Defence Life Science Journal, Vol. 5, No. 1, January 2020, pp. 54-62, DOI : 10.14429/dlsj.5.14398

REVIEW PAPER

Applications of Food Irradiation Technology

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ABSTRACT

Food irradiation provides an effective means for controlling the physiological processes causing spoilage and for eradication of microbes, insect pests and parasites. Irradiation has multipurpose role in food processing and is applicable for a variety of food commodities such as fruits, vegetables, cereals, pulses, spices, meat, poultry and seafood. Several years of scientific research, evaluation, and testing have resulted in regulatory approvals for the food irradiation technology in a number of countries. Commercial application of this technology has greatly advanced in recent years following the approval of the health authorities of different countries. This review summarises the applications of irradiation technology in controlling pathogens and food spoilage, and the development of irradiation treatment worldwide.

Keywords: Foodborne pathogens; Spoilage microbes; Disinfestation; Sprout inhibition; Delayed ripening

1. INTRODUCTION

Food irradiation is a processing and preservation method involving exposure of food to specified doses of ionising radiation such as gamma rays, electrons, and X-rays in a radiation shielded chamber[1]. Food irradiation includes several processes with the objective to kill or impair the reproduction capacity of undesired living organisms thereby eliminating health risks or to affect the morphology of the product in a beneficial way for extending the shelf life. During irradiation, DNA or RNA in the nuclei of cells is damaged by direct action of the ionising radiation or due to the indirect action of free radicals generated on radiolysis of cellular water[2]. This induces biological and chemical changes that can prevent replication of cells. These biological effects prevent reproduction of microorganisms, insect gametes and plant materials which consequently has various preservative effects depending on the absorbed radiation dose.

Microbial inactivation by ionising radiation depends on the resistance of the contaminating organisms[3,4]. Radiation resistance varies among different species of bacteria, yeast and moulds. Bacterial spores due to their lower moisture content are generally more resistant than vegetative cells and viruses are the most radiation resistant. Effectiveness of ionising radiation is also affected by environmental factors such as temperature, pH, oxygen and solute concentration that influence the formation of radiolytic products during irradiation.

The radiation dose used is determined by the type of food being processed and the effect desired. The optimum radiation dose for processing of a product is a balance between what is needed and what can be tolerated[5]. Also all foods are not appropriate for irradiation due to their sensitivity to radiation. Safety and wholesomeness of irradiated foods for human consumption has been established and endorsed by the International agencies based on the radiological safety, toxicological safety, microbiological safety and nutritional adequacy[1]. Good manufacturing practices are required to be followed by the producers and processors for food irradiation. Irradiation cannot reverse the spoilage process or make bad spoiled food look or taste good. Foods with initial microbial load in the acceptable range can only be irradiated.

Practical applications of food irradiation are divided based on the radiation doses into three categories: low dose applications (up to 1 kGy), medium dose applications (1 kGy to 10 kGy) and high dose applications (above 10 kGy). Low doses 0.02-0.2 kGy are used for sprout inhibition in bulbs and tubers; 0.25-1.0 kGy for delay in fruit ripening and 0.1-1.0 kGy for insect disinfestations and destruction of food borne parasites. Medium dose of 1.0–3.0 kGy are used for reducing spoilage microbes for shelf life extension of meat, poultry and sea foods at refrigeration temperature; 3.0–7.0 kGy for reduction of pathogenic microbes in fresh and frozen meat, poultry and sea foods and 10.0 kGy for reducing the microbial load of spices and herbs to improve hygienic quality. High doses of 25.0-70.0 kGy are used for sterilisation of packaged meat, poultry, and their products that are shelf stable without refrigeration.

2. SPROUT INHIBITION IN VEGETABLE CROPS

Significant losses of vegetable crops like potatoes, onions, garlic, shallots, yam and ginger occurs due to sprouting. However, storage up to several months is necessary to ensure regular supply to the consumers. Sprouting can be inhibited by refrigeration and the pre and postharvest application of various chemicals. Refrigeration for inhibition of sprouting

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Received : 05 April 2019, Revised : 11 November 2019
Accepted : 17 December 2019, Online published : 19 February 2020

is an expensive technique for practical use in the tropical and subtropical regions of the world. Chemical treatment with sprout inhibitors like maleic hydrazide, isopropyl carbamate and chloroisopropyl carbamate is relatively inexpensive and efficient. However, these chemicals leave toxic residues and many countries have prohibited their use[6]. Irradiation is a safe and effective alternative for extending shelf life of potatoes, onion bulbs, yam and other sprouting plant foods[7-9]. A very low radiation dose of 0.2 kGy or less inhibits sprouting, leaves no residues and allows storage at higher temperatures (Fig. 1). The first practical application of irradiation for a fresh food commodity was for potatoes to inhibit sprouting in Canada in 1965[10].

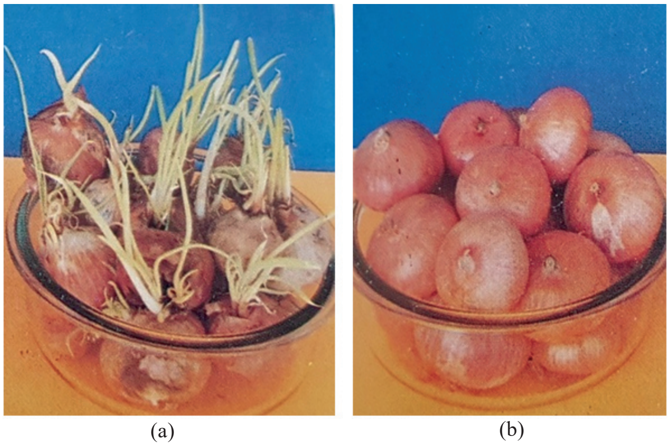
(a) (b)

Figure 1. Sprout inhibition in onion bulbs (a) Unirradiated and (b) Irradiated.

3. DELAYED RIPENING OF FRUITS

Post harvest shelf life of fruits is governed by several factors like rate of respiration, endogenous metabolism, physical injury and spoilage caused by microbes or insects. Post harvest exposure of tropical fruits such as bananas, mangoes and papayas to ionising radiations at doses of 0.25 to 1.0 kGy can delay the ripening and senescence (Fig. 2). Irradiation of fresh fruits can improve the shelf life and prevent the ripening and chilling damage during refrigerated transport[11,12]. The market life of irradiated bananas and mangoes is extended by about 5 to 7 day under ambient conditions. Response of fruits and vegetables to irradiation is dependent on the time of harvest. For delaying ripening in fruits, it is important to irradiate them before ripening starts. Some fresh fruits and vegetables cannot be irradiated due to unacceptable changes in the colour and texture.

4. INSECT DISINFESTATION

A very promising application of irradiation is destruction of insects in cereals, pulses (Fig. 3), flours and their products, nuts, dried fruits and vegetables, dried fish and spices[13]. Infestation by insects and pests cause significant loss of farm produce. Insects, mites and other pests can also be vectors for pathogenic bacteria and parasites[6]. Various fumigants like ethylene dibromide, methyl bromide and phosphine have been used for the control of insects in agricultural products. However, most of the countries have forbidden or severely restricted the use of these pesticides. Irradiation is an effective disinfestation method and prevents losses due to insects during storage of cereals, grains, flour, pulses, coffee beans, dried fishes, dried fruits and dried nuts[14,15]. The radiation dose to control pests at different growth stages is in the range of 100-1000 Gy. Irradiation as a technique for control of insect, was applied commercially for the first time in the early 1957s in the Federal Republic of Germany[10]. Insect disinfestation is the main purpose of irradiation of nuts and dried fruits and vegetables. However, treatment with ionising radiation may also inactivate disease causing microorganisms and inhibit sprouting in nuts. Proper packaging is recommended to prevent insect reinfestation of irradiated products.

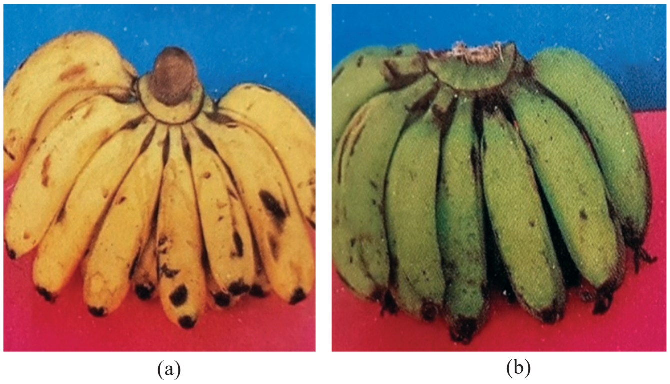
(a) (b)

Figure 2. Delayed ripening of banana (a) Unirradiated and (b) Irradiated.

Figure 3. Insect disinfestation of cereals and pulses.

5. QUARANTINE TREATMENT

Insect pests present in fresh fruits and vegetables create significant barrier in international trade. Quarantine or phytosanitary treatment of imported fruits and vegetables is required to minimise the risk of movement of invasive species in new areas which would harm the crops and environment. Effective quarantine treatment for insect disinfestation that are safe for the commodity and the consumer are needed for allowing unrestricted distribution of fresh fruit and vegetables. A number of chemicals like methyl bromide, phosphine, and hydrogen cyanide used for quarantine treatments have toxic effects. Import of fresh fruits and vegetables treated with certain fumigants has been banned by major importing countries due to health hazards. Thermal treatment of fresh commodities also has limitations. Use of ionising radiation for quarantine treatment is one of the most promising applications[16,17]. Irradiation has broad spectrum activity against quarantined pests of fresh fruits and has no adverse effects on the quality characteristics of the commodity[18]. Irradiation has been accepted as a quarantine treatment against major insects of phytosanitary concerns including fruit flies and weevils. Low doses of up to 1 kGy ionising radiation is effective against arthropod pests of fresh agricultural produce. Irradiation for phytosanitary purpose is a growing use of food irradiation. Disinfestation by radiation can facilitate trade in fresh fruits that often harbour insect pests of quarantine importance. 25,000 t of fresh fruits and vegetables is reported to be irradiated globally in 2015 for phytosanitation[19].

6. ELIMINATION OF MEAT AND FISH PARASITES

Parasites in meat and fish products that are commonly consumed raw or undercooked pose significant health risks. Common parasites are bovine and pork tape warm *Cysticercus* spp; intra cellular protozoan parasite, *Toxoplasma gondii* in beef, mutton and pork. Parasites causing disease such as *Taenia solium* and *Trichinella spiralis* are of significant concern in developing countries. Irradiation at low doses of 0.3 to 1 kGy is an effective method to inactivate parasitic protozoa and helminths in meat and fish (Fig. 4). Irradiation doses approved by US FDA to control *Trichinella spiralis* in pork are 0.3 kGy to 1.0 kGy[20].

Figure 4. Irradiation of fish.

7. EXTENSION OF SHELF LIFE OF FRESH FRUITS AND VEGETABLES

Extension of the very short shelf life of fresh fruits and vegetables is highly desirable. Medium-dose irradiation in combination with refrigeration can considerably prolong the shelf life of many fruits and vegetables. Exposure to a medium dose of radiation can control fungal rot in some fruits thereby extending their shelf life. Shelf life of strawberry can be extended up to 14 days by irradiation (Fig. 5(a)) at a dose of 2 to 3 kGy followed by storage at 10 °C to control spoilage by *Botrytis* mould. However, efficacy of the treatment depends on initial quality of the fresh fruit. Irradiation is reported to be a safe and cost effective method for increasing shelf life of mushrooms. The qualitative and quantitative reduction in the microflora of mushrooms contributes to overall increase in the shelf life of fresh mushrooms[21]. The recommended dose is 1-3 kGy for treatment of fresh mushroom for extension of shelf life. Higher radiation doses of 10-50 kGy is recommended for the decontamination of dried mushrooms used as seasonings[21,22]. Fruit products such as fresh fruit salads and non pasteurised fruit juices have been reported to cause several foodborne outbreaks[23,24]. Irradiation doses applicable for fruit products are limited by their impact on quality. Radiation doses between 1 and 2 kGy can be applied to fruits and vegetables depending on the type of products[25]. Radiation dose of up to 4000 Gy could be applied for some salad vegetables without causing physical-chemical damages and quality loss[26]. Lettuce leaves and some apple fruit varieties are reported to be sensitive to radiation and doses applied should not be more than 600 Gy[27,28]. Irradiation of tomatoes (Fig. 5(b)) at dose of 0.75 to 1.0 kGy was effective in enhancing the shelf life without any changes in quality and sensory attributes[29].

(a) (b)

Figure 5. Irradiation of (a) strawberries and (b) tomatoes for shelf life extension.

8. RADIATION PROCESSING OF MEAT, POULTRY AND SEAFOOD

Irradiation of fresh meat, poultry and seafood can extend shelf life by reduction of microbial load[30]. Irradiation is an effective method for inactivation of pathogenic microorganisms in raw and frozen food (Fig. 6). A number of studies have shown that there is 2 to 5 log reduction of pathogenic and non spore forming bacteria at irradiation dose of 3 kGy[31,32]. Irradiation destroys the spoilage and foodborne pathogens without increase in temperature and enhances the keeping quality and storage life of meat, poultry and seafood.

Raw meats and poultry products are reported to be contaminated with pathogens such as *Campylobacter, Salmonella* and *Escherichia coli* O157:H7 that are normally present in the intestinal tracts[33,34]. Low dose irradiation can inactivate more than 90% of bacteria present in meat. Irradiation in frozen state and atmospheric packaging is used to minimize undesirable organoleptic attributes on irradiation of fresh meats and sea foods. *Escherichia coli* O157:H7 is reported to be a leading pathogenic organism in undercooked hamburgers. Irradiation is an effective method to control *Escherichia coli* O157:H7 in prepackaged meat product such as minced meat, ground beef and hamburgers[35].

Figure 6. Irradiation of seafood.

Microbiological quality of chicken is significantly improved on irradiation at doses of 1 to 2 kGy. Complete elimination of bacterial contaminants was observed on irradiation of boneless chicken breasts fillets[34]. Also no effect of irradiation on color as compared to the non-irradiated samples was observed[34]. Doses of 3-5 kGy are recommended for treatment of frozen poultry and 1.5-2.5 kGy for chilled poultry. Extension in organoleptic quality of fresh chicken by more than 15 days was obtained on irradiation with doses of 2.0 kGy as compared to unirradiated fresh chicken[36]. Cut and deboned poultry products get contaminated with the bacteria during the process of portioning and skinning. Poultry products are usually contaminated with *E. coli, Salmonella* sp*., Listeria monocytogenes*, and *Campylobacter jejuni*[37,38].

Studies have shown that *Yersinia* spp. and *Listeria* spp. were inactivated in fish at irradiation doses of 2 and 3 kGy respectively and were not detected during post-irradiation storage[39]. Fishery products contaminated with *Vibrio parahaemolyticus* is reported to be the leading cause of bacterial gastroenteritis in South-East Asia. *Vibrio parahaemolyticus* in frozen seafoods can be eliminated by irradiation at 1 kGy. *Vibrio vulnificus* in oysters can also be eliminated by irradiation at 1 kGy[40].

Pathogenic microorganisms such as *Salmonella, Vibrio parahaemolyticus* and *Shigella* present in sea foods pose a public health hazard. Raw and inadequately cooked shellfish such as oyster and clams pose significant health risks due to contamination with pathogenic organisms. Irradiation doses up to 4 kGy are required to control pathogens in frozen fishery products such as shrimps and prawns[41].

Irradiation is an effective means of inactivating *Salmonella* and other pathogens in frog legs. Eggs and egg products are also irradiated for elimination of *Salmonella.* Irradiation dose of 2 kGy has been found to be suitable for destruction of *Salmonella* in egg powder without any quality loss.

9. IRRADIATION OF SPICES AND DRIED VEGETABLE SEASONINGS

Spices and vegetable seasonings are the most common food product irradiated commercially for microbial decontamination (Fig. 7). Spices are prone to contamination with microorganisms during harvest, processing and storage. Pathogenic microorganisms like *Salmonella, Escherichia coli, Clostridium perfringens, Bacillus cereus* and toxigenic moulds can be present in contaminated spices[42]. Contaminated spices and dry ingredients are of serious concerns to food processors that can contribute to spoilage of food and diminish microbial safety[43]. Irradiation of spices, herbs and other dried ingredients with doses of 3-10 kGy is established as reliable method for improving microbiological safety[44,45]. A number of studies have shown that irradiation of spices at the dose of 10 kGy can eliminate microbial load without significant organoleptic or chemical alterations[46-48]. Irradiation of turmeric at the dose of 10 kGy does not alter the antioxidant activity and curcumin content[49]. Treatment of spices, herbs, and dried vegetable seasonings with ionising radiation to eliminate microbial contamination is more effective than the thermal treatment, and does not leave any chemical residues like fumigants[50,51]. Irradiation of spices reduces post-harvest losses, ensures hygienic quality, and facilitates trade. Irradiation of spices is practiced on a commercial scale in over 20 countries.

Figure 7. Irradiation of spices for microbial decontamination.

10. REDUCTION OF MICROBIAL LOAD IN READY-TO-EAT FOODS

Irradiation is an effective treatment for improving microbiological safety of ready-to-eat foods. Foodborne pathogenic bacteria like *Escherichia coli* O157:H7, *Salmonella* spp*., Yersinia enterocolitica,Listeria monocytogenes, Staphylococcus aureus* can be destroyed from ready-to-eat food products by irradiation at 2 to 4 kGy[52-53]. Irradiation of these products can be carried out after packaging. Feliciano *et al*[54] reported significant reduction in microbial load of pre-cut fresh fruits and mixed vegetables on irradiation at 1 kGy.

Cheeses are also one of the commonly consumed ready-to-eat foods. The pathogenic and toxin producing microorganisms are *Listeria monocytogenes*, pathogenic *E. coli, Salmonella, Clostridium, Staphylococcus* (mycotoxins), *Brucella* and *Mycobacterium*[55]. Gamma irradiation of Camembert cheese at dose of 2.5 kGy was found to be acceptable[56]. Reduction of *Listeria monocytogenes* inoculated into soft whey cheese was observed at dose of 2-4 kGy gamma radiation[55]. Irradiation of fried-frozen cheese balls at dose of 3 kGy was effective in reduction of microbial load[57].

Odueke *et al*[58] assessed the effects of gamma irradiation on the shelf life of pseudo-dairy food product. The study demonstrated the efficacy of radiation treatment in enhancing the shelf life of food products with no significant change in the physic-chemical properties.

11. STERILISATION OF FOODS

High dose irradiation (>25 kGy) or radappertisation is applied for preparation of shelf-stable ready-to-eat food[59]. Radiation sterilised foods can be stored almost indefinitely at room temperature. The food is heated at 75 °C or higher to inactivate autolytic enzymes to prevent the spoilage during storage without refrigeration. Vacuum packaging of food and irradiation in frozen state at −30 °C or less prevents changes in sensory properties induced by radiation. Radiation sterilised products because of their superior quality and safety are eaten by astronauts in the National Aeronautics and Space Administration (NASA) space shuttle programme. Irradiated food is useful for immuno-compromised patients who are highly susceptible to food borne diseases[60,61]. Immuno-compromised patients are dependent on pasteurised juice, milk, cheese, and well-cooked eggs, poultry, meat, fish to avoid complications due to infectious and foodborne pathogens. Irradiated fruits, vegetables, salads and ready-to-eat meals can be safely consumed by them. Use of food irradiation technology is being expanded for developing ready-to-eat and ready-to-cook foods. Park *et al*[62] studied application of radiation technology for sterilisation of ready-to-cook *Bibimbap* space food. Combined treatment with irradiation was useful to produce ready-to-cook Korean traditional cooked rice mixed with vegetables, mushrooms, ground meat, and seasoned with red pepper paste for the use in space. Radiation-sterilised foods are used in the USA and the United Kingdom for patients undergoing chemotherapy, or organ transplant. Various ready-to-eat foods sterilised by high dose irradiation have been used in South Africa by military personnel, campers, yachters and hikers.

12. COMMERCIAL APPLICATIONS OF FOOD IRRADIATION

Food irradiation has been extensively studied for assuring safety and efficacy of the technology. Internationally recognised bodies like World Health Organisation (WHO), Food and Agriculture Organisation (FAO), International Atomic Energy Agency (IAEA) and Codex Alimentarius have commended irradiation technology for processing of food. China, USA and Ukraine are the leading countries irradiating food. China has more than 200 irradiation facilities. Designed capacity of about 100 irradiators is > 300 kCi and for more than 40 irradiators is > 1000 kCi. 20 new irradiators were established in China during 2006-2010[5]. Most common food products irradiated in China are garlic, chicken legs, spices, and dehydrated seasonings[63]. USA has given clearance for irradiation of spices and dry aromatic ingredients, fresh fruits and vegetables, pork, poultry, red meats, shell eggs, and food enzymes. About 300,000 tons of grains is reported to be disinfested per annum at the grain irradiator in the port of Odessa, Ukraine. Potatoes, onions, wheat and wheat flour, spices and dry ingredients are cleared for irradiation in Canada. Precooked, shelf-stable meat products irradiated at 45 kGy are allowed for retail sale in the Republic of South Africa. The first use of radiation for phytosanitation was by Australia in 2004 for exporting to New Zealand.

The quantity of irradiated foods was 405,000 tonnes in the world in 2005[64]. Treatment of spices and dry vegetables for microbial decontamination accounted for 46%, grains and fruits for disinfection 20%, meat and fish for decontamination 8%, and garlic, potato for inhibition of sprouting 22%. Irradiation of mushroom, honey and health foods comprised 4% of the total irradiated food. About 400,000 tonnes of food was irradiated in 2010 in US, EU and parts of Asia alone[65]. The amount of irradiated foods in the 28 EU member States was 9000 tonnes in 2010 and 5686 tonnes in 2015. Belgium and Netherlands are the leading countries irradiating food and the main commodities irradiated are frog legs and dried aromatic herbs, spices and vegetable seasonings[66]. In Asia, approximately 600000 tonnes of food products were irradiated in 2015[63]. Approximately 60 countries have approved irradiation of about 60 food products[67].

12.1 Commercialisation of Irradiation Technology in India

Irradiation of potatoes, onions and spices were the first food items approved for domestic marketing by health authorities of India in 1994. Further approval was granted in 1998 and 2001 for additional commodities[68]. Classes of food products permitted by the Government of India for radiation processing and the dose limits was published in the Official Gazette of India on August 23, 2016 (Table 1). The Atomic Energy (Control of Irradiation of Food) Rules, 1996 provides the general statutory rules for the authorisation, licencing, approval and guidelines for the operators, radiological safety officer, quality control officer of irradiation facilities for the treatment of foods. Atomic Energy (Radiation Processing of Food and Allied Products) Rules 2012 are the current regulations enforced by Atomic Energy Regulatory Board (AERB) in India.

Multipurpose gamma irradiation facility, Raksha Anusandhan avumVikas Irradiator (RAVI) was established by Defence Research and Development Organisation at Defence Laboratory, Jodhpur in 1994. Technology demonstration plant for radiation processing of spices and dehydrated vegetables was set up at Vashi, Navi Mumbai in 2000 by Department of Atomic Energy. Irradiation plant KRUSHAK for low dose application of sprout inhibition was established in Lasalgaon near Nasik, Maharashtra in 2002. Irradiation was approved for quarantine treatment in 2004. Private entrepreneurs have now set up about 15 irradiation plants in the country for radiation processing of food.

13. CONCLUSIONS

Food irradiation has been applied for agricultural commodities, meat, poultry and seafood for improving the safety and reduction of spoilage losses. The process can be applied to fresh produce or frozen food products with no changes in quality. Radiation is also used for pasteurisation or sterilisation of all classes of food. Elimination or sterilisation

Table 1. Classes of food products allowed for radiation processing by Govt. of India and their absorbed dose limits

Class	Food	Purpose of Treatment	Absorbed dose range (kGy)
Class 1	Bulbs, stem and root tubers, rhizomes	Inhibit sprouting	0.02 – 0.2
Class 2	Fresh fruits and vegetables (other than Class 1)	Delay ripening	0.2 – 1.0
		Insect disinfestation	0.2 – 1.0
		Shelf life extension	1.0 – 2.5
		Quarantine application	0.1 – 1.0
Class 3	Cereals and their milled products, pulses and their milled products, nuts, oil seeds, dried fruits and their products	Insect disinfection	0.25 – 1.0
		Reduction of microbial load	1.5 – 5.0
Class 4	Fish, aquaculture, seafood and their products (fresh or frozen) and crustaceans	Elimination of pathogenic microorganisms	1.0 – 7.0
		Shelf life extension	1.0 – 3.0
		Control of human parasites	0.3 – 2.0
Class 5	Meat and meat products including poultry (fresh and frozen) and eggs	Elimination of pathogenic microorganisms	1.0 – 7.0
		Shelf life extension	1.0 – 3.0
		Control of human parasites	0.3 – 2.0
Class 6	Dry vegetables, seasonings, spices, condiments, dry herbs and their products, tea, coffee, cocoa and plant products	Microbial decontamination	6.0 – 14.0
		Insect disinfestation	0.3 – 1.0
Class 7	Dried foods of animal origin and their products	Insect disinfestation	0.3 – 1.0
		Control of moulds	1.0 – 3.0
		Elimination of pathogenic microorganisms	2.0 – 7.0
Class 8	Ethnic foods, military rations, space foods, ready to-eat, ready-to-cook, minimally processed foods	Quarantine application	0.25 – 1.0
		Reduction of microbial load	2.0 – 10.0
		Sterilisation	5.0 – 25.0

of insect pests by irradiation of fresh fruits and vegetables with negligible impact on quality has important role in facilitating trade between countries. The food irradiation technology also has tremendous potential for supplying fresh and safe food to the Armed forces deployed in remote and far flung locations. Food irradiation is an effective and safe technology with multipurpose role and benefits to the consumers and food industry.

REFERENCES

1. Singh, R. & Singh, A. Food irradiation: An established food processing technology for food safety and security. *Def. Life Sci. J.,* 2019, **4**, 206-13. doi: 10.14429/dlsj.4.14397
2. Farkas, J. Irradiation for better foods. *Trends Food Sci. Technol*., 2006, **17**, 148-52. doi: 10.1016/j.tifs.2005.12.003
3. Singh, R. & Singh, D. Evaluation of radiation resistance of the bacterial contaminants from femoral heads processed for allogeneic transplantation. *Radiat. Phys. Chem.,* 2009*,* **78**, 810-7. doi: 10.1016/j.radphyschem.2009.04.019
4. Singh, R.; Gupta, P.; Purohit, S.; Kumar, P.; Vaijapurkar, S.G. & Chacharkar, M.P. Radiation resistance of the microflora associated with amniotic membranes. *World J. Microbiol. Biotechnol*., 2006, **22**, 23-7. doi: 10.1007/s11274-005-2890-8
5. European Food Safety Authority. Statement summarizing the conclusions and recommendations from the opinions on the safety of irradiation of food adopted by the BIOHAZ and CEF panels. *EFSA J*., 2011, **9**, 2107.
6. Mostafavi, A.H.; Fathollahi, H.; Motamedi, F. & Mirmajlessi, S.M. Food irradiation: Applications, public acceptance and global trade. *Afr. J. Biotechnol*., 2010, **9**, 2826–33.
7. Singh, A.; Rao, S.R.; Singh, R. & Chacharkar, M.P. Identification and dose estimation of irradiated onions by chromosomal studies. *J. Food Sci. Technol.*, 1998**, 35**, 47-50.
8. Singh, R. Effect of medium and post-irradiation storage on rooting of irradiated onions. *J. Food Sci. Technol.,* 2000, **37**, 178-83.
9. Barkai-Golan, R. & Follett, P.A. Sprout inhibition of tubers, bulbs, and roots by ionizing radiation. *In* Irradiation for Quality Improvement, Microbial Safety and Phytosanitation of Fresh Produce, edited by R. Barkai-Golan, & P.A. Follett. Academic Press, Cambridge, UK, 2017. pp. 47-53.
10. Diehl, J.F. Safety of Irradiated Foods. 2nd Edition. Marcel Dekker Inc, New York, USA, 1995. 189 p.
11. Thomas, P & Moy, J.H. Radiation preservation of foods of plant origin. III. Tropical fruits: Bananas, mangoes, and papayas. *CRC Crit. Rev. Food Sci. Nutr.,* 1986, **23**, 147-205. doi: 10.1080/10408398609527423
12. Gloria, M.B.A. & Adao, R.C. Effect of gamma radiation on the ripening and levels of bioactive amines in bananas cv. Prata. *Radiat. Phys. Chem*., 2013, **87**, 97-103.

doi: 10.1016/j.radphyschem.2013.02.032

13. Ahmed, M. Disinfestation of stored grain, pulses, dried fruits and nuts, and other dried foods. *In* Food Irradiation: Principles and Applications, edited by R. Molins. John Wiley & Sons Inc, New York, USA, 2001. pp. 77-112.
14. Azelmat, K.; Sayah, F.; Mouhib, M.; Ghailani, N. & Elgarrouj, D. Effects of gamma irradiation on fourth-instar *Plodia interpunctella* (Hubner) (*Lepidoptera*: Pyralidae). *J. Stored Prod. Res.*, 2005, **41**, 423-31. doi: 10.1016/j.jspr.2004.05.003
15. Boshra, S.A. & Mikhaiel, A.A. Effect of gamma radiation on pupal stage of *Ephestia calidella* (Guenee). *J. Stored Prod. Res*., 2006, **42**, 457-67. doi: 10.1016/j.jspr.2005.09.002
16. Lires, C.M.L.; Docters, A. & Horak, C.I. Evaluation of the quality and shelf life of gamma irradiated blueberries by quarantine purposes. *Radiat. Phys. Chem.*, 2018, **143**, 79-84. doi: 10.1016/j.radphyschem.2017.07.025
17. Gomez-Simuta, Y.; Hernandez, E.; Aceituno-Medina, M.; Liedo, P.; Escobar-Lopez, A.; Montoya , P.; Bravo, B.; Hallman, G.J.; Bustos , E.M. & Toledo, J. Tolerance of mango cv. 'Ataulfo' to irradiation with Co-60 vs. hydrothermal phytosanitary treatment. *Radiat. Phys. Chem.,* 2017, **139**, 27-32. doi: 10.1016/j.radphyschem.2017.05.015
18. Kheshti, N.; Melo, A.A.M.; Cedeno, A.B.; Obenland, D. & Prakash, A. Physiological response of 'Fuji' apples to irradiation and the effect on quality. *Radiat. Phys. Chem*., 2019, **165**, 108389. doi: 10.1016/j.radphyschem.2019.108389
19. Hallman, G.J. & Loaharanu, P. Phytosanitary irradiation – Development and application. *Radiat. Phys. Chem*.**,** 2016, **129**, 39-45. doi: 10.1016/j.radphyschem.2016.08.003
20. Food and Drug Administration. Irradiation in the Production, Processing, and Handling of Food. Fed. Reg. 50, 29658-59. FDA, 1985.
21. Akram, K. & Kwon, J.H. Food irradiation for mushrooms: A review. *J. Korean Soc. Appl. Biol. Chem*., 2010, **53**, 257-65. doi: 10.3839.jksabc.2010.041
22. International Consultative Group on Food Irradiation. Facts about Food Irradiation. ICGFI, Buckinghamshire, United Kingdom. 1999.
23. Lynch, M.F.; Tauxe, R.V. & Hedberg, C.W. The growing burden of foodborne outbreaks due to contaminated fresh produce: Risks and opportunities. *Epidemiol. Infect*., 2009, **137**, 307-15. doi: 10.1017/S0950268808001969
24. Vojdani, J.D.; Beuchat, L.R. & Tauxe, R.V. Juice-associated outbreaks of human illness in the United States, 1995 through 2005. *J. Food Protect*., 2008, **71**, 356-64. doi: 10.4315/0362-028X-71.2.356
25. Arvanitoyannis, I.S.; Stratakos, A.C. & Tsarouhas, P. Irradiation applications in vegetables and fruits: A review. *Crit. Rev. Food Sci. Nutr.*, 2009, **49**, 427-462. doi: 10.1080/10408390802067936
26. Nunes, T,P.; Martins, C.G.; Behrens, J.H.; Souza, K.L.O.; Genovese, M.I.; Destro, M.T. & Landgraf, M. Radioresistance of *Salmonella* species and *Listeria monocytogenes* on minimally processed arugula (*Eruca sativa* Mill.): Effect of irradiation on flavonoid content and acceptability of irradiated produce. *J. Agric. Food Chem*., 2008, **56**,1264-8. doi: 10.1021/jf072873j
27. Dionísio, A.P.; Gomes, R.T. & Oetterer, M. Ionizing radiation effects on food vitamins – A review. *Braz. Arch. Biol. Technol*., 2009, **52**, 1267-78. doi: 10.1590/S1516-89132009000500026
28. Niemira, B.A.; Sommers, C.H. & Fan, X. Suspending lettuce type influences recoverability and radiation sensitivity of *Escherichia coli* O157:H7. *J. Food Protect*., 2002, **65**, 1388-93. doi: 10.4315/0362-028X-65.9.1388
29. Singh, A.; Singh, D. & Singh, R. Shelf life extension of tomatoes by gamma radiation. *Radiat. Sci. Technol*., 2016, **2**, 17-24. doi: 10.11648/j.rst.20160202.12
30. O'Bryan, C.A.; Crandall, P.G.; Ricke, S.C. & Olson, D.G. Impact of irradiation on the safety and quality of poultry and meat products: A review. *Crit. Rev. Food Sci. Nutr.*, 2008, **48**, 442-57. doi: 10.1080/10408390701425698
31. Kudra, L.L.; Sebranek, J.G.; Dickson, J.S.; Mendonca, A.F.; Zhang, Q.; Jackson-Davis, A. & Prusa, K.J. Control of Salmonella enterica Typhimurium in chicken breast meat by irradiation combined with modified atmosphere packaging. *J. Food Prot.,* 2011, **74**, 1833-9. doi: 10.4315/0362-028X.JFP-11-195
32. Lim, S.; Jung, J. & Kim, D. The effect of gamma radiation on the expression of the virulence genes of *Salmonella typhimurium* and *Vibrio* spp. *Radiat. Phys. Chem*., 2007, **76**, 1763-6. doi: 10.1016/j.radphyschem.2007.02.098
33. Mead, P.S.; Slutsker, L.; Dietz, V.; McCaig, L.F.; Bresee, J.S.; Shapiro, C.; Griffin, P.M. & Tauxe R.V. Food-related illness and death in the United States. *Emerg. Infect. Dis*., 1999, **5**, 607–25. doi: 10.3201/eid0505.990502
34. Lewis, S.J.; Velasquez, A.; Cuppett, S.L. & McKee, S.R. Effect of electron beam irradiation on poultry meat safety and quality. *Poultry Sci.*, 2002, **81**, 896-903. doi: 10.1093/ps/81.6.896
35. Thayer, D.W. & Boyd, G. Elimination of Escherichia coli O157:H7 in meats by gamma irradiation. *Appl. Environ. Microbiol.*, 1993, **59**, 1030–4. PMID: 8476281
36. Balamatsia, C.C.; Rogga, K.; Badeka, A.; Kontominas, M.G. & Savvaidis, I.N. Effect of low-dose radiation on microbiological, chemical, and sensory characteristics of chicken meat stored aerobically at 4 degrees C. *J. Food Prot*., 2006, **69**, 1126-33. doi: 10.4315/0362-028x-69.5.1126
37. Anang, D.M.; Rusul, G.; Bakar, J. & Ling, F.H. Effects of lactic acid and lauricidin on the survival of *Listeria*

monocytogenes, Salmonella enteritidis and *Escherichia coil* O157:H7 in chicken breast stored at 4^0 C. *Food Control*, 2007, **18**, 961-9.
doi: 10.1016/j.foodcont.2006.05.015

38. Hong, Y.; Ku, K.; Kim, M.; Won, M.; Chung, K. & Song, K.B. Survival of *Escherichia coli* O157:H7 and *Salmonella typhimurium* inoculated on chicken by aqueous chlorine dioxide treatment. *J. Microbiol. Biotechnol*., 2008, **18**, 742-5.
39. Arvanitoyannis, I.S.; Stratakos, A. & Mente, E. Impact of irradiation on fish and seafood shelf life: A comprehensive review of applications and irradiation detection. Crit. Rev. Food Sci. Nutr., 2008, 49, 68-112.
doi: 10.1080/10408390701764278
40. Mallett, J.C.; Beghiam, L.E.; Metcalf, T.G. & Kaylor, J.D. Potential of irradiation technology for improved shell fish sanitation. *J. Food Safety*, 1991, **11**, 231-45.
doi: 10.1111/j.1745-4565.1991.tb00055.x
41. Ito, H.; Adulyatham, P.; Sangthong, N. & Ishigaki, I. Effect of gamma irradiation on frozen shrimps to reduce microbial contamination. *Radiat. Phys. Chem*., 1989, **34**, 1009-11.
42. Thanushree, M.P.; Sailendri, D.; Yoha, K.S.; Moses, J.A. and Anandharamakrishnan, C. Mycotoxin contamination in food: An exposition on spices. *Trends Food Sci. Technol*., 2019, **93**, 69-80.
doi: 10.1016/j.tifs.2019.08.010
43. Farkas, J. Irradiation as a method for decontaminating food - A review. *Int. J. Food Microbiol*., 1998, **44**, 189-204.
doi: 10.1016/S0168-1605(98)00132-9
44. Farkas, J. Irradiation of Dry Food Ingredients. CRC Press Inc, Boca Raton, Florida, 1988. 153 p.
45. Gryczka, U.; Migdal, W. & Bulka, S. The effectiveness of the microbiological radiation decontamination process of agricultural products with the use of low energy electron beam. *Radiat. Phys. Chem.*, 2018, **143**, 59-62.
doi: 10.1016/j.radphyschem.2017.09.020
46. Singh, R. & Tak, B.B. Effect of gamma irradiation on microbial contamination and volatile oils of spices. *In* Proceedings of the NAARRI Annual Conference on Industrial Applications of Radioisotopes and Radiation Technology, Mumbai, 1997. pp. 50-1.
47. Singh, R.; Kumar, P.; Tak, B.B. & Chacharkar, M.P. Microbiological changes in gamma irradiated spices. *Indian J. Microbiol.*, 2002, **42**, 29-34.
48. Esmaeili, S.; Barzegar, M., Sahari, M.A. & Berengi-Ardestani, S. Effect of gamma irradiation under various atmospheres of packaging on the microbial and physicochemical properties of turmeric powder. *Radiat. Phys. Chem*., 2018, **148**, 60-7.
doi: 10.1016/j.radphyschem.2018.02.028
49. Almeida, M.C.; Sampaio, G.R.; Bastos, D.H.M. & Villavicencio, A.L.C.H. Effect of gamma radiation on turmeric: Antioxidant activity and curcumin content. *Radiat. Phys. Chem*., 2018, **152**, 12-6.
doi: 10.1016/j.radphyschem.2018.07.008
50. Loaharanu, P. Food irradiation in developing countries: A practical alternative, *IAEA Bull*., 1994**, 1**, 30-5.
51. Olson, D.G. Irradiation of food: Scientific status summary. *J. Food Technol*., 1998, **52**, 56-62.
52. Sommers, C.H. & Boyd, G. Variations in the radiation sensitivity of foodborne pathogens associated with complex ready-to-eat food products. *Radiat. Phys. Chem.,* 2006, **75**, 773- 8.
doi: 10.1016/j.radphyschem.2005.12.036
53. Zhu, M.J.; Mendonca, A.; Ismail, H.A. & Ahn, D.U. Fate of Listeria monocytogenes in ready-to-eat turkey breast rolls formulated with antimicrobials following electron-beam irradiation. Poult. Sci. 2009, 88, 205-13.
doi: 10.3382/ps.2007-00386
54. Feliciano, C.P.; de Guzman, Z.M.; Tolentino, L.M.M.; Asaad, C.O.; Cobar, M.L.C.; Abrera, G.B.; Baldos, D.T. & Diano, G.T. Microbiological quality of brown rice, ready-to-eat pre-cut fresh fruits, and mixed vegetables irradiated for immuno-compromised patients. *Radiat. Phys. Chem.*, 2017, **130**, 397-9.
doi: 10.1016/j.radphyschem.2016.09.030
55. Tsiotsias, A.; Savvaidis, I.; Vassila, A.; Kontominas, M. & Kotzekidou, R. Control of *Listeria monocytogenes* by low-dose irradiation in combination with refrigeration in the soft whey cheese' Anthotyros'. *Food Microbiol.*, 2002, **19,** 117-26.
doi: 10.1006/fmic.2001.0469
56. Scientific Committee on Food. Revision of the Opinion of the Scientific Committee on Food on the Irradiation of Food. European Commission Health and Consumer Protection Directorate General, SCF/CS/NF/IRR/24. SCF, 2003.
57. Lee, J.W.; Kim, J.H.; Kim, J.H.; Oh, S.H.; Seo, J.H.; Kim, C.J.; Cheong, S.H. & Byun, M.W. Application of gamma irradiation for the microbiological safety of fried-frozen cheese ball. *J. Korean Soc. Food Sci. Nutr.*, 2005, **34**, 729-33.
doi: 10.3746/jkfn.2005.34.5.729
58. Odueke, O.B.; Chadd, S.A.; Baines, R.N.; Farag, K.W. & Jansson, J. Effects of gamma irradiation on the shelf-life of a dairy-like product. *Radiat. Phys. Chem.*, 2018, **143**, 63-71.
doi: 10.1016/j.radphyschem.2017.09.013
59. Placek, V.; Svobodova, V.; Bartonicek, B.; Rosmus, J. & Camra, M. Shelf-stable food through high dose irradiation. *Radiat. Phys. Chem.,* 2004, **71**, 515-8.
doi: 10.1016/j.radphyschem.2004.03.075
60. Mohacsi-Farkas**, C.** Food irradiation: Special solutions for the immuno-compromised. *Radiat. Phys. Chem.***,** 2016, **129,** 58-60.
doi:10.1016/j.radphyschem.2016.06.033
61. Feliciano**,** C.P**.** High-dose irradiated food: Current progress, applications, and prospects. *Radiat. Phys. Chem*., 2018, **144**, 34-6.
doi: 10.1016/j.radphyschem.2017.11.010
62. Park, J.N.; Song, B.S.; Kim, J.H.; Choi, J.; Sung, N.Y.; Han, I.J. & Lee, J.W. Sterilization of ready-to-cook *Bibimbap* by combined treatment with gamma irradiation for space food. *Radiat. Phys. Chem*., 2012, **81**, 1125-7.

doi: 10.1016/j.radphyschem.2012.02.042

63. Eustice, R.F. Global status and commercial applications of food irradiation. *In* Food Irradiation Technologies: Concepts, Applications and Outcomes, edited by Isabel CFR Ferreira, Amilcar L. Antonio & Sandra Cabo Verde. Royal Society of Chemistry, Cambridge, UK, 2018. pp. 397-424.
64. Kume, T., Furuta, M., Todoriki, S., Uenoyama, N. & Kobayashi, Y. Status of food irradiation in the world. *Radiat. Phys. Chem*., 2009, **78**, 222–6.
    doi: 10.1016/j.radphyschem.2008.09.009
65. Kume, T. & Todoriki, S. Food irradiation in Asia, the European Union, and the United States: A status update. *Radioisotopes,* 2013, **62**, 291–9.
    doi: 10.3769/radioisotopes.62.291
66. European Commission. Report from the Commission to the European Parliament and Council on Food and Food Ingredients treated with ionizing radiation for the year 2015. COM (2016) 738 Final. EC, 2016.
67. Roberts, P.B. Food irradiation: Standards, regulations and world-wide trade. *Radiat. Phys. Chem*., 2016, **129**, 30-4.
    doi: 10.1016/j.radphyschem.2016.06.005
68. Sharma, A. & Madhusoodanan, P. Techno-commercial aspects of food irradiation in India. *Radiat. Phys. Chem*., 2012, **81**, 1208-10.
    doi: 10.1016/j.radphyschem.2011.11.033

ACKNOWLEDGEMENTS

Authors are grateful to Director, Defence Laboratory, Jodhpur for the support to research activities in the field of food irradiation.

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