and may also lead to a reduction in available amino acids (Vagadia et al., 2017). Phytic acid, in turn, can form complexes with proteins, which affects their digestibility, as well as insoluble chelates with minerals, such as calcium, magnesium, zinc, copper or iron, which can pass through the digestive tract, decreasing or preventing the absorption of essential minerals from the diet (Kumar et al., 2020). Saponins are also responsible for decreasing the absorption of minerals and vitamins (Soetan et al., 2014) and for the inhibition of digestive enzymes activities, as lipase and α-amylase (Ercan & El, 2016). Tannins have the ability to form complexes with proteins, which affects the digestibility of the latter and the reduction of essential amino acids (Samtiya et al., 2020).

Irradiation (2.5 - 10 kGy) of fava beans (*Vicia faba* L.) reduced the phytic acid content, this decrease being more evident at 10 kGy. A similar result was obtained for the trypsin inhibitory activity of the irradiated seeds, this reduction being proportional to the irradiation dose (Al-Kaisey et al, 2003).

In general, the irradiation of Mucuna pruriens seeds caused a significant decrease in the phytic acid content, being its degradation complete with doses between 15 and 30 kGy. The elimination or reduction of phytic acid seems to be related to the low content of inositol and inositol phosphates, resulting from the action of free radicals generated during irradiation (Bhat et al, 2007). According to Luo et al (2021), electron beam irradiation of quinoa resulted in a 19% decrease in phytic acid content at 8 kGy. Although irradiation can destroy the chemical structure of aglycones, the results indicated that doses up to 8 kGy did not significantly interfered with saponin content analized in quinoa (Luo et al., 2021). Increasing the irradiation dose (2.5 - 10 kGy) decreased the total tannin content of millet paste millet (cereal with several applications in human and animal food) flours, which may be related to the degradation of the complex protein structure (Gowthamraj et al., 2021). Irradiation can thus result in an increase in the bioavailability of minerals, trace elements and amino acids.

There are also some studies that proved that irradiation, a high quality, low cost, and eco-friendly process, reducing plant-derived allergens, namely soybean, bean, peanut, pistachio, tree nut, wheat, white sesame seeds and moringa oleifera seeds (Pan et al., 2021; Pi et al., 2021). Soybeans are rich in proteins, and several allergenic proteins have been identified in these grains, especially Gly-m Bd 30 K and Gly-m Bd 28 K in 7S globulin and Gly-m Bd 60 K in soy β-globulin (Pan et al, 2021). To avoid allergic reactions caused by soy proteins, irradiation can be an ideal alternative. Wang et al. (2020) prepared a glycosylated soy protein under gamma-ray irradiation from soy protein isolate and maltose. The results of the study showed that the Maillard reaction occurred between the soy protein isolate and maltose, causing a change in the structure and properties of the reaction product: depending on the radiation dose, a considerable increase in the solubility, emulsification and water or fat absorption capacity of the products is achieved, as well as an increase in foam formation and stability of the latter. Such changes considerably improve the functional properties of the modified soy protein.

Peanuts also contain allergenic proteins, being Ara h 1, Ara h 2, Ara h 3, and Ara h 6 the most important. So, gamma irradiation is also a suitable procedure to reduce protein derivative allergens of peanuts and derivatives (Yu, 2016).

The gamma irradiation of flours from nuts, cashews, hazelnuts and almonds gived rise to a significant decrease in the levels of total aerobic bacteria, mold, yeast, Escherichia coli and Salmonella, however not causing changes in the total protein or allergen content of these products (Penumarti et al., 2021). The γ-irradiation did not interfered in the allergenicity of bean, black grass and peanut samples. However, the combination of boiling and γ-irradiation proved to reduce IgE binding and biopotency of soluble and insoluble proteins, decreasing the allergenicity of these legumes (Kasera et al., 2012).

3 IMPORTANCE OF RADIATION INTENSITY IN THE BIOACTIVITY

Irradiation cannot be used as a substitute for good manufacturing practice. In fact, primary food production should still be managed in a way that ensures that food is safe and of suitable quality for human consumption. Moreover, irradiation is also used to maintain the food quality, improving its microbiological safety or also reducing food waste. The Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture estimates that the quantity of food irradiated is approximately 700 000 tonnes. Vinha et al. (2021a) investigated the effect of irradiation on the bioactive compounds content in two sedes varieties, pumpkin and mung bean, respectively. Results showed tha ionizing radiation at 1.5 KGy, increased the content of phenolics and flavonoids. Those results are in agrement with other studies. Abdelaleema and Elbassiony (2021) studied phytochemical and antioxidant properties of irradiated quinoa seed. Total phenolic content and total flavonoid contents increased after exposure to gamma radiation, reaching maximum concentration at 3 kGy intensity. Gallic acid and catechin concentrations increased with 6 kGy gamma radiation. On the other hand, saponin contents after exposure to 3 and 6 kGy decreased compared to non-irradiated quinoa. In recent years, there is a consensus that bioactive compounds plays an important role in preventing many diseases. Duo, the study of antioxidants and their biological properties in several fields, from food engineering to medicine and pharmacy, is of major interest to the scientific community. Vinha et al. (2021a) described a direct relationship between the content of bioactive compounds and their antioxidant activity in both irradiated simples. The highest antioxidant activity was observed for irradiated seeds using an intensity of 3 kGy. A study performed by Azeem et al (2022) showed that γ-radiation (10 kGy) significantly increases the total flavonoid and total phenolic content of raw pumpkin seeds, and consequently their antioxidant activity. In this way, γ-irradiation, in addition to being used as a phytosanitary treatment, increases the phytochemical quality of the seeds. According to Bhat et al. (2007) the irradiation of *Mucuna pruriens* seeds caused an increasement of the activity of phenylalanine ammonia-lyase, which is responsible for the synthesis of phenolic compounds. Moghadam et al. (2019) studied the effects of gamma irradiation (5, 10, 15 and 20 kGy) on flaxseed. Radiation at 5 kGy increased total phenolic compounds of flaxseed compared to control, but higher irradiation doses decreased the referred compounds content, being the reduction of 37.45% at 20 kGy. Flavonoid and γ-tocopherols content decreased at all the used irradiation doses, with a reduction of 33.85% for the first at 20 kGy. On the other side, gamma irradiation had no significantly effects on organic matter, crude fiber, crude protein and fatty acids composition of flaxseed. However gamma irradiation of black gram (*Vigna mungo* L. Hepper) seeds causes an increase in the fractions of proteins, lipids, amino acids and polysaccharides compared to the control (Yasmin et al., 2019).

Curcuma alismatifolia var. *Sweet pink* leaves, irradiated at 10, 15 and 20 Gy, exhibited higher content of total phenolic and total flavonoid compared to control. The phenolic compounds gallic acid, salicylic acid, caffeic acid, cathechin, cinnamic acid, ellagic acid and resorcinol contents enlarged as the irradiation dose increased. The same behavior was observed for flavonoids rutin, naringin, apigenin, quercetin and myricetin (Taheri et al., 2014). This increase in flavonoids and total phenols can be explained by the degradation of larger phenolic compounds into smaller ones, or it can be due to in the release of phenolic compounds of the glycosidic components of the irradiated leaves (Harrison and Were, 2007). So, these results show that gamma irradiation can be a way of accumulating bioactive compounds in products of plant origin, improving their free radicals scavenging and antioxidant activities (Taheri et al., 2014).

The study performed by Choi et al. (2021) evaluated the effect of acute (8 h) or chronic (10 days) gamma irradiation on rice plants (*Oryza sativa* L.). DNA analysis of plants exposed to irradiation showed that all indicators of oxidative stress increased immediately after exposure to acute and chronic irradiation in a dose-dependent manner, with the former having a more significant effect. In fact, the levels of H_2O_2 and free radicals increased significantly with acute and chronic irradiation, this effect being more noticeable in plants irradiated acutely. The activity of the antioxidant enzymes catalase, peroxidase, ascorbate peroxidase and superoxide dismutase generally increased after acutely and chronically irradiation.

According to Hassan et al. (2019) gamma radiation can be used to control the growth of fungi in sesame seeds, simultaneously causing a significant increase in their total phenolic content and consequent scavenging activity, but without significant effects on the fatty acid composition of the oil extracted from said seeds. Rizki et al. (2019) reported that gamma irradiation (3, 6, 9 and 12 kGy) preserved the antioxidant activity of sesame seeds, as well as their high phenolic and flavonoid content during the storage period (12 months), simultaneously allowing them to be free of bacteria during this entire time.

According to the results reported, it can be concluded that the relationship between irradiation and the content of antioxidant compounds in foods is still unclear. However, in general, irradiation, at the appropriate dose, allows an increase in the antioxidant potential.

There are studies that report the reduction of antioxidant activity of food after irradiation treatments. The total phenolic content of finger millet flours decreased relative to the control and as the gamma radiation dose increased (2.5 - 10 kGy), while the total flavonoid content increased under the same conditions (Gowthamraj et al., 2021). Verma et al. (2016) reported that high moisture and high dose of γ-irradiation decreased the antioxidant properties of mung bean. The variation in antioxidant activity seems to be related to the radiation dose used, exposure time, composition and state of the raw material (Lima et al., 2018).

4 CONCLUSION

Food irradiation is a procedure that allows, in addition to its conservation, the removal of undesirable components (such as antinutrients and allergens), as well as improving its functional properties. Nevertheless, the potential benefits of food irradiation are yet to be realized due to slow progress in the commercialization of the technology. In the current years, many studies have been optimizing the intensity of different doses of gamma radiation in order to ensure the food quality attributes (organoleptic and rheological characteristics, bioactive compounds, and antioxidant activity) of different plant foods. Also, irradiation can remove antinutrients and allergens, that is essential to improve the nutritional quality and security of foods. Irradiation is far from being considered an innocuous method, however, its benefits have shown that an adequate optimization can be an asset to guarantee food quality and safety, without prejudice to public health.

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