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ENHANCING FOOD SAFETY AND STABILITY THROUGH IRRADIATION: A REVIEW

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ABSTRACT

Food irradiation is one of the non thermal food processing methods. It is the process of exposing food materials to the controlled amounts of ionizing radiations such as gamma rays, X-rays and accelerated electrons, to improve microbiological safety and stability. Irradiation disrupts the biological processes that lead to decay of food quality. It is an effective tool to reduce food-borne pathogens, spoilage microorganisms and parasites; to extend shelf-life and for insect disinfection. The safety and consumption of irradiated foods have been extensively studied at national levels and in international cooperations and have concluded that foods irradiated under appropriate technologies are both safe and nutritionally adequate. Specific applications of food irradiation have been approved by national legislations of more than 55 countries worldwide. This review aims to discuss the applications of irradiation in food processing with the emphasis on food safety and stability.

Keywords: Irradiation, radiation sources, food safety, shelf-life, disinfestation

INTRODUCTION

Food preservation is a process to extend the shelf life of foods while maintaining their safety and organoleptic properties. It involves the actions taken to maintain foods with the desired properties or nature for a desired time frame. A number of new preservation techniques are being developed to satisfy the current demands for more efficient preservation and higher consumer satisfaction with regard to nutritional and sensory aspects, convenience, safety, absence of chemical preservatives, low price, and environmental safety **(Rahman, 2012)**. These methods include thermal processing, drying, freezing, chemical treatment, high pressure processing and so on. But all these preservation methods have both beneficial and adverse effects on food quality. Since there is an increasing demand for nutritious, fresh-like food products with high organoleptic attributes, improved safety and prolonged shelf life, various non-thermal processes like high hydrostatic pressure, pulsed electrical field, and irradiation technologies have been investigated **(Junqueira-Gonçalves *et al.*, 2011)**. Among them food irradiation is considered as one of the most effective methods of food preservation.
Food irradiation is the exposure of food to controlled amounts of ionizing radiation to improve microbiological safety and stability. Food irradiation technology is being used in an increasing number of countries for decontamination and/or sterilization of dehydrated vegetables, fruits, meats, poultry, fish and seafood to improve product safety and shelf life, and an increasing number of clearances for radiation decontaminated foods have been issued or are expected to be granted in the near future **(Ayari *et al.*, 2009)**. **Farkas and Mohácsi-Farkas (2011)** have reviewed the history and future of food irradiation.

TYPES AND SOURCE OF IONIZING RADIATION

There are three types of ionizing radiation used in processing of food materials viz., high energy gamma rays, accelerated electrons and X-rays. Gamma rays are high energy photons and produced by spontaneous disintegration of radionuclides like cobalt-60 and cesium-137. A major characteristic of gamma rays is their high penetrating power, which facilitates their use in treatment of bulk items. Since gamma rays do not give rise to neutrons, irradiated foods and their material are not made radioactive **(Diehl, 1995)**. Cobalt-60 is the most commonly used radionuclide for food. Cobalt-60 emits ionizing radiation in the form of gamma-rays and its advantages include a deep penetration, uniformity of dose, decay to nonradioactive nickel when spent, a low risk to the environment, and up to 95% of the emitted energy is available for use. Disadvantages of Cobalt-60 include a relatively short half-life of 5.3 y and a slower treatment of food compared to other forms of irradiation **(Hirneisen *et al.*, 2010)**. The other radionuclide source, Cesium-137, is not widely used, due to its handling problems **(Lee, 2004)**. Cesium-137 has a half-life of 30 years. In a typical gamma radiation facility, the radioactive material (Cobalt-60 or Cesium-137) is placed at the top of an elevator that can be moved up and down under water when not in use. Materials that need to be irradiated are placed around the radioactive material at a suitable distance for their desired dose. The main drawbacks of using radioactive material are that these isotopes emit radiation in all directions and cannot be switched off when not in use **(Moreira, 2006)**.
The second main source of ionizing radiation is accelerated electrons produced by electron accelerating machines known as electron accelerators. By the acceleration to the speed of light, the electron beam accelerator subsequently passes the high-energy electrons onto the product, resulting in microbial inactivation. The main advantage of electron accelerators is that they can be switched off when not in use, thus leaving no radiation hazard. Electron-beam processing does not alter the temperature of the processed food and permits the application of high dose rates (1000 to 100000 kGy/s in comparison to only 0.01 to 1 Gy/s for gamma radiation) **(Tahergorabi *et al.*, 2012)**. However, the depth of penetration is only 8 to 10 cm, for typical food products, therefore before irradiation of food products, the size has to be considered prior processing **(Jaczynsky and Park, 2003)**. Despite this limitation, electron beams can be used for treatment of various food products like grains on a conveyor, low density foods such as ground spices, and for surface decontamination of prepared meals.
The third but less used source is X-rays generated from bombardment of high energy electrons on a metal target. X-rays carry the dual advantage of high penetration power and switch off capability **(Lee, 2004)**. X-ray machines have a maximum energy of 5 MeV that is too low to induce radioactivity in food. X-radiation penetrates foods more shallowly than gamma irradiation but much more deeply than electron beams **(Sadler *et al.*, 2001; Tahergorabi *et al.*, 2012)**.

APPLICATIONS OF FOOD IRRADIATION

Radiation processing of food and agricultural commodities has been recognized as one of the most reliable and safest methods, for preservation of food and agricultural commodities for maintenance and improvement of hygienic quality and nutritional value, and has been used to overcome quarantine and trade-related barriers in the international arena **(Diehl, 2002; Bhat *et al*., 2007 a)**. Ionizing radiation has also been proven to be beneficial for the removal of antinutritional factors and inhibition of food allergies **(Bhat *et al*., 2007 b; Bhat and Sridhar, 2008)**. Irradiation treatments do not induce a significant increase in temperature, require minimal sample preparation, are fast, and have no dependence on any type of catalysts **(Farkas, 1998; Diehl, 2002)**.

Irradiation efficiency depends on both the accelerator characteristics and irradiation technique, as well as on a number of factors including the type of material, geometric dimensions, shape, packaging material, etc **(Moreira, 2006)**. The dose unit in this system is the Gray (Gy). One Gy is the dose at which 1 joule of energy is absorbed by 1 kg of a substance. The dose rate is expressed in kGy/s. The total dose absorbed by the irradiated material is directly related to the dose and irradiation time. The nature of the food product and purpose of irradiation determine the doses necessary for processing **(Hirneisen *et al*., 2010)**. Applications of food irradiation are usually organized into three categories according to the range of delivered dose as shown in the **Table 1**.

Table 1 Various Dosage Levels of Irradiation and their Uses

	Dose level	Purpose	Food items
1.	***Low Dose Disinfestations/ delay in ripening (upto 1 kGy)***	Inhibits growth of sprouts on potatoes and other foods. Kills insects and larvae in wheat, flour, fruits and vegetables after harvesting. Slows ripening process. Kills certain harmful parasites associated with foods.	Potatoes, onions, garlic, ginger, bananas, mangoes and certain other non-citrus fruits, cereals and pulses, dehydrated vegetables, dried fish and meat, fresh pork.
2.	***Medium Dose Pasteurization (1-10 kGy)***	Dramatically reduces number of or eliminates certain microbes and parasites that cause food to spoil. Reduces or eliminates many pathogenic microorganisms.	Fresh fish, strawberries, grape, dehydrated vegetables, fresh or frozen seafood, raw or frozen poultry and meat.
3.	***High Dose Sterilization (10-50 kGy)***	Sterilizes food for a variety of uses such as meals for hospital patients who suffer from immune disorders and can eat only bacteria-free foods. Eliminates some disease causing viruses. Decontaminates certain food additives and ingredients.	Meat, poultry, seafood and other food prepared for sterilized hospital diets, spices, enzyme preparations, natural gum.

Food safety enhancement

The predominant effect of irradiation on microorganisms relies upon the reaction of free radicals with the DNA and also RNA of microorganisms. DNA is much larger than the other molecular structures in a cell and this is an important reason for its high sensitivity to the effect of ionizing radiation **(Scott and Suresh, 2004)**. The free radicals disrupt the hydrogen bonds between the double stranded DNA molecules which prevent replication and causes cell death while exerting minimal effect on non-living tissues **(IFST, 2006)**.

The resistance of microorganisms to radiation varies depending on strains and the physiological state of the strain used. In general, cells under stress show higher levels of resistance to irradiation **(Verma and Singh, 2001)**. Starved cells consistently exhibited higher irradiation D_{10} values, that is, the amount of radiation necessary to achieve a 90% (1 log) reduction, than controls in both saline and ground pork **(Mendonca *et al*., 2004)**. The other factors which affect the efficiency of irradiation are temperature, atmosphere surrounding the food, type and physiological state of the microorganism, irradiation dose and time of exposure.

The endospores of spore-forming bacteria are resistant to most treatments and also to irradiation. Doses used to pasteurize foods below 10 kGy may only give a 2-3 log reduction in spore numbers. This is not sufficient to produce shelf-stable foods **(Patterson, 2005)**.

Fungi and viruses are typically more resistant to radiation than are bacteria. D_{10} values, are in the range of 1 to 3 kGy for fungi **(Niemira and Deschenes, 2005)** and somewhat higher for viruses **(Yu *et al*., 1996)**. The doses required to achieve meaningful population reductions of fungal and viral contaminants (3–5 log) typically result in a loss of the sensory quality of fresh and freshcut produce. Low-dose irradiation has been shown to suppress, but not eliminate, some phytopathogenic fungi responsible for storage losses **(Niemira and Deschenes 2005)**. In contrast, the D_{10} values for pathogenic bacteria on produce ranges from 0.2–0.8 kGy **(Niemira, 2003; Martins *et al*., 2004)**; this degree of sensitivity would allow a 5 log reduction with doses between 1 and 4 kGy, a more achievable level of treatment.

Yeasts are different in their radiation resistance. *Alternaria* sp. and *Fusarium* sp. are more resistant, the *Penicillium* sp. and *Aspergillus* sp., *Fusarium* and *Alternaria* spores are multicellular. If only one cell escapes damage, the spore may still have the ability to germinate. So, these spores are more radiation resistant as higher doses will be needed to destroy all the cells **(Patterson, 2005)**.

Viruses are generally more radiation resistant than other organisms since the size of the DNA molecule generally increases with the complexity of an organism **(Koopmans and Duizer, 2004)**. Due to their small size and genome, enteric viruses are more resistant to inactivation by ionizing irradiation compared to bacteria, parasites, and fungi **(Farkas, 1998)**. However, radiation sensitivity is affected by many other factors. These include temperature, the composition of cellular medium, and the growth cycle of the cell **(Stewart, 2004 a)**. Lowering the temperature decreases the metabolism rate (simple water activity) and the formation and mobility of free radicals. For the same reason, drying and freezing also generally decrease radiation sensitivity. Whereas, viruses can be inactivated by heat, the combination of heating with irradiation can be used successfully **(Koopmans and Duizer, 2004)**. **Bidawid *et al*. (2000)** studied the efficacy of irradiation on hepatitis A virus inactivation on strawberries and lettuce at doses less than 10 kGy. They observed a linear decrease in virus numbers as irradiation doses increased for both food products. At 10 kGy, a >3 log inactivation occurred for both strawberries and lettuce. **Jay *et al*. (2005)** observed that viruses are able to survive a radiation 12D process for *Clostridium botulinum* in meat products unless previously damaged by other methods.

Beef, pork, poultry, seafood, eggs and dairy products are all recognized as major sources of food borne illness. The most serious contaminants are *E.coli* and *Listeria* for beef and for poultry and eggs, the predominant pathogens are *Salmonella* and *Campylobacter*. Excellent control of all these organisms can be achieved with doses in the range of 1 - 3 KGy **(Mostafavi *et al*., 2010)**. Ready-to-eat chicken breast was manufactured, vacuum-packaged, and irradiated at 0, 5, and 40 kGy. The populations of total aerobic bacteria were 4.75 and 2.26 log cfu/g in the samples irradiated at 0 and 5 kGy, respectively. However, no viable cells were detected in the samples irradiated at 40 kGy. On day 10, bacteria were not detected in the samples irradiated at 40 kGy but the number of bacteria in the samples irradiated at 5 kGy was increased **(Yun *et al*., 2012)**.

Fallah *et al*. (2010) reported that the food-borne pathogens *L. monocytogenes*, *E. coli* and *S. typhimurium* were reduced to undetectable levels in the ready-to cook Iranian barbecued chicken samples irradiated at 4.5 kGy. According to **Badr (2012)** gamma irradiation at dose of 3 kGy can be successfully applied to provide significant improvement in the safety of cold smoked salmon with respect to *L. monocytogenes* and *Vibrio parahaemolyticus*. **Medina *et al*. (2009)** reported that treatment with 1.5 kGy electron beam irradiation significantly reduced *L. monocytogenes* on smoked salmon by 2.0 log cfu/g. **Robertson *et al*. (2006)** reported that radiation doses of 0.5, 1.0 and 1.5 kGy X-ray reduced the populations of *L. monocytogenes* on smoked mullet by 1.1, 1.6 and 2.1 log cfu/g, respectively. In this study, a 2.0 kGy dose of X-ray reduced *L. monocytogenes* in the smoked catfish to undetectable levels. According to **Mahmoud *et al*. (2012)** the initial L. *monocytogenes* population on smoked catfish was significantly ($P < 0.05$) reduced to undetectable level by a treatment of 1.0 kGy or higher. The initial psychrotrophs count on smoked catfish was significantly reduced from 4.7 cfu/g to below the detectable level by a treatment with 2.0 kGy.

Rajkowski and Thayer (2000) reported that salmonellae were not recovered from alfalfa sprouts irradiated with 0.5 kGy even though the seeds used to produce the sprouts contained detectable levels of the pathogen and concluded that ionizing radiation can be used to reduce pathogen populations on sprouts. It has been shown that irradiation at medium doses (less than 3.0 kGy) can reduce or eliminate nonspore-forming pathogens such as *Salmonella* in food products including eggs **(Farkas, 1998)**. Using an inoculum of 10^7 to 10^8 CFU/egg, shell eggs were artificially contaminated with reference strains of *S. Typhimurium*, *S. Enteritidis*, *Campylobacter coli*, and *C. jejuni*. The range of irradiation doses for the determination of D_{10} values was 0.2 to 1 kGy for *Salmonella* spp. and 0.2 to 0.7 kGy for *Campylobacter spp*. The gamma irradiation doses were included in the range 0.5 to 5 kGy. The D_{10} values varied between 0.31 and 0.26 and 0.20 and 0.19 kGy for *S. Typhimurium* and *S. Enteritidis*, respectively, and between 0.21 and 0.18 kGy and 0.07 and 0.09 kGy for *C. coli* and *C. jejuni* for the eggshell **(Cabo Verde *et al*., 2004)**. **Al-Bachir and Zeinou (2006)** performed another study on the irradiation of shell eggs. Using a suspension of 10^7 CFU/mL of *Salmonella* spp. the shell eggs were inoculated and subjected further on to doses of gamma irradiation from 500 to 3000 Gy, with the estimation of survival curves. The radiation dose required to reduce the *Salmonella* spp. load one log cycle (D_{10}) was 448 Gy.

A dose of 1.0 kGy reduced total aerobic plate count and *Listeria monocytogenes* on pre-cut bell pepper by approximately 4 log cfu/g; storage (4 days) at abuse temperatures (10 or 15°C) led to regrowth, but refrigeration temperature (4°C) suppressed regrowth of the pathogen, preserving the initial efficacy of the treatment **(Farkas *et al*., 1997)**. *E. coli* and *L. monocytogenes* were effectively eliminated (>5 logs) from diced celery by 1.0 kGy **(Prakash *et al*., 2000 a)**. Peeled, ready-to-use carrots that were treated with 1 kGy showed aerobic plate counts reduced by 4 log cfu when packed in air, and 4.5 log reductions when packed under modified atmosphere **(Lafortune *et al.*, 2005)**. The effect of irradiation on the microflora of foods is shown in **Table 2**.

Table 2 Effect of irradiation on microflora of foods

Food item	Target pathogen	Treatment dose applied (kGy)	Log reduction of target pathogen (cfu/g)	Reference
Turkey ham	*L. monocytogenes*	1.0-2.5	2-5	Zhu *et al.*, 2005
Chicken breast meat	*S. typhimurium*	0-3	4	Sarjeant *et al.*, 2005
Ready-to-cook Iranian barbecued chicken	*L. monocytogenes*	3	3.8	Fallah *et al.*, 2010
	E. coli O157:H7	3	Reduced to undetectable levels	
	Salmonella typhimurium	3	5.5	
Rabbit meat	*Salmonella*	3	Reduced to undetectable levels	Badr, 2004
	Staphylococcus aureus	3	3	
	L. monocytogenes	3	3	
	E. faecalis	3	1.4	
	Enterobacteriaceae	3	4	
Buffalo meat	*Staphylococcus spp.*	2.5	3	Kanatt *et al.*, 1997
Lamb meat	*Staphylococcus spp.*	2.5	2	
Eggs	Mesophilic aerobic bacteria	1	2	Al Bachir & Zeinou, 2006
	Coliforms		2	
Liquid egg white & yolk	*Salmonella, S. aureus, Enterobacterium*	3	Reduced to undetectable levels	Badr, 2006
Eastern oysters (*Crassostrea virginica*)	*Cryptosporidium parvum*	2	Eliminated completely	Collins *et al.*, 2005
Salmon (cold-smoked)	*L.monocytogenes*	3	Reduced to undetectable levels	Badr, 2012
	Vibrio parahaemolyticus	3		
Salmon (cold-smoked)	*L. monocytogenes*	1	2.5	Su *et al.*, 2004
		2	Eliminated completely	
Mullet (*Mugil cephalus*), vacuum packaged and smoked	*L. monocytogenes*	0.5	1.1	Robertson *et al.*, 2006
		1	1.6	
		1.5	2.1	
		2	Reduced to undetectable levels	
Tomato	*L. monocytogenes*	1	2	Mohácsi-Farkas *et al.*, 2006
Cabbage	*E.coli*	0.8	4-5	Khattak *et al.*, 2005
	L. monocytogenes	1.0	5.2	Bari *et al.*, 2005
	Enterobacteriaceae	1.0	3.8	López *et al.*, 2005
Carrots	*L. monocytogenes*	2.2	6.0	Lacroix *et al.*, 2009
	L. innocua	0.25	0.6	Caillet *et al.*, 2006a
	E. coli O157:H7	0.3-0.9	>6	Lacroix & Lafortune, 2004
	L. monocytogenes	2.4	6.5	Caillet *et al.*, 2006b
Celery	*Enterobacteriaceae*	1.0	5.1	Prakash *et al.*, 2000a
	E. coli	1.0	3.6	López *et al.*, 2005
Cantaloupe (*Cucumis melo*)	*L. monocytogenes*	1	2	Mohácsi-Farkas *et al.*, 2006
	E. coli O157.	1	5	

Wang *et al.* (2006) investigated microorganism survival in Golden Empress cantaloupe juice after Cobalt-60 irradiation and found that that *E. coli* was sensitive to irradiation and could be reduced by 7 log cycles at 1 kGy, whereas total colony and target spore bacteria in the juice demonstrated greater endurance to the irradiation, suggested by D_{10} values of 0.9908 and 1.1923 kGy, respectively. The study revealed that gamma-irradiation cannot completely inactivate total colony and target spore bacteria in cantaloupe juice on the premise of acceptable off-odor.

Gamma irradiation (doses of 0.75 and 1 kGy) reduced the lesion size caused by *Colletotrichum gloeosporioides* and anthracnose incidence in papaya fruit (*Carica papaya*) when applied after fruit inoculation, but it did not protect the fruit when applied 24, 48, or 72 hours before inoculation. These doses inhibited *C. gloeosporioides* conidial germination and mycelial growth but stimulated fungal sporulation. The fruits were stored at 25°C/80% RH for 7 days **(Cia *et al.*, 2007)**.

Hussain *et al.* (2008) investigated the quality of gamma-irradiated (0.1–0.5 kGy) Ambri, Golden Delicious, and Royal Delicious apples stored under ambient (15°C) and refrigerated (3°C) conditions. The irradiation doses of 0.2, 0.3, and 0.5 kGy proved beneficial to maintaining the overall quality of all three varieties of apple under both storage conditions. Gamma-irradiation significantly reduced the yeast and mold counts of apples under storage. **Shurong *et al.* (2006)** determined the D_{10} values of *E. coli* O157:H7, *Listeria innocua*, and *Salmonella enteritidis*. D_{10} values of *E. coli* O157:H7 inoculated in cherry tomato and fresh precut carrot were 0.08 and 0.13 kGy, respectively. D_{10} values of *S. enteritidis* inoculated in cherry tomato, fresh precut carrot, and a mixture of blanched celery and peanut were in the range of 0.24–0.33 kGy. Irradiation with doses less than 2.0 kGy could ensure a 5 log reduction of the most resistant examined pathogen, *S. enteritidis*. Moreover, irradiation could effectively control the growth of pathogens during the storage period. **Song *et al.* (2007)** reported that the initial populations of the total aerobic bacteria and coliform counts observed in the carrot juice were 10^6 cfu/ml, and those of the kale juice were 10^7 cfu/ml. All the aerobic bacteria and coliforms in the fresh carrot juice were eliminated with irradiation at 3 kGy, and the D_{10} value of the microflora in the carrot juice was found to be approximately 0.5 kGy. However, a radiation dose up to 5 kGy could not completely eliminate the bacteria in the fresh kale juice. The D_{10} value was higher than 1.0 kGy in the kale juice.

According to **Jo *et al.* (2007)** a low-dose irradiation can improve the microbial quality and reduce the risk from any food-borne pathogens in ice cream, which has limited alternative sterilization methods due to the temperature characteristics of the products.

Shelf-life extension

The same dose levels appropriate for control of food borne pathogens can also significantly extend the shelf life of the products by reducing populations of spoilage bacteria, molds and yeasts. For example, a dose of 2.5 kGy can extend the shelf life of chicken and pork by as much as a few weeks, while the shelf life of low-fat fish can be extended from typically 3 - 4 days without irradiation to several weeks with 5 kGy **(Patterson, 2005)**. The shelf life extension for strawberries, carrots, mushrooms, papayas and packaged leafy vegetables also appears to be promising at dose levels of a few kGy or less. Irradiation of mushrooms at 2 – 3 kGy inhibits cap opening and stem elongation and shelf life can be increased at least by two-fold (by storage at 10°C). Ripening in bananas, mangoes and papayas can be delayed by irradiation at 0.25 - 1 kGy. It is important to irradiate them, before ripening starts **(Mostafavi *et al*., 2010).**

Since moist heat treatment is not generally suitable for such dry products, spice producers in the past routinely used fumigants for disinfestations. Producers are now increasingly turning to ionizing radiation. In fact, the commercial irradiation of spices has been approved and practiced in many countries for several years. Doses of 5 -10 kGy usually give quite satisfactory results (elimination of bacteria, mold spores and insects) without a negative impact on chemical or sensory properties **(Farkas, 2004).**

Mathew *et al*. (2007) conducted an investigation to extend the shelf life and maintain the quality characteristics of tomatoes (*Lycopersicum esculentum*) under the effect of MAP in low-density polyethylene (LDPE) film pouches, with γ-irradiation at 0–4 kGy and low-temperature (12 °C) storage at 90–95% RH. Results revealed that tomatoes packed with LDPE pouches alone as well as treatment with MAP and low doses (1 and 2 kGy) of irradiation showed good storability up to 21 days at 12 °C and 90–95% RH with maximum retention of fruit quality characteristics compared to 7 days for the control tomatoes kept in the open.

Icekson *et al*. (1996) performed experiments using ionizing radiation to prolong the shelf life of two groups of refrigerated fish (*Cyprinus carpio*) stored at 0–2°C. Non-irradiated fish reached the non-acceptability point in 16 days and irradiated fish reached that point in 31 days, based on sensory evaluation. **Aziz *et al*. (2002)** examined the effect of γ-radiation treatments on different beef products. When beef samples with an initial bacterial count of 4.9×10^6 cfu/g were exposed to γ-rays at a dose level of 5 kGy, counts of bacteria were reduced by 2 or 3 log cycles, and when heated in a microwave oven, bacterial counts were reduced by 1 log cycle in 20 seconds and by 2 log cycles in 30 seconds exposure. Untreated samples had a shelf life of less than 7 days, whereas samples that were irradiated at a dose level of 3 kGy and then heated in a microwave oven for 20 seconds had a shelf life of at least 2 weeks at 5°C.

Electron irradiation treatment up to 3 kGy is useful to manufacture ready-to-eat meat products enriched with folic acid. During storage, the products maintained a good sensory quality and even it could be enhance until a period of 90 days **(Galan *et al*., 2013)**. The irradiation dose of 2.0 kGy may inhibit the growth of spoilage micro-organisms such as coliforms and *Pseudomonas* sp. without affecting the sensorial characteristics of mozzarella cheese **(Huo *et al*., 2013)**.

Insect disinfestations

Insects, mites and other such pests are higher level multi-cellular organisms responsible for considerable loss of fresh produce and grains. They can also serve as vectors for carrying pathogenic parasites and bacteria. Excellent control of insects in agricultural products can be achieved by using fumigants, such as ethylene bromide, ethylene oxide, but the use of these pesticides has been banned or severely restricted in most countries for health and environmental issues **(Mostafavi *et al*., 2010)**. Although, the other methods like heat and cold treatments are capable of insect disinfestation but they also acutely degrade the taste and appearance of the produce **(Stewart, 2004 b)**. Therefore, radiation has been suggested as an alternative to them. Ionizing energy breaks chemical bonds within DNA and other molecules, thereby disrupting normal cellular function in the insect. Insect response to irradiation varies with the insect species and life stage, and the absorbed dose received by the insect. Tissues with undifferentiated, actively dividing cells are most susceptible to irradiation. Consequently, eggs are normally the most susceptible life stage and adults are the most tolerant. Insect gonads and midgut contain mitotically active tissues, and irradiated insects are often sterile and stop feeding soon after treatment **(Arvanitoyannis, 2010).** Cobalt-60 gamma ray target doses of 100,150, 200 and 250 Gy were used to irradiate immature and adults of mealy bug, *Dysmicoccus neobrevipes* (Beardsley) and it was found that the tolerance to irradiation in *D. neobrevipes* increased with the advanced life stage and adult was the most tolerant stage. The dose range between 200 and 250 Gy could be sufficient to prevent the reproduction of this mealy bug **(The *et al*., 2012).**

Practical experience shows that the required radiation dose is in the range of 150 - 700 Gy. A dose level of 250 Gy can be effective on quarantine treatment of fruit flies, whereas a dose of 500 Gy can control all stages of most pests **(Farkas, 2004; Miller, 2005)**. Two of the most radiotolerant insects are the Indianmeal moth, *Plodia interpunctella*, and the Angoumois grain moth, *Sitrotroga cerealella*, both stored products pests **(Ahmed, 2001; Ignatowicz, 2004).**

Hayashi *et al*. (2004) treated four stored product insect pests *Tribolium castaneum* (Herbst), *Plodia interpunctella* (Hübner), *Callosobruchus chinensis* L. and *Sitophilus zeamais* (Mothschulsky) using ‘‘soft electrons’’ (low-energy electrons) with an energy of 60 keV. Adults of *C. chinensis* survived at 750 Gy but were inactivated having lost the ability to walk at 250 Gy. Soft electrons at 60 keV inactivated eggs, larger larvae (fourth instars), and pupae of *S. zeamais* in rice grains, which indicated that *S. zeamais* was exposed to electrons even inside the grains. Moreover, a dose of 1000 Gy inactivated eggs, larvae, and pupae of *T. castaneum* and *P. interpunctella* and eggs of *C. chinensis*. **Hallman and Martinez (2001)** developed a low-dose γ-irradiation quarantine treatment against the Mexican fruit fly, *Anastrepha ludens* (Loew), for citrus fruits. The measure of efficacy of the treatment was prevention of adult emergence from third instars that were reared and treated in Rio Red grapefruit, *Citrus paradisi* Macf. The percentage of Mexican fruit fly adults emerging from grapefruit irradiated with 25, 30, 40, 50, or 60 Gy was 2.5, 1.4, 0.0005, 0, and 0%, respectively. **Allinghi *et al*. (2007)** found a significant reduction in the female relative performance index with increasing irradiation dose. The tested doses were 0, 40, 70, and 100 Gy. The analysis of induced sterility indicated that treatment with 40 Gy reduces male fertility from approximately 80 to 0.75%, and higher doses produce total sterility. In females, the 40-Gy dose reduces fertility to approximately 2% and higher doses prevent egg laying. The Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), is one of the most important quarantine pests in the world. The research conducted by **Torres-Rivera and Hallman (2007)** on cage-infested ‘‘Haden’’ mangoes in Peru showed that 100 Gy was sufficient to provide a high level of quarantine security against this important pest. A dose of 100 Gy might allow for irradiation of avocados, one of the few fruits that does not tolerate more than 100–200 Gy.

Other potential applications

Radiation processing has been highlighted as providing a low-cost and environment-friendly alternative to alter the physical, chemical, and/or biological characteristics of a product. It has been reported to reduce or eliminate undesirable or toxic substances including food allergens **(Seo *et al*., 2007; Lee *et al*., 2007; Vaz *et al*., 2012)**, carcinogenic agents **(Ahn *et al*., 2002; Fan and Mastovska, 2006)**, biogenic amines **(Kim *et al*., 2003; Mendes *et al*., 2005; Badr, 2012)**, embryo-toxicity of gossypol **(Jo *et al*., 2003)**, and trypsin and tannin inhibitors **(de Toledo *et al*., 2007)**, and phytic acid with enhancement of the antioxidant activity **(Ahn *et al*., 2004).**

Bhat *et al*. (2007 a) assessed the impact of γ-irradiation on the phytic acid content of seeds of *Mucuna pruriens* upon exposure to various doses and concluded the treatments showed significant decreases in phytic acid, with complete degradation attained at 15 and 30 kGy. According to **Vaz *et al*. (2012)** food irradiation has proved effective and safe in combating immunological and allergic effects of wheat-germ agglutinin. In another study, **Vaz *et al*. (2013)** reported that the reduction in allergenicity is highly related to the irradiation level, low doses do not show reduction and high doses do. **Křížek *et al*. (2012)** reported that the contents of biogenic amines in vacuum-packed trout meat stored at 3.5 °C can be noticeably reduced by the application of high-energy electron beam irradiation. The concentrations of the most toxicologically important biogenic amines histamine and tyramine did not exceed a value of 1 and 10 mg/kg respectively for those samples with good organoleptic properties.

There is a great potential for an application of irradiation as a new processing technology such as the development of traditional fermented foods **(Byun *et al*., 2006)** and the drying procedure of food commodities (**Wang and Du, 2005).** Irradiation has proved to be an effective method for improving the quality of fermented foods **(Kim *et al*., 2002; Park *et al*., 2008).** According to **Wang and Chao (2003)**, the dehydration rate and rehydration ratio of apples (Fuji) were greatly affected by the irradiation dose (0, 2, 5 and 6 kGy); the greater the dose, the higher the dehydration rate and the lower the rehydration ratio.

NUTRITIONAL AND SENSORY QUALITY OF IRRADIATED FOODS

Irradiation has become one of the successful techniques to preserve food with minimum interruption to the functional, nutritional, and sensory properties of food products at lower doses. However, high-dose irradiation, especially higher than 10 kGy, can lead to physicochemical changes and significantly deteriorate sensory properties of foods, including taste, flavor, texture, and color (**Kim *et al*., 2006)**. Studying the radiation chemistry of food components in model systems would provide a rational basis for extrapolating the results obtained to the complex situation existing in food **(Kempner, 2001).** The advances in the radiation chemistry entailed the uniformity of the reaction mechanisms and permitted reasonable predictions to be made on the changes that are likely to occur in food or food products. In lipids, it has been found that a relatively high dose of irradiation would give rise to a relatively milder decomposition compared to decomposition produced by normal cooking temperature **(Nawar, 1983).** Concurrently, the reaction on globular and fibrous proteins was also found to differ upon irradiation **(Stewart, 2001)**. The progress in the radiation chemistry of carbohydrates showed that degradation often occurred. A review on the effects of radiation processing on starch has been reported by **Bhat and Karim (2009).** The effects of radiation on protein properties that are relevant for food and food-based industries have been reviewed by **Kuan *et al*. (2013)** However, less degradation was found to occur in food than that of model systems **(Stewart, 2001).**

Fan *et al*. (2003) did not find any difference in total ascorbic acid of Iceberg lettuce during 21 days of storage. According to **Mohácsi-Farkas *et al*. (2006)**, a radiation dose of 1 kGy had no significant effect on total carotenoid and the vitamin C content of sliced tomatoes (*Lycopersicon* syn. *L. esculentum*). **Bandekar *et al*. (2006)** reported that there was no significant difference in the vitamin C content and total carotenoids in the irradiated (1 and 2 kGy) samples and control samples of carrot and cucumber. **Vanamala *et al*. (2007)** reported that irradiation caused little change in the content of total soluble solids in grapefruits (*Citrus paradisi* cv. Rio Red). According to **Antonio *et al*. (2011)** the use of gamma irradiation increased the antioxidant compounds such as polyphenols of chestnuts (*Castanea sativa*) fruits and skins. Irradiation doses upto 3 kGy resulted in no change in vitamin E content of sunflower whole grain cookies **(Taipina *et al*., 2011). Stefanova *et al*. (2011)** reported that there was an increase in the amount of saturated fatty acids and a decrease in the amount of polyunsaturated fatty acids in the triacylglycerol composition of irradiated samples of beef compared to non-irradiated sample with an increasing irradiation dose.

Irradiation at 1.0 kGy maintained color, texture, and aroma to give products preferred by taste panelists compared to other conventional treatments such as chlorination and acidification (**Prakash *et al*. 2000 a)**. **Prakash *et al*. (2000 b)** observed a 10% loss in firmness of Romaine lettuce at 0.35 kGy. Irradiation at 0.35 kGy had no effect on color, off-flavor, or appearance. **Magee *et al*. (2003)** found that irradiation up to 1.25 kGy decreased instrumental firmness of diced Roma tomatoes. **Gunes *et al*. (2001)** found irradiation at doses above 0.34 kGy reduced firmness of fresh-cut apples, while **Mahrouz *et al*. (2004)** determined that 0.3 kGy enhanced the organoleptic quality of clementines. **Landgraf *et al*. (2006)** reported that the cubes of mango (*Mangifera indica*) cultivar Tommy Atkins were sensory accepted until Day 4 when exposed to 1 kGy.

Horak *et al*. (2006) reported that the sensorial evaluation of conventional chicory (*Chicorium endive*) and soy sprouts (*Glycine max*), showed a higher general acceptability after irradiation with at least twice the disinfection dose (1.2 and 2 kGy, respectively). **Song *et al*. (2007)** found that immediately after irradiation, the overall sensory scores of the irradiated and non-irradiated carrot and kale juice were not considerably different. However, the sensory quality of the non-irradiated carrot and kale juice decreased with storage time.

According to **Fallah *et al*. (2010)** gamma irradiation had no significant effect on the initial sensory attributes of the irradiated samples of ready-to-cook Iranian barbecued chicken. Moreover, at the end of the storage period of 15 days the irradiated samples were more acceptable than non-irradiated samples. **Badr (2012)** reported that gamma irradiation dose of 3 kGy can be applied to cold smoked salmon without any adverse effects on the chemical or sensory quality attributes of the product. **Kundu and Holley (2013)** reported that irradiation at absorbed doses of $\leq$1 kGy did not affect the overall ratings of beef aroma, off-aroma, tenderness, juiciness, beef flavor, and off-flavor of treated ground beef patties even when made with 100% irradiated beef. Raw, irradiated intact beef muscle pieces were more brown compared to non-irradiated muscles, but displayed less off-aroma after 14 d of storage at 4 °C. **Yun *et al*. (2012)** reported that there was no difference in the sensory scores of the ready-to-eat chicken breast samples, except for off-flavor, which was stronger in samples irradiated at 5 and 40 kGy than control. However, no difference in off-flavor between the irradiated ones was observed. After 10 days of storage, only the samples irradiated at 40 kGy showed higher off- flavor score.

CONSUMER PERCEPTIONS

Food irradiation has been in use for more than 100 years and specific applications of food are approved by national legislations in over 55 countries worldwide. However, the use of this technology is quite limited owing to different environmental and health safety concerns. Extensive research over decades has addressed all related concerns and demonstrated the general safety of this technology **(Farkas and Mohácsi-Farkas, 2011)**. Treatment of foods and agricultural products with ionizing radiations (e.g., gamma rays, X-rays, and electron beams) is increasingly being accepted in Europe as well as Asia Pacific region in order to meet sanitary and phytosanitary requirements in the international trade **(Kume *et al*., 2009; Luckman, 2002)**. Therefore, many countries have recognized irradiation as a useful technology for the reduction of pathogens for public health significance as part of overall good manufacturing practice (GMP) and hazard analysis critical control points (HACCP) systems **(Luckman, 2002)**. In the USA, a mandatory was set to label irradiated food with “Treated with irradiation” or “Treated by irradiation” and is required to use the RADURA-logo at the point of sale **(Ehlermann, 2009)**. However, a few countries allow its optional use; particularly the European Union.

Many surveys and market studies have been carried out to assess consumer attitudes to food irradiation **(Resurreccion *et al*., 1995; Fox, 2002; Wilcock *et al*., 2004)**. Results have consistently shown that many consumers have misconceptions about the technology and believe that it makes food radioactive. A substantial proportion of the public believes that technological progress poses a serious threat to present and future generations **(Slovic *et al*., 1995)**. The general public tends to associate the word “irradiation” with the words “atomic” and “nuclear” **(Stefanova *et al*., 2010)**. Along these lines, research has found that consumer willingness to buy irradiated foods depends on food labelling **(Enneking, 2004; Bond *et al*., 2008)**. Consumers react more positively to labels such as “cold pasteurization” and “electronic pasteurization” to “treated by irradiation” **(Fingerhut *et al*., 2001; Fox, 2002; Fox *et al*., 2002; Frenzen *et al*., 2001).**

However, when consumers are given information about the process and a chance to try irradiated products for themselves they are much more likely to accept the technology. Food irradiation appears to be gaining consumer acceptance in the US, but it is slow to gain support within many parts of Europe, including the UK **(Olsen, 1999).** The studies have consistently shown that many consumers have misconceptions about the technology in the sense that irradiation could make the food radioactive (**Mossel and Drake, 1990).** Interestingly, when consumers were given information on the irradiation process and a chance to try irradiated products, as in market trials, they were much more likely to accept this technology **(Mossel and Drake, 1990).** One of the most successful trials was carried out in 1991 in a small food store in Chicago, where US irradiated strawberries, oranges and grapefruits outsold the non-irradiated fruits by a 9:1ratio. In the following season, irradiated strawberries became the best selling fruit in that store with the ratio expanding to 20:1over the non-irradiated product. This positive experience encouraged approximately 60 stores in Indiana, Illinois and Ohio to sell a variety of irradiated foods **(Mossel and Drake, 1990).** Consumers indicated in focus group discussions that the most important information on food irradiation was the safety and wholesomeness of irradiated food, the effectiveness of the process to destroy bacteria and protect against food borne illness, and the safety endorsement by health authorities (**Bruhn, 1998).** Consumer studies consistently demonstrated that, when provided with scientific information, a high percentage of consumers preferred irradiated foods **(Bruhn, 1995).**

CONCLUSION

Food irradiation is one of the non-thermal methods of food preservation. It is the process of exposing the food, either in package or in bulk, to controlled amounts of ionizing radiation to achieve a purpose such as extension of shelf-life, insect disinfection, the elimination of food-borne pathogens and parasites. Since the radiation source does not come into direct contact with the food material being irradiated, it leaves no chemical residue in the food. It is considered a more effective and appropriate method to enhance food stability and safety, when compared to other processing methods like heat and chemical methods. Also, it does not reduce significantly the nutritional and the sensory quality of food at lower doses.

Irradiation of food is useful for the sterilization of products that are prone to microbial attack, especially for foods that are sold without heat treatment, such as raw poultry, meat, and seafood. It is also useful in slowing ripening of fruit and for inhibiting sprouting of plant products such as potatoes. It has been to reduce toxic and undesirable compounds in food. It has been efficiently used for various food processing operations and modifications of various food constituents.

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