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Food Irradiation: An Established Food Processing Technology for Food Safety and Security

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ABSTRACT

Food irradiation is a well-established and effective technology for food processing and preservation. The technology aids in reducing food losses and ensuring food safety by elimination of pathogens and parasites causing illness and death. Radiation treatment can be applied to agricultural produce and animal food products to get extended shelf life with improved microbiological safety and quality. Irradiating food can greatly reduce illness from foodborne pathogens thereby preventing morbidity and mortality. Various national and international food and health organisations have endorsed and supported the safety of food and foodstuffs subjected to ionising radiation based on the research and testing data of more than 50 years. A review is presented on the historical developments of food irradiation technology, radiation sources for treatment of food and, the safety and wholesomeness of foods processed by ionising radiation.

Keywords: Food irradiation; Gamma radiation; Wholesomeness; Nutritional adequacy

1. INTRODUCTION

Advanced agro-animal technologies have resulted in increased food production. However, about 25 per cent of agricultural produce is lost worldwide due to damage by insects, microbes and physiological spoilage. Significant losses of food occur due to microbial contamination and pest infestation during post-harvest storage, transportation and marketing. Sprouting is the major cause of losses of vegetable crops like tubers and bulbs. Use of contaminated ingredients and raw materials are also responsible for spoilage and wastage of food[1].

Contamination of food with pathogenic and parasitic organisms is also an important cause of human suffering. One of the leading causes of death worldwide is reported due to the contamination of foods with pathogenic non-spore forming bacteria, parasitic helminths and protozoa[1,2]. Food safety is a global concern causing hospitalisations, deaths, patient-related costs for treatment and reduced economic productivity[3].

Significant losses of food due to infestation, microbes, spoilage and the safety concerns regarding foodborne diseases has resulted in increased interest in food preservation technologies. A number of food processing techniques have been explored to control spoilage and ensure safety of the food. Pasteurisation, canning, freezing, refrigeration and chemical preservatives are the common food processing techniques in use. Novel technologies that can keep foods fresher, with higher nutritional value, with minimum food additives and no toxins or allergens are emerging[4,5]. These non-thermal food processing techniques include pulse electric field processing, oscillating magnetic fields, high pressure processing, high power ultrasound waves and irradiation[6].

The technology of food irradiation is increasingly gaining acceptance around the world and can supplement or replace some of the traditional food processing methods. Food irradiation is the application of ionising radiation to food for improving safety and increasing storage and distribution life. The process consists of exposing the food material in bulk or packaged form to specific doses of ionising radiation for achieving certain beneficial effects[7]. The technology has multipurpose role and can be effectively used for treatment of agricultural commodities[8,9] and animal food such as meat, poultry and seafood[10,11]. Recent applications include high-dose irradiated specialty food for immunocompromised patients[12].

Interest in radiation technology has been due to persistent losses of food by infestation, spoilage by bacteria and fungi, rising concern about foodborne diseases and strict import standards of quarantine for international trade in food products. Ionising radiation as a means of food preservation and effectiveness of irradiation treatment in controlling the growth of food spoilage and pathogenic microbes is established. Food irradiation technology addresses both food quality and safety by inactivating the parasites, reducing spoilage microbes, eliminating foodborne pathogenic microorganisms, delaying the ripening of fruits, inhibiting sprouting in bulbs and tubers, and controlling the post-harvest losses caused by insect infestation. Scientific data and recommendations from different agencies have established food irradiation as a safe and effective technology for reduction of food losses and foodborne illness.

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2. HISTORY OF FOOD IRRADIATION

The concept of preservation of food by ionising irradiation was speculated immediately following the discovery of radioactivity in 1895 by Henri Becquerel[13]. The idea of employing ionising radiation for destruction of pathogens and spoilage microbes in food was reported in a German Medical Journal. This was followed by other studies and patents. Patent was issued in the United Kingdom in 1906 for irradiating particulate food in a flowing bed using radioactive isotopes[14]. In 1918, US patent was issued for the food preservation using X-rays. The importance of X-rays for killing of insects, eggs, larvae in the tobacco leaves and for elimination of *Trichinella* from pork was studied. However, the process of using X-rays for irradiation of pork was feasible only after the development of accelerated electron technology. French first patent on food irradiation was issued in 1930.

Food irradiation technology got recognition in US during the World War II. Irradiated food was first used for the US Army in 1943. Research on food irradiation was commenced in early 1950's. Experiments were conducted at the US Army Natick Soldier Systems Center (NATICK) for irradiation of military rations[15]. Cobalt source 1.3 MCi (megacurie) and electron linear accelerator 18 kW (kilowatt) were acquired by the US Army Natick Laboratories, Massachusetts. Application of high dose radiation for development of sterilised meat products for substituting canned or frozen military ration was studied. National Research programs on irradiation of food were simultaneously undertaken in Canada, France, Netherlands, Poland, Russia, Belgium, Germany and United Kingdom. Research on low dose pasteurisation was carried out at Low Temperature Research Station Programme of UK[16].

Irradiated food for human consumption was first cleared in 1958 by the Soviet Union. Clearance was granted for irradiation of potatoes to inhibit sprouting and a year later, irradiation of grains for insect infestation was approved. The first commercial food irradiation was started in 1958. Accelerated electrons produced by a Van de Graaff electron accelerator was used by a spice manufacturer in Stuttgart, Germany. In Canada, irradiation was first approved in 1960 for inhibition of sprouting in potatoes. The irradiation plant using a Co-60 source was installed by Newfield Products Ltd. at Mont St. Hillaire, near Montreal for processing of potatoes. Further clearance was granted by Canada for irradiation of onions in 1965. Approval for irradiation of foods was granted in the USA in 1963 by the FDA for wheat and wheat products. Construction of the first irradiator dedicated for food processing in the USA began in 1990[17]. Spices, tubers, onions, frog legs and seafood were among the first foods irradiated for sale at retail[13].

A major landmark in the history of food irradiation is the recommendation of the Joint Food and Agriculture Organisation (FAO), World Health Organisation (WHO), and International Atomic Energy Agency (IAEA) Expert Committee on Food Irradiation (JECFI) in 1980 about the safety of food irradiated with an overall dose of up to 10 kGy. FAO/IAEA/WHO Joint Study Group on High-Dose Irradiation in 1997 recommended no upper dose limit for food irradiation. Industrial exploitation of radiation processing of food was limited due to the availability of suitable radiation source. Radiation source suitable for food irradiation application have become available with the development of nuclear technologies and food irradiation has become a standard technology today. Presently irradiation of one or more food or food products has been permitted by almost sixty countries[18].

3. FOOD IRRADIATION PROCESS

3.1 Radiation Sources

Food irradiation is the process of exposing food to radiant energy from specified radiation source. Radiations that do not penetrate deep enough into the irradiated matter or can make the irradiation material radioactive are not suitable for irradiation of foods. Codex General Standard for Irradiated Foods has specified the radiation sources appropriate for irradiation of foods. There are three source of ionising radiation that can be used for treatment of food: Gamma rays produced from the radioisotopes cobalt-60 (^{60}Co) and cesium-137 (^{137}Cs), X-rays generated from machine sources operated at or below an energy level of 5 MeV and electron beams generated from machine sources operated at or below an energy level of 10 MeV[19]. These recommended radiation sources have low energies that do not induce radioactivity in food or packaging materials. Also, these types of radiation sources are available in quantities and at costs suitable for commercial applications[20].

Neutron bombardment of cobalt-59 pellet in a nuclear reactor generates Cobalt-60, and cesium-137 is generated during the fission of uranium. Cobalt-60 and cesium-137 emit highly penetrating gamma radiations that can be used to treat food.

Electron beams and X-ray generated from machines are operated by electricity and does not involve any radioactive substance in the whole processing system. Accelerating electron beams that travel up to the speed of light are produced using linear accelerators. Limited penetrating power of high energy electron beams makes them suitable only for foods of relatively shallow depth. Electron beam is characterised by its low penetration and is best used for processing of food in thin packages and free flowing grains. Foodborne pathogens on the surface of the slices can be effectively inactivated by electron beam radiation[21]. Electron beam technology has also been used for treatment of fresh produce for elimination of pathogens[22]. X-rays with varying energies are generated by machines and are the least commonly used source for food irradiation. Penetration of X-rays is deeper than accelerated electrons, but shallower than gamma rays.

The effect of irradiation on food depends on the absorbed dose which is determined by the strength of the source and the exposure time. The irradiation dose is measured using a unit called the Gray (Gy). In terms of energy relationships, one gray equals one joule of energy absorbed per kilogram of food being irradiated[23].

3.2 Irradiation Facilities

Commercial food irradiation facilities basically consist of an irradiation chamber and a system for transportation of the food material into the irradiation chamber. Shielding of concrete about 1.5 m to 1.8 m thick surrounds the irradiation chamber to ensure protection from radiant energy. The transport system is a conveyor similar to that used in irradiation facilities for sterilisation.

Gamma radiation for food processing is limited to radionuclides ^{60}Co and ^{137}Cs. Gamma rays with energies of 1.17 MeV and 1.33 MeV are emitted by the cobalt-60 and energy of 0.66 MeV is emitted by cesium-137. Half-life of Co-60 is around 5.3 years and Cs-137 has a longer half-life of around 30.1 years. Majority of the commercial facilities use Co-60 as a gamma radiation source[23]. Gamma irradiation is suitable for treating large or bulk packages of food as it has high penetrating ability.

Electron beams is produced from machines by acceleration of a stream of electrons. Distinct advantage of electron beam compared to gamma radiation is that it does not involve any radioactive material and can be switched off when not required. X-rays are generated by machines when accelerated electrons beam bombards a metallic target. The efficiency of conversion to X-rays is very low and this has hindered the use in the commercial food irradiation facilities.

4. SAFETY AND WHOLESOMENESS OF IRRADIATED FOODS

Safety and wholesomeness is one of the most important aspects of any food processing technology. Food irradiation is the controlled process of treating foods with ionising radiation to attain the benefits similar to other processing technologies such as heat, refrigeration, dehydration, freezing, or chemical treatment[24]. Radiation enhances the shelf life and microbiological quality of food by reduction and elimination of microbial contaminants. However, the development of food irradiation technology was hindered with the myth of food becoming radioactive, generation of toxic compounds and the concern of the consumers regarding excessive nutrient denaturation[25]. Both the activists and consumers have questioned the nutritional value of the irradiated foods. Food irradiation has been studied extensively to examine the concern about safety of food for human consumption. Animal and human studies have provided clear evidence that processing food with ionising radiation is safe and wholesome[13,26]. Expert Groups and International Agencies have evaluated and endorsed the safety of irradiated food. Safety and wholesomeness of irradiated foods for consumption involve four aspects: radiological safety, toxicological safety, microbiological safety, and nutritional adequacy.

4.1 Recommendations from Expert Groups and International Agencies

The international bodies including Food and Agriculture Organisation (FAO), World Health Organisation (WHO), International Atomic Energy Agency (IAEA) and Codex Alimentarius Commission (CAC) have reviewed the studies on food irradiation for verification of the safety of irradiated food products. The Joint Expert Committee of the FAO, WHO and IAEA stated in its conclusions in 1980 that the irradiation of any food commodity up to an overall average dose of 10 kGy presents no toxicological hazard; hence, toxicological testing of foods so treated is no longer required. The Committee considered that the irradiation of food up to an overall average dose of 10 kGy introduces no special nutritional or microbiological problems. Codex General Standard for Irradiated Foods was published in 1983 by the Codex Alimentarius Committee in collaboration with FAO and WHO[27]. A joint FAO/IAEA/WHO Study Group on High-Dose Irradiation concluded in 1999 that food treated with irradiation at any dose required for achieving the desired technological effect is safe and nutritionally adequate[28]. Codex General Standard for Irradiated Foods was revised reflecting acceptability of food treated at any high dose as long as it is palatable[19]. European Food Safety Authority[29] and US Food and Drug Administration[30] have also endorsed the safety and nutritional adequacy of irradiated foods.

4.2 Radiological Safety of Irradiated Foods

Food irradiation is a controlled and regulated process using defined radiation sources and energy levels. The maximum energy of gamma radiation emitted by the commonly used radioactive sources ^{60}Co is 1.33 MeV and ^{137}Cs is 0.66 MeV. These sources are not energetic enough to induce radioactivity in the constituent elements of food. The maximum allowable energies for machine-generated sources of radiation that can be used for food irradiation are 10 million electron volts (MeV) for electrons and 5 MeV for X-rays.

There is a considerable safety margin between these approved energy levels and those capable of inducing measurable radioactivity. Ionising radiation at high energy levels can make certain constituents of food radioactive[31]. Short-lived radioactive isotopes have been detected in foods irradiated with 14 MeV electrons, and radioactive isotopes with half-lives of hours or days when electron energies of higher than 20 MeV are used. X-rays have higher efficiency in induction of radioactivity as compared to electrons of the same energy. Induced radioactivity is therefore not an issue in foods exposed to with maximum permissible energy. Secondly, it is not possible for the food to become contaminated with radioactive material. During the process of irradiation, the food passes through a field of radiation and does not come in contact with the source of radiation.

A number of studies have demonstrated the radiological safety of irradiated food. Irradiation of food to doses up to 60 kGy with cobalt-60 or cesium-137 gamma rays, 10 MeV electrons and 5 MeV X-rays was observed to cause insignificant changes in the background radiation. Irradiation of ground beef and beef ashes with X-rays generated from 7.5 MeV electrons showed lower radioactivity as compared to present in natural food. The study showed that there is no risk from consumption of food irradiated with X-rays generated by electrons of energy as high as 7.5 MeV[32]. The radiological safety of chicken meat treated with 7.5 MeV X-rays to doses of 30 kGy was evaluated by Song[33], *et al*. Gamma-ray spectrometric patterns were recorded and no radioactivity was detected suggesting safety for human consumption in terms of radiology.

4.3 Toxicological Safety of Irradiated Foods

A number of toxicological studies have been conducted since the 1950s to evaluate possible toxicological effects of consuming irradiated foods. Subchronic studies, chronic studies, reproductive studies and mutagenicity tests were carried out in rats, mice, dogs, monkey, hamsters and pigs. FAO, IAEA and WHO convened a number of Joint Expert Committees on the Wholesomeness of Irradiated Foods in 1964, 1969, 1976 and 1980 to assess all possible toxicological effects of irradiated foods. Results of toxicological studies were reviewed by the Joint FAO/IAEA/WHO Expert Committee on the Wholesomeness of Irradiated Food (JECFI) and in 1980, it was concluded that the use of ionising radiation at an average overall dose of 10 kGy did not adversely impact the safety of the treated foods[34]. Lack of teratogenicity, mutagenicity, and toxicity due to intake of irradiated foods was confirmed from multigenerational feeding studies in mammals[35]. International Project in the Field of Food Irradiation (IFIP) conducted a large number of animal feeding studies during 1970 to 1982. More than 70 report on feeding studies have demonstrated no adverse effects of irradiation. A study group meeting of WHO, FAO and IAEA was organised in 1997 to assess high dose irradiation for treatment of food. The group concluded that doses greater than 10 kGy "will not lead to changes in the composition of the food that, from a toxicological point of view, would have an adverse effect on human health".

The most comprehensive study on toxicological testing was conducted at Raltech Laboratory, USA which involved feeding of test animals with chicken meat treated with radiation. The lack of treatment related effects confirm that there is no hazard with the consumption of irradiated food. Several animal feeding studies have been conducted in different countries including India, China, Germany, Denmark, France, Japan, Thailand, the United Kingdom and the USA using various types of irradiated food. These studies have clearly established no toxicity as a result of the consumption of irradiated food. Besides feeding tests using laboratory animals, few human clinical studies have also been conducted. These short term studies have shown no clinical abnormalities attributed to the irradiated diet in the subjects[36]. Short and multigenerational feeding studies have provided no evidence of toxicity in mammals with the consumption of food treated with radiation[37]. Several generations of animals fed with diets irradiated with doses of 25 kGy to 50 kGy have also shown no mutagenic, teratogenic and oncogenic ill effect[38]. The toxicological safety of irradiated food is also supported by several recent studies. Sub-chronic toxicity tested in mice fed with irradiated chicken meat showed no toxicological effects[33].

Radiolytic changes in food have also generated some concerns about the safety of irradiated foods. Glucose, acetaldehyde, carbon dioxide and formic acid are the radiolytic products produced in irradiated food and are also formed during thermal treatment. No toxicity of these products formed on irradiation has been observed. Fat-containing food generates 2-alkylcyclobutanones (2-ACBs) due to radiation induced breakage of triglycerides on irradiation[39,40]. Radiolytic products produced from lipids including saturated and unsaturated hydrocarbons, aldehydes, and 2-alkylcyclobutanones are toxicologically not significant in the quantities found in irradiated foods[41,42].

4.4 Microbiological Safety of Irradiated Foods

Food is irradiated to extend the shelf life of food and to reduce or eliminate illness caused by pathogens. Reduction or destruction of spoilage and pathogenic microorganisms present in food is the aim of food irradiation from the microbiological point of view. Most applications of irradiation at recommended doses of below 10 kGy do not completely kill the microbial contamination in the food. However, microbial load is significantly reduced at these doses. Certain concerns regarding microbiological safety of the irradiated food have been expressed. These issues are possibility of selective killing and differential growth of microorganisms in irradiated foods, induction of mutation by irradiation and enhanced mycotoxin production.

Differential growth is possible with irradiation when doses are not sufficient for complete destruction of microbial contamination. Theoretically spoilage microorganisms may be destroyed on irradiation which would result in unchecked growth of pathogenic microorganisms. Studies were conducted to examine the effect on the quantitative and qualitative microbial contamination in food and during storage. The probability of reduction in competing microorganisms by irradiation may help the proliferation of pathogenic microorganisms has been examined by several workers. It has been observed that no preferential growth of pathogenic bacteria occurs due to the absence of spoilage microbes[43].

The effect of irradiation on survival depends on the type of microbial species and food. This problem of selective killing and preferential growth of microorganisms in food is not unique to irradiation. All non-sterilising treatments favour the survival and growth of certain microorganisms. Low temperature favours the growth of *Listeria* and *Yersinia,* vacuum packing of anaerobic species and salting of halophilic species, while the growth of many other organisms is suppressed. It has also been hypothesised that irradiated foods would support the growth of foodborne pathogens[44]. Studies in chicken contaminated with Salmonellae and ground beef contaminated with *Escherichia coli* O157:H7 showed no differences in bacterial growth rates in non-irradiated and irradiated meats. The results suggested that the growth parameters of pathogenic bacteria are not normally influenced by the indigenous microflora in these products[45].

Issue of mutation in microbial strains with higher pathogenicity, virulence and resistance due to radiation has been addressed. Induction of mutation in microbial populations can occur on exposure to repeated cycles of radiation[46]. However, no situation is conceivable under industrial conditions where a microbial population would be repeatedly exposed to sub lethal radiation[47]. Studies with radiation sources and at irradiators have shown no induction of radiation resistant mutant strains[48]. Also, there are no incidences of development of pathogenic strains due to irradiation of food[34,49]. Irradiation also does not result in increased threat of mycotoxin production in irradiated food[50]. In summary, food irradiation is similar to other processing technologies used for microbial reduction of food and causes no specific microbiological concerns.

4.5 Nutritional Adequacy of Irradiated Foods

Nutritive value of foods treated with ionising radiation is essentially unchanged and that ingestion of irradiated foods is safe has been demonstrated by the multigenerational animal studies[35,51]. Macronutrients carbohydrates, protein and fats are not significantly changed on irradiation[34,52]. Main radiolytic products formed on gamma-irradiation of starches from maize, wheat, rice or potatoes are the aldehydes, formic acid and hydrogen peroxide[53]. Malonaldehyde was produced on gamma irradiation of fructose, glucose, sucrose and starch solution. Reducing the presence of oxygen and low temperature decreased the accumulation of aldehydes formed on irradiation of fruit juices[54,55]. Starch content of brown rice was not significantly altered by gamma radiation at doses of 5 kGy or 10 kGy[56]. Modifications in mono and polysaccharides by thermal treatment are reported to be more as compared to irradiation[57].

The irradiation of proteins causes changes like dissociation, aggregation, cross-linking, oxidation depending on the state, structure, composition, and the physical status. Cystine, methionine and tryptophan were observed to be stable at higher doses of 71 kGy[58]. Electron-beam irradiation of processed haddock fillets at a dose of 53 kGy did not affect the essential amino acids[59]. Various studies on irradiation of meat at commercial doses of 2-7 kGy have demonstrated no significant effect on the nutritional value of proteins or amino acids. Long-term feeding studies on irradiated meat, shrimp and chicken have shown no reduction in the protein nutritional value[60]. Irradiation at low and medium doses result in conversion of proteins in food into amino acids and protein parts with lower molecular weight, and the chemical reactions are less as compared to steam heat sterilisation[61].

The irradiation of lipids at high doses in oxygen rich environment can lead to the formation of liquid hydroperoxides. The oxidation products formed on irradiation of lipids often have undesirable odours and flavour[62]. The extent of lipid oxidation is dependent on the irradiation dose[63]. Meat irradiation at low radiation doses has shown that lipids are not sensitive to radiation-induced peroxidation due to the presence of natural protectors. No significant loss of nutritional value is observed when lipids are irradiated to doses applicable under commercial food processing. Freezing and removal of oxygen during irradiation results in significant reduction of lipid oxidation due to free radicals[53].

Certain vitamins can be affected by irradiation as with other food processing methods like drying and canning. There are no significant changes in vitamins at low and medium doses due to the primary effects of radiation. Free radicals generated on irradiation can influence the antioxidant properties of vitamins[53]. Water soluble vitamin, thiamine is relatively sensitive to radiation and losses can occur on irradiation treatment. Some vitamins such as folic acid, pantothenic acid, riboflavin, niacin, pyridoxine, biotin are usually stable and Vitamin A, Vitamin B-1 (thiamine), Vitamin C, Vitamin E, Vitamin K have higher sensitivity to radiation. A number of studies have shown that vitamin losses in the food are similar with high doses of gamma radiation, e-beam or heat sterilisation[29,64]. Irradiation also does not affect the nutritional value of minerals and trace elements.

Based on published data and deliberations of international expert committees, it has been concluded that the composition and nutritional quality of the food is not significantly changed on irradiation. Changes in vitamins on irradiation are similar to other food preservation methods. Foods treated with ionising radiation are safe and nutritionally adequate.

5. ADVANTAGES OF FOOD IRRADIATION

Food irradiation is beneficial to the consumers and the food industry by improving microbiological quality of food and extending the shelf life. The technology provides an alternative to the toxic chemicals used for fumigation of food and food ingredients that are prohibited for health and environmental safety reasons. Irradiation is a cold process as the effects can be achieved without any significant temperature changes in the food. Food irradiation can be used for treatment of packaged commodities. Irradiation after packaging prevents post irradiation contamination or infestation of the treated product. Irradiation is also effective in inactivating pathogenic microorganisms in frozen food. Irradiation is an efficient, cost effective method and offers distinct advantages over other food processing technologies.

6. CONCLUSIONS

Food irradiation is an important innovation in food preservation proven as wholesome and toxicologically safe. It has remained as an underutilised technology due to the concerns to consume food treated with radiation. Extensive research and testing carried out on irradiation processing of food has established the technical superiority and safety of the technology. Food irradiation offers several benefits and alternative to chemicals affecting the environment and human health. The technology is now in use worldwide for many commodities and is gaining acceptance from the food industry and the consumer. Irradiation processing technology can play an effective role in meeting the challenges of food safety issues and postharvest losses.

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