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An Overview of the Principles and Effects of Irradiation on Food Processing & Preservation

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Abstract

When food irradiation is carried out under Good Manufacturing Practice conditions, is commended as an effective, widely applicable food processing method judged to be safe on extensive available evidence, that can reduce the risk of food poisoning, control food spoilage and extend the shelf-life of foods without detriment to health and with minimal effect on nutritional or sensory quality. This view has been endorsed by international bodies such as the World Health Organisation(WHO), the Food and Agricultural Organisation (FAO) and Codex Alimentarius. Food irradiation is the processing of food products by ionising radiation in order to control foodborne pathogens, reduce microbial load and insect infestation, inhibit the germination of root crops, and extend the durable life of perishable produce. The use of irradiation has been approved for about 50 different types of food and at least 33 countries are using the technology commercially. Despite the fact that irradiation has been used for decades for food disinfection that satisfies quarantine requirements in trade, health concerns over the consumption of irradiated food continue to attract attention. This study reviewed the basic principles, applications and the associated potential health risk, if any, posed to consumers as a result of consumption of irradiated food. Review of the available evidence showed that although irradiation processing leads to chemical changes and nutrient losses, the safety and nutrient quality of irradiated foods are comparable to foods that have been treated with other conventional food processing methods such as heating, pasteurisation and canning when the technology is used as recommended and good manufacturing practices are followed.

Keywords: *Chemical Changes, Food Irradiation, Food Processing And Preservation, Shelf-Life, Spoilage*

1.0 Introduction

There are many processing methods have been developed to help prevent food spoilage and improve safety. The traditional methods of preservation, such as drying, smoking and salting have been supplemented with pasteurisation (by heat), canning (commercial sterilisation by heat), refrigeration, freezing and chemical preservatives. Food irradiation is another technology that can be added to the list. It is not new; interest was shown in Germany in 1896 and it began in the early 1920s, while in the 1950/60s the US Army Natick Soldier Center (NATICK) experimented with both low dose and high dose irradiation for military rations (Steward, 2004(a)). In the UK, at the same time, the Low Temperature Research Station programme concentrated on low dose pasteurisation (Hannan, 1955). Irradiation is extensively used in the medical field for sterilising instruments, dressings etc.

Food irradiation is the processing of food products by ionising radiation in order to control foodborne pathogens, reduce microbial load and insect infestation, inhibit the germination of root crops, and extend the durable life of perishable produce (International Consultative Group, 1991).

Food irradiation is perhaps the single most studied food processing technology for toxicological safety in the history of food preservation. Studies pertaining to the safety and nutritional adequacy of irradiated foods date back to the 1950s and were frequently associated with the use of radiation to sterilize foods. Hundreds of short-term and long-term safety studies led to the approval of one or more foods for irradiation by presently more than sixty countries. These studies are thoroughly reviewed in *The Safety and Nutritional Adequacy of Irradiated Foods*, published by the World Health Organization (WHO 1994). The international symbol showing irradiated food is called Radura, showed below.

Fig 1: The 'Radura', the international symbol for irradiated food. In the center is an agricultural product, a food, which is in a closed package denoted by the circle, and which is irradiated by penetrating rays.

According to the International Atomic Energy Agency (IAEA), more than 50 countries have approved the use of irradiation for about 50 different types of food, and 33 are using the technology commercially. The positive list of irradiated products varies between countries but is often limited to spices, herbs, seasonings, some fresh or dried fruits and vegetables, seafood, meat and meat products, poultry and egg products. Despite the fact that irradiation has been used for decades for food disinfection and satisfying quarantine requirements in trade, there is considerable debate on the issue of health concerns over the consumption of irradiated food. These include concerns over the toxicity of the chemicals generated and the change in nutritional quality of food products after irradiation. Below is the facility used for irradiation.

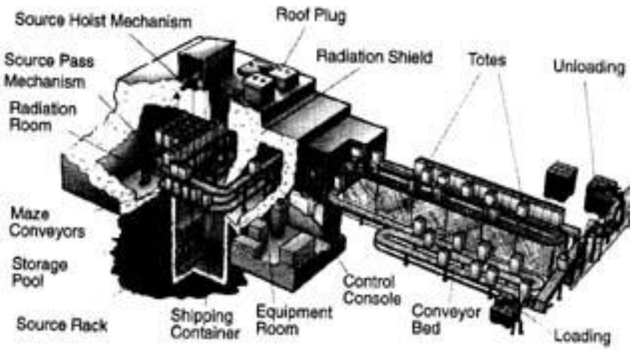

Fig. 2: Typical food irradiation facility (courtesy Nordian International, Ontario, Canada)

2.0 Principles of Food Irradiation

Foods such as poultry are processed, packaged with oxygen-permeable film, and transported fresh or frozen to an irradiation facility. Currently the only commercial poultry irradiation facility approved by the U.S. Department of Agriculture (USDA) is Food Technology Services, Inc., in Mulberry, Florida. At the irradiation facility, the palletized product is transferred by conveyor to an irradiation chamber. The food is exposed to gamma rays from a radioactive source such as cobalt60 (main source for gamma processing of foods) or cesium137 at a controlled rate. The gamma rays evenly penetrate the food product, killing harmful microorganisms, parasites, or insects without altering the nature of the food. These rays do not remain in the food (Roberts et al., 1995).

Gamma rays are more powerful than the rays emitted by a microwave oven. Rays from a microwave oven cause food to heat rapidly, whereas gamma rays, with much shorter wavelengths and higher frequencies, penetrate through the food so rapidly that no heat is produced. After food is irradiated, it is stored and may be transported back to the processing plant for further handling and packaging. Once the food has been irradiated, it must be handled appropriately to prevent recontamination (Roberts et al., 1995).

The irradiation cell (source) consists of cobalt60 or cesium137 rods in stainless steel tubes. These tubes are stored in water and raised into a concrete irradiation chamber to dose the food. Over a period of years the cobalt60 or cesium137 rods slowly decay to non-radioactive nickel and non-radioactive barium, respectively. No radioactive waste is produced at a food irradiation facility, and no irradiation facility could have a meltdown that could jeopardize the safety and health of plant workers and other citizens of a community. Food irradiation facilities do not have nuclear reactors. The food is exposed only to the degrading of the cobalt60 or the cesium137 (Roberts et al., 1995).

Foods may be irradiated with electron beams produced from accelerators. This method of irradiation can only be used on foods less than 4 inches thick because of the limited penetrating capacity of the electron beams. This method would be very effective on food such as hamburger patties.

Table1: Irradiation Conversion Units

1,000,000	1 megarad (Mrad)
1 gray (Gy)	100 rads
1 kilgray (kGy)	100,000rads
1kGy	100 kilorads (krads)
1kGy	0.1Mrad
10kGy	1Mrad

The irradiation dose applied to a food product is measured in terms of kilograys (kGy) (Table 1). One kilogray is equivalent to 1,000 grays (Gy), 0.1 megarad (Mrad), or 100,000 rads. The basic unit is the gray, which is the amount of irradiation energy that 1 kilogram of food receives. The amount of irradiation applied to a food product is carefully controlled and monitored by plant quality control personnel and USDA inspectors. The irradiation dose applied to a food product will depend upon the composition of the food, the degree of perishability, and the potential to harbor harmful microorganisms. The amount of radiation that a food product absorbs is measured by a dosimeter (Roberts et al., 1995).

2.1 Ionising radiation and their sources

According to the Codex General Standard for Irradiated Foods, ionising radiations recommended for use in food processing are: (I) gamma rays produced from the radioisotopes cobalt-60 (^{60}Co) and cesium-137 (^{137}Cs), and (II) machine sources generated electron beams (maximum level of 10 MeV) and X-ray (maximum level of 5 MeV) (CAC,2003).

(I) Gamma rays produced from radioisotopes cobalt-60 and cesium-137

Cobalt-60 is produced in a nuclear reactor via neutron bombardment of highly refined cobalt-59 (^{59}Co) pellets, while cesium-137 is produced as a result of uranium fission. Both cobalt-60 and cesium-137 emit highly penetrating gamma rays that can be used to treat food in bulk or in its final packaging. Cobalt-60 is, at present, the radioisotope most extensively employed for gamma irradiation of food (Steward, 2001).

(II) Electron beams and X-ray generated from machine sources

A major advantage of machine-sourced ionising radiation is that no radioactive substance is involved in the whole processing system. Powered by electricity, electron-beam machines use linear accelerators to produce accelerating electron beams to near the speed of light. The high-energy electron beams have limited penetration power and are suitable only for foods of relatively shallow depth (Steward, 2001). Electron beams can be converted into various energies of X-rays by the bombardment with a metallic target. Although X-rays have been shown to be more penetrating than gamma rays from cobalt-60 and cesium-137, the efficiency of conversion from electrons to X-rays is generally less than 10% and this has hindered the use of machine sourced radiation so far (ICGFI, 1999).

3.0 Some Effects of Food Irradiation

3.1 Effect of irradiation on lipids

In response to the continuously growing role of irradiation in food preservation, several reviews and research studies have been published on the irradiation of foods of both animal and plant origin over the past years (Arvanitoyannis et al., 2009; Arvanitoyannis et al., 2010). The application of ionizing radiation results in the radiolysis of water, which is present in most foods such as meat and fish products. This triggers the development of species such as OH−, hydrated electron and H+, which can then induce several chemical reactions with food constituents. Studies show that the quantity of radiolysis products varies as a function of fat content and fat composition, as well as with the temperature during the irradiation process and the actual dose of radiation used (Merrit et al., 1979). When fatty acids are exposed to high-energy radiation they undergo preferential cleavage in the ester-carbonyl region giving rise to certain radiolytic compounds that are specific for each fatty acid (Nawar et al., 1996). The strong oxidizer ozone is produced from oxygen during food irradiation and can promote the oxidization of lipids and myoglobin (Venugopal et al., 1999).

Many research studies have been carried out in recent years on meat and fish irradiation and its impact on lipids. Experiments carried out on chicken revealed no significant difference in total saturated and unsaturated fatty acids between irradiated (1, 3, 6 kGy) and non-irradiated frozen (−20°C) chicken muscle (Rady et al., 1987). Other studies showed that e-beam irradiation (2.5 kGy) seemed to increase the levels of thiobarbituric acid-reactive substances (TBARS) in ground beef, but the difference between irradiated and non-irradiated samples was not statistically significant (Nam et al.,2003). The results of Yilmaz and Gecgel (2007) showed that irradiation in ground beef induced the formation of trans fatty acids. However, the ratio of total unsaturated fatty acids to total saturated fatty acids was 0.85, 0.86, 0.87, and 0.89 in irradiated ground beef samples (1, 3, 5, and 7 kGy, respectively) whereas for the control samples it was 0.85. Fish lipids are more unsaturated than lipids in red meats and therefore are more susceptible to oxidation (Khayat et al., 1983). An examination of the effect of irradiation at 10 kGy on the linoleic and linolenic acid contents of grass prawns found that irradiation resulted in 16% decrease in linoleic acid content, whereas linolenic acid was not affected significantly (Hau et al., 1993). In the case of Spanish mackerel, C16:0 and C16:1 fatty acids decreased when irradiated at 1.5 to 10 kGy. (Al-Kahtani et al., 1996). No changes were reported in the fatty acid composition of two species of Australian marine fish irradiated at doses up to 6.0 kGy and the levels of fatty acids in oil remained stable in the irradiated fish samples whereas they decreased in non-irradiated fish (Armstrong et al., 1994). The extent of lipid oxidation was dependent on the irradiation dose. An analysis of the literature concluded that when lipids are irradiated under conditions which are met in commercial food processing (≤7 kGy), there is no significant loss of nutritional value (Thomas, 1988).

3.2 Effect of irradiation on proteins and amino acids

Damage caused to protein by ionizing radiation includes deamination, decarboxylation (Diehl, 1990), reduction of disulfide linkages, oxidation of sulfydryl groups, cleavage of peptide bonds and changes of valency states of the coordinated metal ions in enzymes (Delincee, 1983). Other studies indicated that there was no significant destruction of cystine, methionine and tryptophan up to a dose of 71 kGy (Josephson et al., 1978). The majority of amino acids in minced lean beef or pork and chicken breast muscle are stable up to a dose of 5 kGy (Partmann et al., 19790. Irradiation does not generally affect the stability of amino acids and proteins in situ. The stability to irradiation at 2 to 45 kGy of tryptophan of shrimp muscle was measured after storage under different temperature and moisture conditions. The results revealed that the loss of tryptophan was small under all the conditions applied (Antunes et al., 1977). Essential amino acids were not affected in electron- beam processed (53 kGy) haddock fillets (Lagunas, 1995). Data obtained from the literature indicate that irradiation of meat at commercial doses (2–7 kGy) has no significant effect on the nutritional value of proteins or amino acids (Thayer, 1987).

3.3 Effect of irradiation on vitamins

Many authors have studied the effect of irradiation on the stability of vitamins in foods (Liu et al., 1991). No loss of riboflavin is found in pork chops and chicken breasts irradiated at temperatures between −200°C and 200°C at doses up to 6.6 kGy. Some irradiated samples even exhibited an increase in riboflavin concentration of up to 25% (Kilcast, 1994). Pork chops irradiated at different temperatures with doses up to 5 kGy displayed no loss in niacin. A loss of 15% was observed with a dose of 7 kGy when irradiation was applied at 0°C (Fox et al., 1989). Furthermore, in the case of pantothenic acid, it has been shown that there is no loss in many foods irradiated at doses of ≥10 kGy (Thayer et al., 1991). The application of gamma irradiation (1, 2, and 6 kGy) on fillets of Black Bream (Acanthopagrus australis) and Redfish (Centroberyx affinis) resulted in vitamin E loss but this could not be correlated with the treatment dosage. All irradiated fillets were found to have vitamin E muscle contents above the levels considered to be desirable for human consumption (Armstrong et al., 1994). No loss of vitamin B12 was observed in haddock fillets irradiated up to 25 kGy. Similarly, there was no loss of niacin in cod irradiated at 1 kGy (Murray, 1981). Irradiation of shrimps at 2.5 kGy induced a 15% loss of riboflavin in air, 8% in vacuum, and 20% in nitrogen (Diehl, 1995).

3.4 Effect of irradiation on organoleptic characteristics

Textural alterations and development of off-flavors are not considered a problem with irradiation at doses lower than 2 kGy. Any sensory changes at lower radiation doses are similar to those associated with thermal processing (Urbain, 1986). It was found that e-beam irradiated (0 or 4.5 kGy) raw pork patties produced more volatiles than did non-irradiated patties, and the proportion of volatiles varied with the irradiation conditions (Ahn et al.,1998). Irradiation produced many unidentified volatiles that could be responsible for the off-odor in irradiated raw meat. The results of an experienced testing panel showed that there was no significant differences in odor and taste between irradiated (4 kGy) and non-irradiated ground beef patties (23% fat) during 7 days of storage at 4°C (Giroux et al., 2001) . Irradiation at 2.5 kGy extended the shelf life of carp, but at doses above 2.5 kGy, the cooked meat had an unacceptable odor and flavor. Other studies showed that the color of brook char (Salvelinius fontinalis) was affected negatively by irradiation and the effect was more pronounced with 3 kGy than with 1 kGy treatment (Paradis et al., 1996). However, the flavor of fish was not affected by irradiation.

There are several methods that can be employed in order to decrease such detrimental effects of irradiation. These include oxygen exclusion, the replacement of oxygen with inert gases, the addition of protective agents such as antioxidants, and post-irradiation storage to allow the flavor to return to near-normal levels (Brewer, 2009).

3.5 Effect of irradiation on microorganisms

A large amount of data is available on the sensitivity of microorganisms to irradiation processing; this varies greatly from micro-organism to micro-organism and is also dependent on other extrinsic factors. Vegetative cells are less resistant to irradiation than spores, whereas moulds have a susceptibility to irradiation similar to that of vegetative cells. However some fungi can be as resistant as bacterial spores (Farkas, 2006). Compared to bacteria, viruses generally require higher radiation doses for inactivation (Crawford et al., 1996). Studies have shown that irradiation doses of 2 and 3 kGy destroyed Yersinia spp. and Listeria spp., respectively, with the microorganisms being undetectable during storage of irradiated fish (Montgomery et al., 2003). Irradiation (1, 2, and 3 kGy) significantly improved the microbiological quality of the chicken by reducing the total bacterial count (TBC), with the decrease in TBC being dose-dependent. In all the irradiated samples, no fecal coliforms were detected (Kanatt et al., 2005).

4.0 Factors affecting the efficacy of Food Irradiation

The efficacy of ionising radiation for micro-organism inactivation depends mainly on the dose of use and the level of resistance of the contaminating organisms. Radiation resistance varies widely among different species of bacteria, yeast and moulds. Bacterial spores are general more resistant than vegetables cells, which is at least partly due to their lower moisture content. Yeast is as resistant as the radiation-tolerant bacterial strains. Viruses are highly radiation resistant (Joint FAO/IAEA/WHO Study Group, 1999). Other factors such as temperature, pH, presence of oxygen and solute concentration have also been shown to correlate with the amount of radiolytic products formed during irradiation which in turn affect the ultimate effectiveness of ionizing radiation (Stewart, 2001).

5.0 Safety of Irradiated Food

5.1 Radiological safety

Irradiation process involves passing the food through a radiation field at a set speed to control the amount of energy or dose absorbed by the food. Under controlled conditions, the food itself should never come into direct contact with the radiation source (US Environmental Protection Agency, 2007)

At high energy levels, ionising radiation can make certain constituents of food become radioactive (WHO, 1988). Studies showed that induced radioactivity was detected in ground beef or beef ashes irradiated with X-rays produced by 7.5 MeV electrons. However, the induced activity was found to be significantly lower than the natural radioactivity in food. Corresponding annual dose is several orders of magnitude lower than the environmental background. The risk to individuals from intake of food irradiated with X-rays generated by electrons with nominal energy as high as 7.5 MeV is trivial (Gregoire et al., 2003).

Studies carried out by IAEA showed that increase in radiation background dose from consumption of food irradiated to an average dose below 60kGy with gamma-rays from cobalt-60 or cesium-137, with 10 MeV electrons, or with X-rays produced by electron beams with energy below 5 MeV are insignificant, and best characterized as zero (IAEA, 2002).

Based on the experimental findings of WHO, FAO and IAEA, Codex has set out the maximum absorbed dose delivered to a food should not exceed 10kGy and the energy level of X-rays and electrons generated from machine sources operated at or below 5 MeV and 10 MeV respectively, in part, to prevent induced radioactivity in the irradiated food (IAEA, 2007).

5.2Microbiological safety

Two concerns that have been raised regarding the irradiation of microorganisms present in food are the effect of the reduction in the natural microflora on surviving pathogens and the potential for the development of radiation resistant mutants.

Ionising radiation significantly reduces the populations of indigenous microflora in foods. There is concern that these “clean” foods would allow a more rapid outgrowth of bacteria of public health concern, since the lower populations of indigenous microflora would have less of an antagonistic effect on the pathogenic bacteria (Jay, 1995). It has also been hypothesised that irradiated foods would be more amenable to the growth of foodborne pathogens if the food was contaminated after irradiation (Dickson, 2001). However, studies in irradiated chicken and ground beef has illustrated that the growth rates of either salmonellae (chicken and beef) or *Escherichia coli* O157:H7 (beef) were the same in both nonirradiated and irradiated meats suggesting that the indigenous microflora in these products does not normally influence the growth parameters of these bacteria (Szczawiska et al., 1991;Dickson et al., 1999).

The concern with radiation mutations is significant because ionising radiation has been known for years to induce mutations (Muller, 1928). Induction of radiation-resistant microbial populations occurs when cultures are experimentally exposed to repeated cycles of radiation (Davis et al., 1973). Mutations developed in bacteria and other organisms can result in greater, less, or similar levels of virulence or pathogenicity from parent organisms. Although it remains a theoretical risk, there was no report of the induction of novel pathogens attributable to food irradiation (Ingram et al.,1977; Joint FAO/IAEA/WHO Study Group, 1981). Bacteria that undergo radiation-induced mutations are more susceptible to environmental stresses, so that a radiation-resistant mutant would be more sensitive to heating than would its nonradiation-resistant parent strain (Joint FAO/IAEA/WHO Study Group, 1999; Joint FAO/IAEA/WHO Study Group, 1981).

5.3 Toxicological safety

5.3.1Toxicity studies in animals

The possible toxicological effects of consuming irradiated foods have been extensively studied since the 1950s (Olson, 1998). Feeding trails involved a variety of laboratory diets and food components given to human and different species of animals including rats, mice, dogs, quails, hamsters, chickens, pigs and monkeys have been conducted to assess the toxicological safety of irradiated foods (Joint FAO/IAEA/WHO Study Group, 1999)

Animal feeding trails conducted included lifetime and multi-generation studies to determine if any changes in growth, blood chemistry, histopathology, or reproduction occurred that might be attributable to consumption of different types of irradiated foods. Data from many of these studies were evaluated by the Joint FAO/IAEA/WHO Expert Committee on the Wholesomeness of Irradiated Food (JECFI). In 1980, JEFCI concluded that “Irradiation of any food commodity up to an overall average dose of 10 kGy introduces no toxicological hazard; hence, toxicological testing of food so treated is no longer required” (Joint FAO/IAEA/WHO Study Group, 1981). The safety of irradiated food was also supported by recent study with laboratory diets that had been sterilised by irradiation. Several generations of animals fed diets irradiated with doses ranging from 25 to 50 kGy, which is considerably higher than dose used for human foods, suffered no mutagenic, teratogenic and oncogenic ill effect attributed to the consumption of irradiated diet (Kava, 2007).

5.3.2 Human clinical studies

There have been relatively few trails performed on humans, the majority being carried out by the US Army. The subjects were assessed by clinical examination and for cardiac performance, haematological, hepatic and renal function. All studies have been short term. No clinical abnormalities were discovered up to one year following the trials (Fielding, 2007).

One of the best known human feeding trails is that performed in 1975 where 15 malnourished children in India were fed a diet containing irradiated wheat at dose of 0.75 kGy. Increase in the frequency of polyploidy and number of abnormal cells were observed during the course of the trial. When the irradiated diet was discontinued, the abnormal cells reverted to a basal level. The author attributed these observations to the consumption of the irradiated food (Bhaskaram et al., 1975). However, when the report was examined more closely, it was found that only 100 cells from each of the five children in each group were counted. The sample number was too small upon which to base any conclusion (ICGFI, 1999).

A number of concerns regarding the impact of irradiated food on health have been raised. Among these was the criticism of the design and execution of a number of *in vitro* studies into toxicological safety. These studies used food juices, extracts and digests in mutagenic studies using cells of mammalian, bacterial and vegetable origin and largely produced negative effects. Some possible chromosome changes and cytotoxic effects were reported but, as food contains many compounds that may interfere with the tests, the result were not deem significant (Ashley et al., 2004) There was also concern that when the WHO published its report on the wholesomeness of foods irradiated at doses of above 10 kGy, five peer reviewed publications, all of which were feeding trails reporting toxicological effects of irradiated food, were disregarded (Joint FAO/IAEA/WHO Study Group, 1981). It also has been pointed out that all the animal studies were of much too short duration to demonstrate carcinogenicity of irradiated food, which usually takes several decades (Tritsch, 2000).

5.3.4 Chemical toxicological studies

The presence of several compounds, most notably 2-alkylcyclobutanones and furan has generated some concerns about the safety of irradiated foods.

2-Alkylcyclobutanones

Irradiation of fat-containing food generates a family of molecules, namely 2-alkycyclobutanones (2-ACBs), that result from the radiation induced breakage of triglycerides (LeTellier et al., 1972).The 2-ACBs have been found exclusively in irradiated fat-containing food, and have until now never been detected in non-irradiated foods treated by other food processes (Crone et al., 19993; Ndiaye et al., 1999). Thus, these compounds were considered to be unique markers for food irradiation. In irradiated foods, level of 2-ACBs generated is proportional to the fat content and absorbed dose (Hartwig et al., 2007). Depending on the dose absorbed, the concentration of 2-ACBs in irradiated food ranged from 0.2 to 2µg/g of fat (Marchioni et al., 2004).

Previous study feeding rats daily with a solution of highly pure solution of 2-ACBs and injected with a known carcinogen azoxymethane (AOM) showed that the total number of tumours in the colon was threefold higher in the 2-ACB-treated rats than in the AOM controls six months after injection. Medium and larger tumours were detected only in animals treated with 2-ACB and AOM. This demonstrated that 2-ACBs found exclusively in irradiated dietary fats may promote colon carcinogenesis in animals treated with a chemical carcinogen. It does also suggest that the 2-ACBs alone does not initiate colon carcinogenesis. However, it is worth noting that the amount of 2-ACBs consumed was much higher in this study than that a human would consume in a diet containing irradiated food.

Conclusion

Food irradiation preserves meat, produce, and seasonings with high-energy gamma rays to improve product safety and shelf life. Spices, seasonings, potatoes, fresh fruits and vegetables, and meats and poultry may be irradiated. This method of preservation prevents growth of food poisoning bacteria, destroys parasites, and delays ripening of fruits and vegetables.Food irradiation has been endorsed by FAO, WHO, USDA, the American Medical Association (AMA), and the Institute of Food Technologists (IFT) as a safe and practical method for preserving a variety of foods and reducing the risk of foodborne disease. International imports and exports of fresh foods could be expanded, increasing the abundance of food worldwide. Food irradiation makes food safer to eat, improves quality, and extends shelf life.

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