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The Potential of Food Irradiation: Benefits and Limitations

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1. Introduction

Preservation of food has been a major anxiety of man over the centuries. Contamination with microorganisms and pests causes considerable losses of foods during storage, transportation and marketing (15% for cereals, 20% for fish and dairy products and up to 40% for fruits and vegetables). Particularly, pathogenic bacteria are an important cause of human suffering and one of the most significant public health problems all over the world. The World Health Organization (WHO) stated, the infectious and parasitic diseases represented the most frequent cause of death worldwide (35%), the majority of which happened in developing countries in 1992 (Loaharanu, 1994). Numerous processing techniques have been developed to control food spoilage and raise safety. The traditional methods have been supplemented with pasteurization (by heat), canning, freezing, refrigeration and chemical preservatives (Agrios, 2005). Another technology that can be added to this list is irradiation. Food irradiation is the process of exposing amount of energy in the form of speed particles or rays for improving food safety, eliminating and reducing organisms that destroy the food products. This is a very mild treatment, because a radiation dose of 1 kGy represents the absorption of just enough energy to increase the temperature of the product by 0.36°C. It means that, heating, drying and cooking cause higher nutritional losses. Moreover, heterocyclic ring compounds and carcinogenic aromatic produced during thermal processing of food at high temperatures were not identified in irradiated foods (Tomlins, 2008). More than one century of research has gone into the understanding of the effective use of irradiation as a safety method. It has been repeatedly considered and judged suitable on available evidence. The international bodies including the Food and Agriculture Organization (FAO), the International Atomic Energy Agency (IAEA), WHO and Codex Alimentarius Commission (CAC) investigate projects on food irradiation to verify the safety and quality of different irradiated products. It has shown that irradiation used on alone or in combination with other methods could improve the microbiological safety and extend shelf-

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life (IAEA, 2009). Furthermore, people are very confused to distinguish irradiated foods from radioactive foods. At no time during the irradiation process does the food come into contact with the radiation source and, it is not possible to induce radioactivity in the food by using gamma rays or electron beams up to 10 MeV (Farkas, 2004). The differences in chemical and physical structure of organisms, environmental factors, moisture content, temperature during irradiation, presence or absence of oxygen and in their ability to recover from the radiation injury cause the distinctions in their sensitivity to radiation. According to long-term animal feeding studies, radiation-pasteurized or sterilized foods are safe and nutritious also for humans (Thayer & Boyd, 1999). Irradiation is used for a variety of reasons, such as disinfesting food, reducing or eliminating food borne pathogens, shelf life extending and may serve as a quarantine treatment for many fruits, vegetables, nuts, cut flowers and animal origin products to facilitating international trade of foods (Marcotte, 2005). But, not all foods are appropriate for irradiation. For instance, some fruits (such as cucumbers, grapes, and some tomatoes) are sensitive to radiation. Nowadays, over 60 countries use irradiation for one or more food products. But, the misconceptions and irrational fear of nuclear technologies mostly caused the lack of acceptance of food irradiation. It should be noted that if irradiated products offer clear advantages, and the science-based information on the process is readily available, consumers would be ready to accept more irradiated products.

2. Effects of Ionizing radiation

Irradiation can be effect direct, caused by reactive oxygen-centred (•OH) radicals originating from the radiolysis of water or indirect on organisms and food products. An indirect effect (the damage to the nucleic acids) occurs when radiation ionizes a neighboring molecule, which in turn reacts with the genetic material. Since, water is a major component of most foods and microbes; it is often ends up producing a lethal product (Hallman, 2001). The optimum dose is a balance between that what is needed and that what can be tolerated by the products (European Food Safety Authority [EFSA], 2011).

2.1 Effects on bio-organisms (microorganisms and insects) and viruses

The biological effects caused by irradiation are primarily the result of disruption of the DNA or RNA in the nuclei of cells. Since, the DNA is much larger than the other molecular structures and very long ladder twisted into a double helix in a cell, if it becomes injured, by either primary ionizing or through secondary free radical attack, the induced biological and chemical changes can prevent replication and destroy cells (Scott Smith & Suresh, 2004; The Institute of Food Science and Technology [IFST], 2006). Therefore microorganisms, insect gametes, and plant meristems are prevented from their reproduction, which consequently results in various preservative effects as a function of the absorbed radiation dose (Scott Smith & Suresh, 2004).

Since, the size of the DNA molecule generally increases with the complexity of an organism, viruses are more radiation resistant than other organisms (Koopmans & Duizer, 2004). Viruses do not grow in food directly, but can contaminate host bacteria (Deeley, 2002). Poliomyelitis viruses and infectious hepatitis can be transmitted by means of infected raw milk and shellfish (DeWit et al., 2003; Frankhauser et al., 2002). More studies showed that

the combination of irradiation with heating can be used successfully to inactivation of viruses (Koopmans & Duizer, 2004).

The spore-forming bacteria are resistant to irradiation and other treatments. Doses used below 10 kGy may only give a 2-3 $\log_{10}$ reduction in spore numbers, and this is not sufficient to foods shelf-life (Patterson et al., 2006). Yeasts are more radiation resistance than molds and vegetative bacteria. So, they are important in the spoilage of irradiated meat products (such as sausages) stored at refrigeration (Patterson et al., 2006; Scott Smith & Suresh, 2004).

Insects, mites and other such pests are higher level, multicellular organisms responsible for considerable loss of fresh produce and grains. Also, they can provide as vectors for carrying pathogenic bacteria and parasites (Ahari et al., 2010). The best control of insects in agricultural products can be achieved by using fumigants (such as ethylene bromide). But, the use of these pesticides has been forbidden or severely restricted in most countries (World Health Organization, 2005). Consequently, radiation has been suggested as an alternative to them. Irradiation as direct control is one aimed primarily at reducing insects population. For the first time in the early 1957s irradiation as a commercial insect control technique was applied to spices in the Federal Republic of Germany (Diehl, 1995). Basis of practical experience, the necessary radiation dose to pests control according to different growth stages is in the range of 100-1000 Gy. A dose level of 250 Gy can be used for quarantine treatment of fruit flies, while a dose of 500-1000 Gy can control all stages of other pests (Landgraf, et al., 2006; Marcotte, 2005). Indirect control, on the other hand is the sterile insect technique (SIT). The principle of the technique is to introduce sterility by rearing great numbers of the pest and release them into the target area. When the released males mate with wild females, the females generate no viable offspring. With a constant releasing rate of sterile males over several generations, this results a rapid decline in the overall population. The sterilization process (in this method) is important in determining the quality of the released pests and their ability to compete with the wild population. SIT has been used against a number of pest species like as Mediterranean fruit fly *Ceratitis capitata* (Wiedemann), melon fly *Bactrocera cucurbitae* (Coquilett), pink bollworm *Pectinophora gossypiella* (Saunders), codling moth *Cydia pomonella* (L.) and tsetse fly *Glossina austeni* Newstead (Hendrichs et al. 2005; Klassen & Curtis, 2005).

2.2 Mutagenic and toxin production effects

Mutation in micro-organisms is a well known event. So, selection of spontaneous mutants and production of mutant strains by various mutagenic agents are practiced for scientific and industrial purposes. Ionizing radiation is able to induce mutations, as a number of physical or chemical antimicrobial agents. Some evidences showed that the pathogenicity of infectious organisms is diminished by irradiation (EFSA, 2011). Studies on transcriptional changes of *S. Typhimurium* and *Vibrio* spp., showed that, the expression of the virulence genes in Salmonella irradiated mutants was reduced, and expression of toxin genes of *Vibrio* irradiated mutants did not increase, compared with non-irradiated counterparts (Lim et al., 2007). The wholesomeness (lack of teratogenicity, mutagenicity, and toxicity) of irradiated products has been studied expansively (IAEA, 2009). Multigenerational feeding studies did not show any confirmation of toxicological effects in mammals due to intake of irradiated foods. It means, multigenerational studies with animals have showed that the nutritive value remains essentially unchanged and that the ingestion of irradiated foods is completely

safe (Thayer & Boyd, 1999; IAEA, 2009). Food irradiation has not provided any evidence of increased threat of mycotoxin formation in irradiated food. Therefore these do not show any specific hazard in relation to mycotoxin production (Kottapalli et al., 2006).

2.3 Radiation resistance

Radiation resistance in organisms is different. For instance, *Alternaria* sp. and *Fusarium* sp. are more resistant than the *penicillium* sp. and *Aspergillus* sp. Fusarium and Alternaria Spores are multicellular. If only one cell survives, the spore may still have the ability to germinate. So, these spores are more radiation resistant (Patterson et al., 2006). The effect of repeated doses of γ-radiation indicated a progressive increase of the radiation resistance of the organisms when exposed at sublethal dose. But, under industrial conditions, no situation is conceivable whereby a population of organisms would be repeatedly resuscitated after sublethal irradiation (Levanduski & Jaczynski, 2008). Some studies on food irradiation facilities and many other radiation-emitting sources showed no evidence for increased occurrence of resistant strains in the environment of these facilities (Scientific Committee on Food [SCF], 2003).

2.4 Selective effects on the microbial flora

Vegetative food pathogens and non pathogenic microorganisms are sensitive to radiation. The medium-dose irradiation processes reduce their populations by several log10 cycles. The possibility that decrease of the competitive microflora could assist growth of food pathogens after irradiation was studied. The study did not show any significant difference in the bacterial growth in irradiated food compared to non-irradiated one. Results indicated that, the absence of the spoilage microflora in food did not provide a competitive advantage to the bacterial growth (Prendergast et al., 2009).

3. Effects on food products

Ionizing radiation produces chemical changes by primary and secondary radiolysis effects. The effect of chemical reactions depends on the absorbed dose, dose rate and facility type, presence or absence of oxygen and temperature. Generally, most food micronutrients (mainly water-soluble and fat-soluble vitamins) and macronutrients (carbohydrates, proteins, and lipids) are not affected by 10 kGy-range -range ionizing dose with regard to their nutrient contents. But, with radiation doses above 10 kGy, the properties of fibrous carbohydrates can be degraded structurally and lipids can become somewhat rancid (Miller, 2005; Brewer, 2009). The physical status of food (frozen or fresh, solid, liquid or powder) and also its composition influence the reactions induced by the radiation (IAEA, 2009). Direct absorption of energy by the irradiated food can produce chemical changes via primary and secondary indirect radiolysis effects. Irradiation effects water molecule to free an electron producing HO+. This product reacts with other water molecules to create a quantity of compounds, including hydrogen and hydroxyl radicals (OH•), hydrogen peroxide (HO), molecular hydrogen and oxygen. Because the hydroxyl radical is an oxidizing agent, and the hydrated electron is a reducing agent, free radical attack can be expected to cause oxidizing and reducing reactions in food (Black & Jaczynski, 2008; Calucci

2003). Chemical reactions and the products generated from major food components like fat, proteins, carbohydrates and vitamins are described as fallow:

3.1 Carbohydrates

The use of gamma-irradiation (up to 6.2 kGy/h) to starches from maize, wheat, rice or potato, induced the aldehydes such as malonaldehyde, formaldehyde, and acetaldehyde, formic acid and hydrogen peroxide as main radiolytic products (Stefanova et al., 2010). Recent studies showed that, gamma irradiated solutions of fructose, glucose, sucrose and starch (at 3 kGy at 5ºC) produced malonaldehyde, But, the accumulation of aldehydes formed after irradiation of fruit juices decreased by reducing the presence of oxygen and using low temperature (Fan, 2003; Fan & Thayer, 2002). In general, irradiation modifies Mono and polysaccharides, but thermal treatment can produce more modifications (Fan, 2005).

3.2 Proteins

The study showed that, the irradiation of proteins could produce chemical reactions depend on the protein structure, state (native or denatured), physical status, amino acid composition, the presence of other substances and the radiation treatment. The most important changes include dissociation, aggregation, cross-linking and oxidation. For example gamma irradiation of hazelnuts at 10 kGy induced protein aggregation and denaturation (Dogan et al., 2007). Also, the reported decrease in pectinase activity (the most sensitive enzyme to irradiation) at 20 kGy was in the range 20% to 50%, (Duliu et al., 2004). Indeed, low and medium doses induce only a small breakdown of food proteins into lower molecular weight protein parts and amino acids. As a result, experiments indicated that such treatments cause less chemical reactions than steam heat sterilization (Fan & Sommers, 2006).

3.3 Lipids

Due to free radicals formed during irradiation, it has been proven to increase lipid oxidation (Stewart, 2009). The chemical effects are more relevant in foods with larger fat content, physical status (liquid or solid), presence of antioxidants, environmental conditions (light, heat, oxygen, moisture, pH), the irradiation treatment, type of storage (vacuum, modified atmosphere, *etc.*), storage conditions (time, temperature, light, *etc.*) and high unsaturated fatty acids content (EFSA, 2011). The use of low temperatures, the presence of oxygen, antioxidants and suitable packaging type showed a great capacity to minimize lipid oxidation (Stefanova et al., 2010). Phytosterols (include sterols and stanols), which are naturally present in cereals, nuts, seeds, fruits and vegetables have a structure similar to cholesterol. These compounds can be oxidized by standard heating treatments and also by irradiation and produce oxyphytosterols (Da Trindade et al., 2009; Johnsson & Dutta, 2006).

3.4 Vitamins

The primary effects of radiation on vitamins at low and medium doses are not considerable. But, the combination of free radicals produced through irradiation with antioxidant vitamins can lose some of their influence (Stefanova et al., 2010). In the case of water soluble vitamins, Thiamine is the most sensitive and significant losses can occur in irradiated meats.

Irradiation of chicken meals with 1 kGy resulted in a 16% decrease in thiamine compared with non-irradiated meals (Stewart, 2009). Mitchell et al. (1992) showed that, irradiation of capsicums (green and red), cucumbers, apples, lemons, lychees, mandarins, mangoes, nectarines, papayas, peaches, persimmons, and zucchinis at doses of 75 - 300 Gy can induce small changes in some parameters, such as vitamin C and dehydroascorbic acid after 3 to 4 weeks of storage at 1–7°C. However, storage effects were higher than irradiation effects. Dionísio et al. (2009) demonstrated that, Strawberries (Shasta variety, *Fragaria* sp.) submitted to 1.0-2.0 kGy doses did not show any significant decrease in vitamin C levels during two and 11 days of storage at 5°C. Folic acid levels decreased 20–30% following irradiation with a dose of 2 kGy, and no additional decrease was observed at the higher dose of 4 kGy (Galan et al., 2010). After gamma irradiation at a dose of 10 kGy, significant losses (10 to 34%) of total ascorbate and carotenoids (about 40-60%) have been reported for cinnamon, nutmeg, black pepper, oregano, parsley, rosemary, bird pepper, and sage. (Calucci et al., 2003). No transforms have been showed for Riboflavin, vitamin B6, vitamin B12 and niacin after gamma irradiation with up to 5 kGy in wheat, maize, mung beans and chick peas (Kilcast, 1994). The different sensitivity levels of food vitamins to processing are shown in Table 1. More studies showed that after high dose gamma-irradiation, E-beam irradiation or heat sterilization treatments, vitamin losses in the food are within similar ranges in all cases (Galan et al., 2010; EFSA, 2011).

Highly sensitive	Moderatly sentitive	Little sensitive
A (retinol)	b-carotene	Folic Acid
B1(thiamin)	K (in meat)	Pantothenic Acid
C (ascorbic acid + dehydro-ascorbic)		B2 (Riboflavin)
E (a-tocopherol)		B3 (Niacin)
		B6 (Pyridoxine)
		B10 (Biotin)
		B12 (Cobalamin)
		Choline
		D
		K (in vegetables)

Table 1. Different sensitivity levels of food vitamins to processing (Dionísio et al., 2009)

3.5 Inorganic salts

Primary radicals are moderately uncreative towards inorganic anions, excepting for nitrates which are reduced by solvated electrons to nitrites. In frozen muscle foods this is considered to be a rare event because of the competition for electrons by the other matrix ingredients (SCF, 2003).

In summary, carbohydrates, proteins, lipids (the macronutrients), vitamins and inorganic salts are not significantly affected by low and medium range doses according to their nutrient content and digestibility. Indeed, traditional food preservation methods (heating, drying and cooking) may cause upper nutritional losses.

4. Main objectives and limitations of food irradiation

The type of food being processed and the desired effects determine the radiation dose used in food processing. The examples of recommended dose ranges and the main purposes of food irradiation for different purposes are listed in Table 2.

Purpose and effects	Dose range (kGy)*
Inhibition of sprouting of stored tubers, roots and bulbs	0.05-0.15
Prevention of post-harvest losses by destruction of insects in stored cereals, fresh and dried fruits, nuts, oilseeds and pulses, or phytosanitary (quarantine) treatment for insect pests infesting fresh fruits and vegetables	0.15-1
Delay of ripening of fruits	0.2-1
Shelf-life extension of fruit and vegetables, meat, poultry, fish and ready meals by reduction of micro-organisms that cause spoilage	0.5-3
Inactivation/destruction of various food-borne parasites	0.3-6
Prevention of food-borne illness by destruction of non-sporeforming pathogenic bacteria (e.g. Salmonella, Campylobacter, Listeria) in fresh or frozen foods	3-7
Shorten drying and cooking times of vegetables and fruits	3-10
Reduction in viable counts of microorganisms in spices and other dry ingredients to minimize contamination of food to which the ingredients are added	5-10
Production of microbiologically shelf-stable, vacuum-packaged meat, poultry and ready-to-eat meals by heat-inactivating of their tissue-enzymes and sterilizing them by irradiation in deep-frozen state	up to 50

*The maximum doses reported are intended for good irradiation practice and not for consumer safety purposes.

Applications up to 1 kGy, between 1 and 10 kGy, and higher than 10 KGy are referred to as low-dose, medium-dose, and high-dose irradiation, respectively.

Table 2. Main purposes of food irradiation and examples of recommended dose ranges (EFSA, 2011).

4.1 Fruits and vegetables

Several food-borne outbreaks have reported in fruit products such as fresh fruit salads and non pasteurized fruit juices (Lynch et al., 2009; Vojdani et al., 2008). Applicable doses on fruit products are limited by their impact on quality (Arvanitoyannis et al., 2009). Irradiation should anticipate 2 to more than 5 log10 reduction of pathogenic (non spore forming bacteria), in some fresh and many processed fruits. But, less than 1.5 log10 reductions should be expected for the most radiation sensitive fruits. In many cases, surface decontamination of fruits, pre-washed and packaged vegetables and ready-to-eat fresh processed products with chemical agents should be less efficient (by at most 2 log10 reduction) than food irradiation (Arvanitoyannis et al., 2009). Most studies indicated that, the irradiation of fresh fruits led to a reduction in firmness. The maximum doses which can be applied on fruits and vegetables range between 1 and 2 kGy. However these maximum

values depend on the type of products and might modify with new, resistant cultivars (Zhu, et al., 2009). For example, some salad vegetables could resist up to 4000 Gy without physical-chemical damages and considerable quality loss (Nunes et al., 2008) whereas, for some products, such as lettuce leaves and apple fruit (Gala and Fuji variety) radiation doses should not exceed 600 Gy (Dionísio et al., 2009; Niemira et al., 2002).

Some products have a very short shelf-life. For instance, within a day at 10°C the cap of mushroom opens, the stem elongates, and the gills darken. Research showed that mushroom irradiated at a dose of 1.5 to 2.0 kGy soon after harvest had a shelf-life at 5° C of 11 days, and at 10°C, of 7 days. Most investigations show that sensory quality of mushroom is unaffected by irradiation (IAEA, 2001). For powdered dehydrated vegetables higher treatments (3-5 kGy) were suggested (Dong-Ho et al., 2002). Treatments for instance calcium chloride could decrease the effect of irradiation on fruit firmness (Prakash et al., 2007). Also, D10 values for various Salmonella strains in orange juice were between 0.6 and 0.8 KGy (Niemira & Lonczynski, 2006). Since, viruses are more resistant to irradiation, the doses applicable to most fresh fruits and fruit products will be of limited efficacy (Koopmans & Duizer, 2004).

4.2 Cereal products

Cereals, grains and dry legume seeds are usually consumed after a wide range of processing. Operations and irradiation (tested at doses between 1 and 10 kGy) can modify the quality and technological properties of cereals and cereal products positively or negatively (Lynch et al., 2009). Irradiation (as a pest control method) has some advantages include the absence of undesirable residues in the foods treated, no resistance development by pest insects and few significant changes in the physicochemical properties or the nutritive value of the treated products (Ahmed, 2001). Several studies had been done on the use of irradiation (as an approved method) to control stored-product pests in wheat, flour and dry legume seeds in many countries (Azelmat et al., 2005; Boshra & Mikhaiel, 2006). Lower radiation doses can not cause immediate death of adults but can prevent an increase in pest populations through lethal effects on the immature stages of adults (Hosseinzadeh & Shayesteh, 2011). The major safety concern since 1986 for cereals has been mycotoxin producing fungi. Some recent studies have shown irradiation up to 10 kGy can reduce the colonization of cereals with mycotoxin producing fungi. For instance, 6 to 8 kGy reduces the risk of mycotoxin accumulation during barley germination for malt production. However, such doses have no impact on toxins already present in the cereals (Kottapalli et al., 2006).

4.3 Tubers

Starchy tubers are an important source of starch used in the food industry. In order to provide consumers a year-round supply of various sprouting foods, storage durations of up to several months are often necessary. Sprouting can be inhibited by refrigeration and the application of various chemicals. But, refrigeration is expensive and particularly in the tropical and subtropical regions of the world. Whereas, the chemical treatments are relatively inexpensive and efficient, they do leave residues and many countries have banned their usage for health reasons (Ahari et al., 2010). In such instances, irradiation can be recommended as a reasonable alternative. The first use of food irradiation for a fresh

commodity was on potatoes in Canada in 1965 to inhibit sprouting (Diehl, 1995). Starchy tubers are also normally consumed after heat treatments and have rarely been the cause of food borne disease. Starch can be a significant source of spores of pathogenic bacteria such as *Bacillus cereus* in processed foods (Guinebretiere et al., 2003; Guinebretiere & Nguyen-The, 2003). Irradiation can be recommended for sprouting inhibition (in the range of 50 -200 Gy) and disinfestations purposes (at doses similar to those used for other dry foods) in sprouting foods such as potatoes, garlic, onions and yams (Marcotte, 2005).

4.4 Spices and condiments

Spices and condiments naturally, contain a great number of microorganisms. They often originate in developing countries where harvest and storage conditions are insufficiently controlled. Thus, Spices and condiments may have been contaminated by a high level of mesophylic, sporogenic,and asporogenic bacteria, hyphomycetes, and faecal coliforms. Also, the public health significance microorganisms such as Salmonella, Escherichia coli, Clostridium perfringens, Bacillus cereus, can be present. (Bendini et al., 1998). Since moist heat treatment is not generally suitable for such dry products, many commercial food processors fumigate spices and condiments with methyl bromide and ethylene oxide to eliminate insects or bacteria and moulds. Nowadays it has been appeared that, methyl bromide and ethylene oxide are high toxic compounds because of safety and environmental concerns. So, ethylene oxide has been banned in many countries and methyl bromide is being phased out globally (Marcotte, 2005). Based on the scientific evidence, irradiation of spices and condiments with a dose in the range of 5-10 kGy permits successful reduction of food-borne pathogens. The accurate dose applied would depend on the desired inactivation factor and the contamination (Farkas, 2006). Producers are now increasingly turning to ionizing radiation. Considering its antimicrobial activity and relatively minor effects on quality, irradiation is a feasible method for reducing the microbial load on spices and condiments (Sádecká et al., 2005). It is confirmed that the treatment with ionizing energy is more effective against bacteria than the thermal treatment and it is also less harmful to the spices than heat sterilization, which implicates the loss of thermo labile aromatic volatiles and/or causes additional thermally induced changes (e.g. thermal decomposition or production of thermally induced radicals). (Loaharanu, 1994; Olson, 1998; Alam Khan, 2010).

4.5 Sea foods and fresh meats

Several diseases originated by pathogenic Vibrios, *Listeria monocytogenes*, parasites and viruses are generally related to consumption of raw products (Venugopal, 2005). Irradiation of sea foods and fresh meats is proposed to extend shelf-life, inactivate parasites and decrease pathogen load (Norhana et al., 2010). Many studies indicated that irradiation at doses of 3 kGy, should yield 2 to 5 log10 reduction of pathogenic, non spore forming bacteria (Guinebretiere et al., 2003; Lim et al., 2007). The applicable dose to fresh meats and sea foods should be adapted to the pathogen reduction and the product (O'Bryan et al., 2008; Norhana et al., 2010). For example, Shrimp is separate from fish and shellfish given that certain pathogens (i.e *Listeria monocytogenes*) for several log10 reductions need doses in excess of 3 kGy. In frozen shrimp the dose required to reduce *Aeromonas hydrophila* and *Vibrio* by 10-4 per gram was about 3 kGy, while 3.5 kGy was needed for *L. monocytogenes* and 1.0 kGy for Salmonella (Hatha et al., 2003; Pinu et al., 2007). Irradiation of fresh meat

can change colour, odour and taste. Some recent studies have shown, irradiation imparts undesirable organoleptic attributes to high-fat products. So, content of fat in the fresh meats and sea foods is a limiting factor (Norhana et al., 2010). These changes can be reduced by adapted atmosphere packaging and minimized fat levels and mainly prevented by irradiating in the frozen state. In frozen poultry products, the average dose of 7 kGy would be adequate to provide at least a 5-log10 reduction in the number of vegetative pathogens. There is no evidence that treatment by ionizing radiation made induce allergenicity. But, some studies showed that application of moderate radiation doses can make foods (which have some natural allergenic factors) less allergenic (EFSA, 2011). For instance, irradiation of eggs and products containing eggs has been used for the reduction of allergenicity and improving egg white foaming ability (Song et al., 2009).

4.6 Other food classes/commodities

Ready-to-eat foods are very various and their consumption has increased. These foods may cause a specific danger to consumers when they do not endure a process pathogen reduction (Sommers & Boyd, 2006). To improve microbiological safety of ready-to-eat foods by irradiation, extensive research has been devoted, specifically to eliminate non spore-forming pathogens from ready-to-eat meat products. Irradiation is an effective treatment that can be used in many of these products after packaging (Romero et al., 2005). Also, Sommers and Boyd (2006) demonstrated that doses of 2 to 4 kGy inactivate food-borne pathogens including *Salmonella* spp., *Listeria monocytogenes*, *Staphylococcus aureus*, *Escherichia coli* O157:H7 and *Yersinia enterocolitica* in a variety of ready-to-eat food products.

Cheeses are also included in ready-to-eat foods. The pathogenic and toxin-producing microorganisms (considered in studies on irradiation of cheeses) are *L. monocytogenes*, pathogenic *E. coli*, Salmonella, Clostridium, Staphylococcus (mycotoxins), Brucella and Mycobacterium (Tsiotsias et al., 2002). The treatment of Camembert cheeses with gamma irradiation at doses up to 2.5 kGy (from a health point of view) was acceptable (SCF, 2003). Tsiotsias et al. (2002) showed the feasibility of gamma irradiation at doses of 2-4 kGy for reducing *L. monocytogenes* inoculated into the freshly produced soft whey cheese. Also, Ju-Woon et al. (2005) studied irradiation of fried-frozen cheese balls and demonstrated that irradiation at dose of 3 kGy is a successful treatment to make sure microbiological safety.

4.7 Quarantine treatments

The amount of transportation in all types of food product reaches millions of tons, annually. While world economic markets shrunk substantially, the cost of all traded agricultural products increased 19% in 2008 (WTO, 2010). During transportation, some invasive species that may cause economic and environmental damage (especially in areas of the world where they do not currently exist) can be transmitted. However, plant pests are not only transported through agricultural goods; they can be found in any commodity. For instance, important tree-infesting beetles (Bostrichid beetles) have been transported in solid wood packing material and pallets arriving from other countries to U.S. states (Haack, 2006). A number of techniques have been investigated as quarantine treatments, and those most commonly used for commercial purposes involve extreme temperatures and fumigants (Heather & Hallman, 2008; IPPC, 2009). Until the late 1920s, phytosanitary treatments were

based on fumigation or nonsynthetic pesticide applications. The chemicals used then were largely not safe enough to be used on food but were used on nursery stock and other nonfood items that could carry invasive species. In 1929, nonchemical treatments (heated air and cold) were used as quarantine treatments against the fruit flies. The first international use of Phytosanitary irradiation was in December, 2004, when Australia sent one-half ton of irradiated mangoes to New Zealand. For a phytosanitary treatment to be commercially possible, the treated commodities must tolerate it. Most food products can tolerate radiation at the doses used for quarantine treatments (150 to 400 Gy) and spice disinfection is the chief use of food irradiation worldwide today with over 185600 tons irradiated each year (Heather & Hallman, 2008; Kume et al., 2009). Phytosanitary irradiation differs from other commercial treatments. The end point of the treatment is not acute mortality but it prevents further biological development and reproduction (Table 3).

Treatment	End point	Commodity tolerance	Cost	Certified organic?	Speed	Logistics	Commonly treated commodity
Cold	Mortality	Moderate	Low	Yes	Very slow	Easy	Citrus, apple
Heated air	Mortality	Moderate	Moderate	Yes	Moderate	Moderate	Mango, papaya
Hot water immersion	Mortality	Moderate	Low	Yes	Fast	Moderate	Mango
Methyl bromide fumigation	Mortality	Moderate	Low	No	Fast	Easy	Citrus
Irradiation	Stop development	High	Moderate	No	Fast	Moderate	Mango, guava

Table 3. Subjective comparison of major phytosanitary treatments (Hallman, 2011).

5. Association with other preservation methods

Irradiation in combination with other treatments may suppress the growth of surviving microorganisms during storage (Fan et al., 2006; Caillet et al., 2006). For example, the effect of irradiation was increased by packaging vegetables in atmospheres enriched with carbon dioxide or containing essential oils (Thayer & Boyd, 1999). Sensory changes on high-fat products can be reduced by vacuum packaging associated to refrigeration and depend on the type of products (Zhu et al., 2009). Ahari et al. (2011) demonstrated that the combination of gamma irradiation and antagonist treatment (*Pseudomonas fluorescens*) was more effective in reducing *Penicillium expansum* growth, than either treatment alone and that integration of irradiation. Whereas, there is a dose rate limitation for application of gamma irradiation to control of postharvest disease on fruits and vegetables, the combination of irradiation and biocontrol agent increase applied range of irradiation for postharvest control by decreasing of dose rate (Ahari et al., 2011). Lee et al. (2005) demonstrated that the combined treatment of gamma irradiation and rosemary extract powder (genus Rosmarinus) improve the quality of a ready-to-eat hamburger steak by changing the storage condition from frozen (−20°C) to a chilled temperature (4°C). Fan et al. (2006) applied dose of 0.5 kGy in combination with mild heat treatment for Shelf-life extension of fresh-cut cantaloupe. Also, Niemira et al.

(2003) used freezing orange juice concentrates after irradiation, to reduction of Salmonella populations. The effect of irradiation on vegetables and sprouted seeds could be completed by washing with water (Rajkowski & Fan, 2008). Chiasson et al. (2005) studied the effect of the combination of irradiation and different atmosphere conditions (CO2, air, MAP with 10% N2, 30% CO2 and 60% O2, and vacuum), a mix of tetrasodium pyrophosphate (TSP) and carvacrol on the reduction of *E. coli* and *Salmonella typhi* in minced beef.

6. Packaging for irradiated foods

The radiation treatment can be applied after packaging, so re-contamination or re-infestation of the products is avoided. In 2001, the FDA illustrated gamma rays, E-beam and X-ray to be equal in conditions of levels and types of radiolysis products formed in the packaging materials (Deeley, 2002; Goulash et al., 2004). Polymers such as polyethylene, polypropylene, poly vinyl chloride, polystyrene, polyethylene terepthalate and polyamide are some of the most common plastic packaging materials presently available. They all contain additives that vary in nature and quantity for obtaining certain useful properties. Some studies have shown, Irradiation can change some physical and chemical properties of polymeric packaging materials and the changes depend on the type of polymer, irradiation conditions and processing exposure (Ozen & Floros, 2001; Hammad et al., 2006). For this reason any packaging materials must be confirmed by FDA before use in food irradiation (Crook & Boylston, 2004; Pentimalli et al., 2000). Nowadays, flexible packages have been developed which tend to be multi-layer films with different barrier properties because, no single flexible material has all the chemical, physical and protective characteristics needed for packaging radiation-processed food (Chytiri et al., 2005; Twaroski et al., 2006).

6.1 Physical effects

Physical effects include changes in crystallinity, permeability, surface structures and post irradiation aging effects. Radiation changes in the physical properties of a packaging material should not delay its function (Han et al., 2004). Since the Permeability is measure of the ease with which gases or vapors can penetrate through the polymer materials, it is a major consideration in the selection of a polymeric material for food packaging (Han, 2007). Kale (1994) showed that, physical properties such as permeability, crystallinity, mechanical strength and IR spectra of irradiated polymers were unaffected at high doses carried out on the effect of radiation on polymeric films both single such as polypropylene, low density polyethylene (LDPE), PET and laminates (BOPP/LDPE, PET/LDPE, PET/PET/LDPE, PET/metalized PE/LDPE, PET/HDPE-LDPE, Polyolefin-Tie layer-Nylon-Tielayer-LDPE and 5 layer nylon coextruded film/Metalized PET). Study on different packaging films, permeating gases and analytical techniques have confirmed that, there is no modification in the permeability, crystallinity and shrinkage in regularly used packaging materials such as low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene, polyethylene terephthalate (PET), poly vinyl chloride and poly vinylidene chloride in the dose range of 0-8 kGy (Goulas et al., 2002). Some researches have shown that, changes in mechanical properties of certain polymers e.g. polyethylene can be minimized (when subjected to higher doses of radiation) using suitable stabilizers (Buchalla et al., 1997; Han, 2007). Also deterioration with respect to dosage was reduced after laminating of some polymers (e.g. polypropylene) with LDPE.

6.2 Chemical effects

Most food packaging materials are originated from polymers. They may be susceptible to chemical changes (after ionizing radiation) that are the result of two reactions, cross-linking (polymerization) and chain scission (degradation). Both reactions are generally relative to dose, and depend on dose rate and the oxygen content of the atmosphere in which the polymer is irradiated (Ahn et al., 2003). Unique chemical markers present in irradiated packaging have not been recognized (Ahari et al., 2010). Chemical effects include evolution of radiolysis products, migration of radiolytic products of the polymers and degradation of antioxidants (Twaroski et al., 2006). Radiolytic degradation should neither be toxic nor affect the sensory qualities of the packed product. The vacuum condition or an inert atmosphere prevents radiation cross-linking of polymers. Also in the presence of oxygen (during irradiation of polymers) chain scission dominates. It is important because it has served as the basis for recent approvals under 21 CFR 170.39 (table 4) for packaging materials irradiated under non-oxygen atmospheres in contact with food (FDA, 2006a). During irradiation, ions and free radicals are produced. These highly reactive materials are responsible for the colour changes in irradiated polymers and could migrate into food and affect taste, odor and safety (Welle et al., 2002; Franz & Welle, 2004; Stoffers et al., 2004). Also post irradiation aging effects could be the result of trapped radicals in crystalline regions of polymers (Buchalla et al., 1993a, 1993b). It must be noted that the radiation-induced changes depend on the polymer composition (additives), processing history of the plastic and the irradiation conditions (presence of oxygen, temperature, dose and dose rate). For example, plastic films containing a phenyl group or an amide linkage (are known to stabilize the polymer) are the most radiation resistant, due to their increased resonance energy (Variyar et al., 2000). Therefore, radiation resistant of polystyrene, polyester and polyamide is due to the high energy requirement to form cross-links (Crook & Boylston, 2004).

21 CFR Citation	Packaging Materials	Max Dose [kGy]
	Nitrocellulose-coated cellophane	10
	Glassine paper	10
	Wax-coated paperboard	10
	Polyolefin film	10
Section 179.45(b)	Kraft paper	0.5
	Polyethylene terephthalate film (basic polymer)	10
	Polystyrene film	10
	Rubber hydrochloride film	10
	Vinylidene chloride-vinyl chloride copolymer film	10
	Nylon 11 [polyamide-11]	10
Section 179.45(c)	Ethylene-vinyl acetate copolymer	30
	Vegetable parchment	60
	Polyethylene film (basic polymer)	60
Section 179.45(d)	Polyethylene terephthalate film	60
	Nylon 6 [polyamide-6]	60
	Vinyl chloride-vinyl acetate copolymer film	60

Table 4. Packaging materials listed in 21 CFR 179.45 for use during irradiation of prepackaged foods (FDA, 2006a).

Any new packaging material not yet listed in 21 CFR 179.45 is subject to a pre-market safety evaluation by FDA prior to irradiation. FDA (2006b) suggests that information be generated in accordance with the available guidance documents (http://www.cfsan.fda.gov/~dms/guidance.html). Nowadays, most of the food packaging materials are normally resistant to doses used in food irradiation practice (EFSA, 2011).

7. Irradiation facilities

Ionizing radiation for food processing is limited to high energy photons (gamma rays) of radio nuclides ^{60}Co or ^{137}Cs, X-rays from machine sources with energies up to 5 MeV and accelerated electrons with energies up to 10 MeV generated by electron accelerating machines (Hvizdzak et al., 2010). These kinds of Ionizing radiation are preferred due to: i) the suitable food preservative effects; ii) do not generate radioactivity in foods or packaging materials; iii) available at costs as commercial use of the irradiation process (Farkas, 2004). The strength of the source and the length of time the food is exposed to the ionizing energy determine the irradiation dose, measured in grays (Gy) or kilo grays (1kGy = 1,000 Gy). One gray is equal with one joule of energy absorbed in a mass of one kilogram (EFSA, 2011).

7.1 Gamma irradiation facilities

Gamma rays with energies of 1.17 and 1.33 MeV are emitted by the cobalt-60 or energy of 0.66 MeV is emitted by caesium-137. The Co-60 is a radioactive metal that decays with a half-life of around 5.3 years. Although Cs-137 has a longer half-life of around 30.1 years, few commercial gamma facilities use Cs-137 as a gamma ray source. Because, Cs-137 emits gamma rays that are approximately half the energy of those emitted by Co-60 (Suresh et al., 2005). Gamma irradiation has higher penetration than Electron beams. Therefore, it is as suitable for treating large bulk packages of food. Gamma facilities are the majority of food irradiation facilities worldwide (Fig. 1). For instance, 27 of the 33 food irradiation facilities (23 in the EU) approved in 2010 are Co-60 gamma facilities and six are E-beam (EFSA, 2011). The gamma radiation can not be switched off and when not being used to treat food, must be stored in a water pool to absorb the radiation energy and protect workers from exposure if they must enter the irradiation room (Hvizdzak et al., 2010).
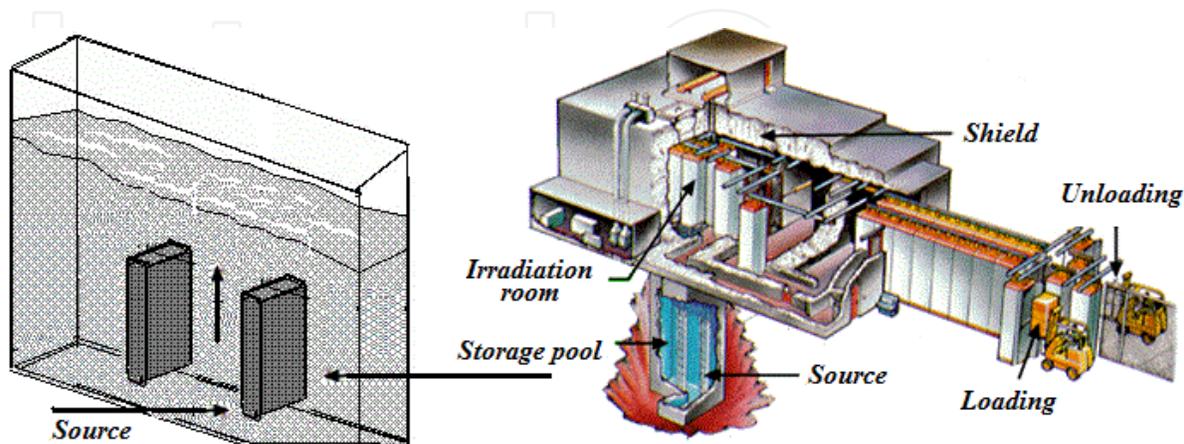

Fig. 1. Schematic diagram of a commercial gamma irradiator. The sealed sources are stored in water and raised into the air to irradiate a product that may be moved into the irradiation room on a conveyor system.

It should be noted that, all radioactive irradiators must be licensed and meet all applicable safety requirements under the Atomic Energy Act of 1954. A license must be obtained from the Nuclear Regulation Commission (NRC) or an Agreement State prior to beginning construction of a new irradiator (NRC, 2009).

7.2 E-beam facilities

E-beams are produced by machines and not by radioactive material. They are generated by accelerating a stream of electrons, which are focused into a narrow beam-spot (Fig. 2b). As food is travels perpendicular to the beam direction, this spot of incident electrons is scanned across food (Suresh et al., 2005). E-beam radiation offers three distinct advantages compared with gamma: first, the need to carry radioactive materials around the country is eliminated. Second, it can be turned off when not in use and the last; E-beam characterized by its low penetration and high dosage rates. It performs best when used on low-density, uniformly packaged products. Therefore, it can effectively inactivate foodborne pathogens on the surface of the slices, with the least negative effect (Jeong-Ok et al., 2008; Hvizdzak et al., 2010).

7.3 X-ray facilities

X-rays are generated by machines and can be switched off. In this case, electrons are accelerated at a metallic target (*e.g.*, tungsten or gold) to generate a stream of X-rays (Fig. 2a). In this process much of the E-beam energy is lost as heat; however the X-ray efficiency can be increased with atomic number of the target material and also with increasing E-beam energy (Kume et al., 2009). Nevertheless, X-ray facilities can process large bulk packages without the need for radioactive material. Nowadays, very few food products are irradiated by X-rays (Follett, 2004). As the technology advances, X-ray irradiation will become more extensive in future. But, it seems that, the commercial food irradiation facilities will continue to be gamma cells for a long period (Kume et al., 2009).
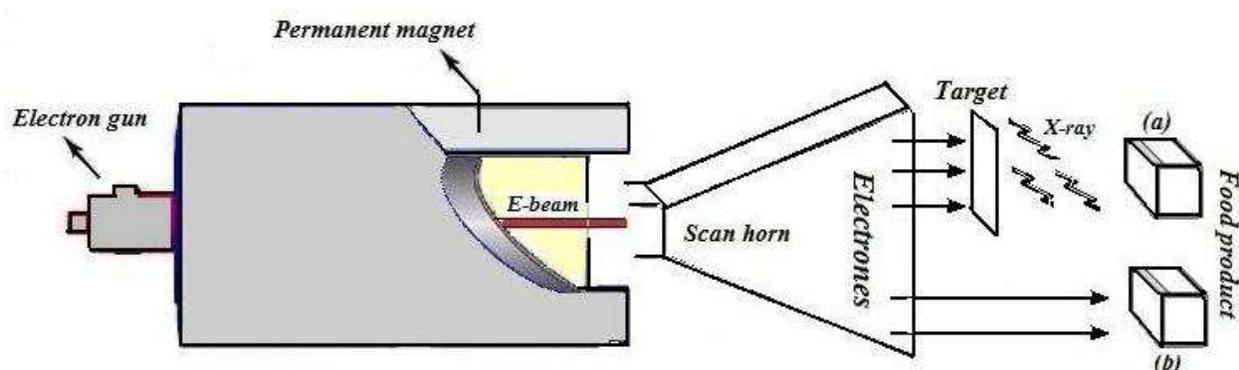

Fig. 2. Schematic diagram of a typical x-ray (a) and E-beam (b) irradiators

8. General aspects of dosimetry

Radiation dosimetry is the measurement of the absorbed dose in matter and products resulting from the exposure to radiation (Codex Alimentarius Commission [CAC], 2003). The estimated range of absorbed dose used in food processing is from 0.01 to 100 kGy. The irradiation dose absorbed by a product is not uniform due to the limits in penetration

capacity of ionising radiations. This can reduce the overall efficacy of the food irradiation in practice (EFSA, 2011). It is necessary to determine the ability of an irradiation facility to deliver the absorbed dose, prior to the irradiation of the food product. Also, it is essential to monitor and document the absorbed dose during each production run (Moreno et al., 2008).

Dosimetry provides important functions in radiation processing, where large absorbed doses and dose rates have to be measured with practical accuracy. When dosimeters are exposed to radiation, they undergo a physical or chemical change in properties that can be recorded. This change is related to dose and dose rate, and it can be calibrated to a standard dose. For example, the basis of a common dosimetry system is plastic film containing a dye that changes color in proportion to dose. The color change can be calculated using a spectrophotometer and the degree color change can be calibrated to a dose standard. Verified dosimetry systems are extensively used to perform radiation measurements, quality control and validation of processes (Moreno et al., 2008).

The success of food irradiation depends on:

1.   Calculations of the absorbed dose delivered to the food product;

In radiation processing, the absorbed dose is a key quantity in the processing of food. Therefore, dosimetry is a fundamental affair in radiation processing. Since the radiation absorbed dose is related to the desired effect in a particular food, the need for appropriate and precise dose measurement techniques must not be underestimated (IAEA, 2002). For instance, the dose received by every part of the product must be between Dmax (limit) and Dmin (Fig. 3).

2.   Determination of the dose distribution patterns in the product package (process qualification);

Process load geometries are commonly limited to conventional shapes and sizes (e.g., rectangular cartons containing cylindrical, spherical or rectangular unit packages) of commercial food packaging. The importance of dosimetry in process qualification is to ensure that the absorbed dose requirements for a specific product can be satisfied. This process (dose mapping) verifies the scale and regions of the maximum and minimum doses (Fig. 3), and helps set up all the parameters required to achieve the absorbed dose (Mehta, 1992).
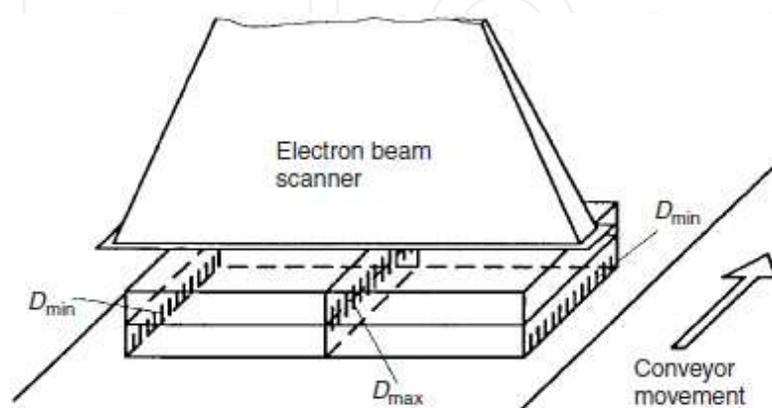
Fig. 3. Regions of Dmin and Dmax (indicated by hatching) for a rectangular process load for tow pass, tow sided electron beam irradiation (IAEA, 2002).

3. Control of the routine radiation process (control procedures);

In order to ensure that the irradiation process is under control and the correct irradiation dose is being received by a specific product, routine dosimeters are used in radiation processing facilities. The routine dosimeters, traceable to national or international standards, are important and necessary in process control of food irradiation (Miller et al., 1989). Theses should be made during operation and records kept of such measurements can be used as supporting evidence (IAEA, 2002).

9. Acceptance and trade

The use of the treatment as a commercial food process depends on its acceptance by consumers. Frequently, consumers are conservative and they are reluctant to accept products processed by new technologies like as food irradiation method. This is often related to the fear and confusion about radiation itself and the lack of understanding of the process. The main worries of consumer organizations included safety, nutrition, detection, and labeling of irradiated products (P. Junqueira-Gonc-alves et al., 2011). The concern about the food irradiation appears to centre on the safety of the process. Giving science-based information on food irradiation leads to positive consumer approaches (Fox, 2002). Many consumers are primarily hostile to irradiation. By other means, "People think the irradiated product is radioactive," but when the process is made clear to them they will become more in favor (Landgraf et al. 2006; Marcotte, 2005). Fox (2002) reported that, consumer awareness of food irradiation was 29%. Also, 80% of consumers were unsure about the safety of irradiated foods. Only 11% of the interviewers expressed that irradiated foods are safe. It should be noted that upon hearing a benefit statement of food irradiation, level of positive attitude increased significantly (62%) towards irradiated foods. On the other hand, unfavorable description of irradiation has a great negative effect on consumer acceptance of irradiated foods. Recent study showed a low level of awareness among consumers about the food irradiation processing. 76.5% of the interviewed people did not know that irradiation could be used as a method for food preservation. 46% of them expressed that irradiated food means the same as radioactive food. Nevertheless, 91% stated that if they knew that ''irradiated'' is not ''radioactive'' and that proper irradiation enhances food safety they would become consumers of irradiated food. 95.8% of the interviewers were not familiar with the ''Radura'' symbol (Fig. 4). However, 55.8% of people expressed that they would buy irradiated food because of the Radura symbol (Junqueira-Gonc-alves et al., 2011). It shows that the labeling of irradiated products (the Radura symbol coupled with either "treated with ionizing radiation" or "irradiated") is the key issue with the consumers. Similar result was observed by Stephen et al. (2009). Because the words "radiation" and "irradiation" may have negative connotations, the labeling requirement has been viewed as an obstacle to consumer acceptance. Some researchers believe that an alternative wording, e.g. "electronically pasteurized," would be helpful (Morehouse & Komolprasert, 2004). These results confirm the importance of training the public on the controversy, technology, and the benefits of irradiation.

Several countries have regulatory approvals in place for irradiation of one or more food products. But all these countries are not practically using the technology for a restricted number of food products (Johnson & Reynolds, 2004; Marcotte, 2005). China, USA and Ukraine make up about three quarters of the whole food irradiated in the world. China is

the most important country in the use of food irradiators. More than 200 facilities are reported from China and has about 100 irradiators with designed capacity of >300 kCi and more than 40 irradiators with designed capacity >1000 kCi. During 2006-2010 China established 20 new irradiators (EFSA, 2011). The number of radiation processing facilities and commercial food irradiation is showing an increasing trend around the world.

Fig. 4. The ''Radura''symbol (in general it is presented in green color). The plant-like structure represents agricultural products in a closed package (the circle) broken in the upper half by penetrating ionizing rays or particles.

10. Conclusions

Food irradiation is approved for use in over 60 countries worldwide for different products, such as grains, herbs and spices, poultry, seafood, and ground beef (Kume et al. 2009). Irradiation does not cause any significant loss of macronutrients. Proteins, fats and carbohydrates undergo little modify in nutritional value through irradiation even with doses over 10 kGy, though there may be sensory changes. In the same way, the essential amino acids, essential fatty acids, minerals and trace elements are also unchanged. There can be a decrease in certain vitamins (mostly thiamin) but these are of the same order of magnitude as occurs in other manufacturing processes such as drying or canning (thermal sterilization) (Ahari et al., 2010). In the world today, 500000 tons of foods are irradiated every year among spices, meat, fresh fruits and vegetables. Despite the clear benefits of the food irradiation, this method remains under estimated in the food trade. It has not been commonly accepted and approved yet (Guy, 2011; Kume et al., 2009). The main factor in the way of commercial application of the food irradiation process is consumer acceptance. From our point of view, as consumer safety questions are discussed, food preservation throughout radiation contribution to food safety will reach the same recognition as the sterilization of medical products has in terms of preventing the spread infectious disease. For this reason, scientists have the responsibility to help the consumer understand the radiation process and it's potential to improve our lives and protect our health.

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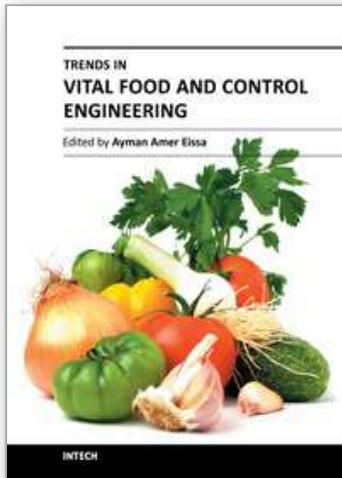
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