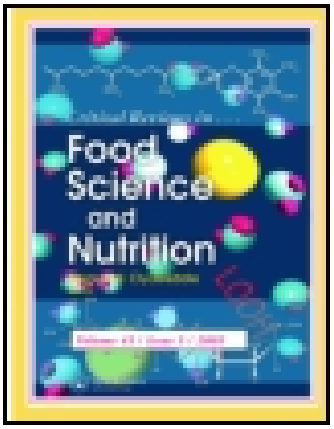

Critical Reviews in Food Science and Nutrition
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/bfsn20

Worldwide Status of Fresh Fruits Irradiation and Concerns about Quality, Safety and Consumer Acceptance

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Accepted author version posted online: 01 Apr 2015.

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Running title: Irradiation of fresh fruits

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Development of knowledge-based food preservation techniques have been a major focus of researchers in providing safe and nutritious food. Food irradiation is one of the most thoroughly investigated food preservation techniques, which has been shown to be effective and safe through extensive research. This process involves exposing food to ionizing radiations in order to destroy microorganisms or insects that might be present on and/or in the food. In addition, the effects of irradiation on the enzymatic activity and improvement of functional properties in food have also been well established. In the present review, the potential of food irradiation technology to address major problems, such as short shelf-life, high initial microbial loads, insect pest management (quarantine treatment) in supply chain, and safe consumption of fresh fruits was described. With improved hygienic quality, other uses, such as delayed ripening and enhanced physical appearance by irradiation were also discussed. Available data showed

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that the irradiation of fruits at the optimum dose can be a safe and cost-effective method, resulting in enhanced shelf-life and hygienic quality with the least amount of compromise on the various nutritional attributes, whereas the consumer acceptance of irradiated fruits is a matter of providing the proper scientific information.

Key words Irradiation, fruits, preservation technique, quarantine, food safety, quality, consumer acceptance

INTRODUCTION

Concerted efforts of scientists to enhance food productivity, quality, nutrition and safety are vital to facilitate proper strategies for defeating hunger and malnutrition (Wu et al*.,* 2012). Fresh food products deteriorate due to physiological aging, biochemical changes, high respiration rate and high ethylene production, where their discoloration, loss of firmness, development of off-flavors, acidification, and microbial spoilage are important concerns. However, consumers are now interested in minimally-processed fresh agricultural produce with superior quality and least compromise on nutritional attributes (Pasha et al*.,* 2012). Food irradiation is the process of exposing food to ionizing radiations, that is, radiation at a high enough energy level can expel electrons from atoms and ionize molecules. Radiations can be in the form accelerated electrons (electron beams) or high-energy photons (gamma rays or x-rays) (Sádecka, 2007) (Fig. 1). Water molecules present in food is the primary target of irradiation producing radiation-induced hydroxyl radicals (Diehl, 1995). However, irradiation of food is not energetic enough to induce radioactivity in the target materials (Maxie and Abdel-Kader, 1966). The initial work on irradiation technology was done by Schwartz (1921) and Brash and Huber (1947). The first commercial application of this technology was for the decontamination of spices in Stuttgart, Germany in 1957 (Diehl, 2001). Gamma rays from cobalt-60 are more energetic than that of cesium-137. Moreover, the initial installation cost is less with a cobalt-60 irradiator than that of a cesium-137 irradiator (Niemira and Deschênes, 2004). Gamma rays are normally emitted from the radioisotopes of cobalt-60 and cesium-137, while high-energy electrons and X-rays are produced by machine sources.

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These types of radiation are selected for the irradiation of food for the following reasons:

(a) They produce the desired food preservative effects;

(b) They do not induce radioactivity in foodstuffs or packaging materials;

(c) They are available in quantities and at costs that allow the commercial use of the irradiation process (Farkas, 2004; Arvanitoyannis, 2010).

Food irradiation attracted a great deal of attention in many countries during the movement to use ñAtoms for Peaceò to overcome food-spoilage problems (Zachmann, 2011; Akram et al., 2012). This has led to the destruction of pathogenic and foo-spoilage bacteria and effective control of parasitic organisms (Fig. 1). Irradiation at a uniform dose cannot be used for all types of fresh and/or minimally-processed fruits and vegetables because of the important relationship between the quality of the food product (texture, color and nutrient content) and the irradiation dose. Higher doses of irradiation produce an undesirable effect on the product quality (Arvanitoyannis et al., 2009). In addition, penetration ability is also an important aspect to be considered. E-beams are less penetrating than gamma rays or X-rays (Castell-Perez et al., 2004). However, e-beam irradiators have a commercial advantage over gamma irradiators since they are electronic in nature and therefore can be completely deactivated or activated depending upon the requirements (Niemira and Deschênes, 2004).

Despite being an extensively studied food processing technology, food irradiation is still considered a relatively innovative technology for several reasons. Humans fear the unknown and are inclined to resist change (Lacroix and Vigneault, 2007). The hindering factors in the way of commercial implementation of the food irradiation process are politics and consumer advocacy (Farkas, 2006). In addition, people do not have a sufficient understanding of food irradiation;

therefore, the technology is often linked with the nuclear establishment (Molins, 2001). Therefore, it may take long time for the wide acceptance of food irradiation. Some remarkable scientific and knowledge-based efforts will be required to educate people in this area (Lacroix and Vigneault, 2007).

Worldwide Status of Fresh Fruits Irradiation

After decades of development, the implementation of radiation technology in horticultural products is finally emerging as a commercial reality. The publication of the International Standard for Phytosanitary Measures no. 18 őőGuidelines for the use of irradiation as a phytosanitary measureőő proved to be a landmark publication in overcoming regulatory barriers for the adoption of radiation technology as a means to facilitate international trade in horticultural products. The implementation of this standard in practice has resulted in exports of irradiated mangoes from Australia to New Zealand and of irradiated mangoes, longans, mangosteens, rambutans, dragon fruits, and guavas from India, Pakistan, Thailand, Vietnam and Mexico to the United States. Significantly greater potential exists for other countries and products depending on business opportunities and the willingness to invest. New Zealand and United States are the major importing countries and Australia, India, Pakistan, Thailand, Vietnam and Mexico are the major exporting ones (Bustos-Griffin et al., 2012).

Kume et al. (2009) investigated the status of food irradiation in the world using published statistical data in the Official Journal of the European Union C122/3 (European Union, 2007) and the RCA Meeting Report (IAEA, 2005) held in Korea in 2005. In addition, correspondence with the representatives of about 60 countries was performed and direct visits to Austria, Germany, France, Belgium, Netherlands, Croatia, USA, Canada, Mexico, South Africa, India, China, Malaysia, Vietnam, Thailand and Ukraine were also conducted. The results showed that the quantity of irradiated foods in the world in 2005 was 405,000 tons consisting of 186,000 tons (46%) of disinfected spices and dry vegetables, 82,000 tons (20%) of disinfected grains and fruits, 32,000 tons (8%) of disinfected meat and fish, 88,000 tons (22%) of disinfected garlic and potatoes, and 17,000 tons (4%) of other disinfected food items that included health foods, mushrooms, honey, etc. They also found China ranked at the top (36%) of the total irradiated food in the world following the USA and Ukraine. There was an increasing trend in commercial food irradiation in Asia, but a decreasing one in the European Union.

After the adoption of the General Standard for irradiated foods (Codex, 2003) by the Codex Alimentarius Commission (CAC), the safety of foodstuffs irradiated at 10 kGy or less was established. This motivated countries to include irradiation in their legislation regulating the treatment of foodstuffs and prepare national standards based on the CAC guidelines. Now, about 60 countries have regulatory structures that allow the use of irradiation for different foodstuffs (Bustos-Griffin et al*.*, 2012; IAEA, 2012). The list of countries having clear permission for the irradiation of fruits is presented in Table 1.

Germany was the first to build a commercial food radiation facility for the treatment of spices in 1957 but the plant was closed after a couple of years when food irradiation was prohibited in that country (Diehl, 1995). A facility in Japan that has been exclusively used since 1973 to treat potatoes for sprout inhibition is the longest continuously operating facility in the world (Hayashi, 1986). South Africa is the most advanced country in the use of irradiation in the African region. South Africa took the initiative to introduce the irradiation of fresh produce to local markets in 1978 (Van der Linde and Brodrick, 1985). China has more than 100 irradiation facilities, including both isotopic and machine sources (Bustos-Griffin et al*.,* 2012).

Safety of Irradiated Fruits

Fresh fruits can become contaminated with pathogens, such as harmful bacteria, viruses or parasites at somewhere along the way from field to table. Salmonella, *E. coli*, and Hepatitis A are the most common pathogens challenging the safety of fresh produce. Eating such contaminated fruits can lead to foodborne illness often termed as ñfood poisoningò (Abadias et al., 2008; Health Canada, 2009). There are several simple safe handling steps to assure the safety of fresh produce. The FDA prescribes to properly wash the fresh fruits with sufficient amount of cold or warm tap water and scrub with a brush to reduce or eliminate the dirt, pesticide residues, or pathogens etc. In addition, proper storage can ensure both quality and safety (Food Facts, 2012).

Irradiation is considered a safe and well proven process that has found numerous applications in food processing and preservation (Akram and Kwon, 2010). However, safety concerns over irradiated foods are an important consideration in getting consumer acceptance (Hunter, 2000; Bruhn, 2001). Higher doses of irradiation may cause damage to the living tissues of food. Therefore, the level of damage, its effect on human health and the acceptance of irradiated foods by consumers are a debatable topic. Generally, the low doses are used for fresh fruits and vegetables with exception of fresh spinach and lettuce. The FDA restricts the maximum level of irradiation for fresh fruits and vegetables to 1.0 kGy (Ferrier, 2010). The WHO Food Safety Unit has endorsed food irradiation as the most significant contribution made

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by food science and technology to the public health since the pasteurization of milk at the end of the 19th century (Boisseau, 1994). The joint FAO/IAEA/WHO expert committee on food irradiation has concluded that irradiated foods are safe for consumption and are nutritionally adequate and wholesome (WHO, 1999).

Irradiation can result in negligible or subtle changes of bioactive compounds as it does not substantially raise the temperature of food during processing (Wood and Bruhn, 2000). Fan and Sokorai (2008) studied the production of furan, a possible carcinogen, in different fresh-cut fruits on gamma irradiation of 5 kGy. They showed that irradiation produced low levels of furan in grape and pine apple, while in other fruits furan levels were not detectable. Considering the low levels and high volatility of furan, they concluded that radiation-induced furan is not a significant concern for fresh-cut produce.

Fan et al. (2011) reported that high dose of irradiation can induce an off-odor called ñirradiation odorò in fruit juices. Volatile sulfur compounds, such as hydrogen sulfide, methanethiol, methyl sulfide, dimethyl disulfide and dimethyl trisulfide, play a significant role in the development of the off-odor. It is observed that irradiation exerts its effect by hydrolysis of water in foods where water is a dominant component. Irradiation of water generates three primary free radicals: hydroxyl, hydrogen atoms, and hydrated electrons. Use of specific scavengers in a model system revealed that hydroxyl radicals are involved in the formation of volatile sulfur compounds. Yoo et al. (2003) reported the formation of sulfur-containing compounds, such as dimethyl sulfide, dimethyl disulfide, and 2-butanone in irradiated orange juice. These compounds are considered to be partly responsible for the off-odor in irradiated orange juice. Fan et al. (2004) stated that irradiation induces undesirable chemical changes, such as the accumulation of volatile sulfur compounds including malondialdehyde, formaldehyde, and tetrahydrofuran which ultimately leads to off-flavor in fruit juices.

Patil et al. (2004) investigated the influence of ɔ-irradiation (0, 70, 200, 400 and 700 Gy), harvest time (early-season and late-season), and storage period on bioactive components and other quality parameters on grape fruit. The results indicated that the response of fruit to irradiation was dependent on harvest date. Lower doses (at or below 200 Gy) of irradiation combined with 35 days of storage were suitable in enhancing health promoting compounds (flavanones and terpenoids) in early season grapefruit. On the contrary, higher doses of irradiation (400 and 700 Gy) coupled with 35 days of storage had detrimental effects on quality (ascorbic acid content, soluble solids, and titratable acidity) of early season grapefruit, however, no significant effect was observed on the quality of the late season fruit. In addition, decrease in flavanone contents was also obvious at higher doses. Similarly, Oufedjikh et al. (1998) evaluated the effect of ɔ-irradiation (300 Gy) on flavonoids content of Moroccan citrus clementina during 3-months storage. Irradiation induced the biosynthesis of flavonoid compounds and the content of these compounds was significantly higher in irradiated samples after 14 days of storage.

It is estimated that postharvest losses of fruits and vegetables can amount to as much as 40% at various points in the distribution system between production and consumption. Food irradiation offers potential as a viable sanitary and phytosanitary treatment for food and agricultural products. Disease-causing pathogens can be easily controlled by the use of this technology. In addition, food irradiation technology can also be used in combination with other technologies to maintain the quality of the fresh fruits and vegetables (Lacroix and Vigneault, 2007). Various insects, parasites, mites, and micro-organisms are important sources of food contamination. Therefore, irradiation is a promising alternative to consider assuring quarantine requirements, controlling for severe losses during transportation and commercialization, and ultimately ensuring food safety (Lacroix and Ouattara, 2000).

Quarantine Treatment of Fruits using Ionizing Radiations

Irradiation is probably the most widely applicable quarantine treatment for fruits with the aim for better quality. Considering its effectiveness, the USDA recommends irradiation quarantine treatment for insects and mite pests shown in Table 2. Seo et al. (1974) and Heather and Corcoran (1992) described that an irradiation dose of 0.1 kGy is adequate to sterilize mango seed weevil and 0.3 kGy will usually prevent adult emergence. The Animal and Plant Health Inspection Service (APHIS) of the United Stated Department of Agriculture (USDA) enforced the mandatory requirement to irradiate fresh pomegranate fruits with a minimum dose of 0.4 kGy on import either outside or inside the U.S.A. The designed phytosanitary treatment would be helpful to eliminate the mite (*Tenuipalpus granati),* the false spider mite (*Tenuipalpus punicae),* and the bacterium (*Xanthomonas axonopodis* pv. *punicae)* from the fresh pomegranate fruits (APHIS, 2012). Follett (2001) proposed a dose level of 0.1 kGy as an irradiation quarantine treatment to sterilize mango seed weevil in mangoes grown in Hawaii. Follett irradiated mixed-age mango seed weevils in mangoes with target doses of 0.5, 0.1, or 0.3 kGy. The 0.3 kGy treatment did not prevent adult emergence. However, emerging adults from the 0.1 and 0.3 kGy treatments were lethargic and short-lived, and laid no eggs indicating sterility. Studies by Thomas (1975) and Milne et al. (1977) also suggested a higher dose to prevent adult emergence in South Africa. Therefore, it is difficult to draw a general conclusion on the effective irradiation dose for mango seed weevils because of many factors including different treatment dose intervals, dosimetry, methods and mango cultivars, etc.

Follett (2004) also reported that at optimum dose levels, irradiation was an effective phytosanitary or quarantine treatment against most insect and mite pests without disturbing the key quality attributes of most fruit commodities. A generic dose of 0.15 kGy has been proposed to control for tephritid fruit flies, and for Hawaiiĉs sweet potato pests, a 0.25ï 0.3 kGy dose level could be sufficient. Follett further found that quarantine treatment doses of 0.21ï 0.25 kGy to control for Mediterranean fruit flies, melon flies, and oriental fruit flies in Hawaii are sufficient.

Follett and Weinert (2009) conducted dose-mapping studies to compare dose variation during radiation treatment at 0.4 kGy of a single type of fruit and of mixed fruits packed in boxes. The study was done on tropical fruits that included papayas, mangoes, bananas, rambutans, longans and dragon fruits. When radiation was applied to a single box containing either one type of fruit or a mixture of two or three types of fruits, the measured doses were sometimes higher in the mixture of fruits.

Torres-Rivera and Hallman (2007) reported that for the majority of hosts for the Mediterranean fruit þy, the phytosanitary treatment dose in the USA is 0.15 kGy. They investigated whether 0.1 kGy is sufficient to provide a high level of quarantine security against this important pest in mangoes in Peru. They also suggested that a dose of 0.1 kGy would be sufficient for the irradiation of avocados.

Hallman and Martinez (2001) developed a low-dose gamma irradiation quarantine treatment against the Mexican fruit fly in citrus fruits. They recommend the minimum absorbed dose for quarantine security against the Mexican fruit fly to be 0.58 kGy, if the confirmatory test is satisfied with 30,000 insects successfully treated, or 0.69 kGy if that requirement is closer to 100,000 insects.

Hawaii has become the pioneer in the world to use irradiation as a quarantine treatment of fruits. Irradiation and marketing of various tropical fruits in the USA have presented commercial efficacy, quality retention, and excellent consumer acceptance (Moy and Wong, 2002). Considering the great potential of irradiation to control quarantine pests, it is approved in 17 fruits and 7 vegetables for export from Hawaii to the US mainland (Follet and Weinert, 2012). The USDA has approved irradiation as a quarantine treatment for nearly all insect pests. In 2007, an irradiation dose of 0.4 kGy was permitted for litchis, longans, rambutans, mangoes, mangosteens, pineapples and rambutans imported from Thailand. At the start of 2003, a 0.15 kGy dose level was recommended for bananas, breadfruits, carambolas (star fruit), Cucurbita spp. (squash, pumpkins), longans, melons, pineapples, papayas, rambutans, sapodillas, and tomatoes imported from Hawaii to the USA (Follett and Griffin, 2006).

Effect of Irradiation on Fruit Microflora

Ionizing radiation can penetrate the protected areas of fruits, and in the case of gamma- and x-rays, penetrate the internal structures to inactivate bacteria. The effects of ionizing radiation on the microbiological quality of fresh fruits are summarized in Table 3. The United Nations Food and Agriculture Organization (FAO) and International Atomic Energy Agency (IAEA) launched a joint research program by bringing together food scientists from 15 nations including the USA, UK, China, Canada, India and Brazil to share their expertise, methodologies and research output related to the use of irradiation to ensure the hygienic quality of fresh fruits including apples, apricots, mangoes, blueberries, pineapples, pomelos, cantaloupes, jackfruits, watermelons, peaches, etc. The research programs were structured to investigate the effect of irradiation on different human pathogens that are associated with a number of whole and cut fruits (IAEA, 2001).

The control of spoilage microorganisms helps to increase the shelf life of fresh produce. Irradiation doses typically in the range of 0.2-0.8 kGy will result in a 1-log reduction in bacterial pathogens of fresh produce. In contrast, pathogenic viruses and fungi are generally more resistant to irradiation, often requiring 1-3 kGy to achieve 1-log reduction (Niemira and Fan, 2005). Many studies have demonstrated that low doses of irradiation (up to 1 kGy) significantly extends the shelf life of fresh and fresh-cut fruits by inhibiting ripening processes and by inactivating the spoilage microorganisms (Fan, 2012). Singh and Pal (2009) reported that ionizing radiation of 0.25 kGy increased the postharvest life of guava fruit by 3-4 days. Janava and Sharma (2005) found that low dose of gamma-irradiation (up to 1 kGy) extended the shelf life of pre-climacteric mangoes by 5-6 days at ambient storage conditions. The extension of shelf life was dose dependent maximum being at 0.2 kGy by about 8-10 days. However, the high doses of irradiation used previously in attempts to produce a sterile or shelf-stable fruit or vegetable commodity have resulted in unpalatable products (Niemira and Fan, 2005).

In a study on sliced cantaloupe inoculated with human pathogens (10^6 CFU/g), after irradiation at 3.0 kGy from a 5-MeV e-beam, Draughon et al. (2001) were able to recover *Salmonella* and *Listeria*, but not *Staphylococcus*. They concluded that for 1 cm thick slices, an e-beam dose of greater than 3.0 kGy would be required to completely eliminate *Salmonella* or *Listeria*. Shashidhar et al. (2007) found that irradiation at 2 kGy was sufficient to eliminate 5 log CFU/g of *S. Typhimirium* in pineapple.

Mahmoud (2010) studied the effects of x-ray treatment on different pathogenic bacteria and on the inherent microflora of tomatoes. The irradiation dose used in that study ranged from 0.1ï 1.5 kGy. The results obtained from the microbiological quality studies showed that x-ray irradiation could be used for preserving product quality. Moreover, the use of x-rays instead of gamma rays could reduce real concerns among consumers about using radioactive materials for the treatment of their foodstuffs. However, Mahmoud did not study the adverse effects of irradiation on the sensory attributes of tomatoes.

Prakash et al. (2007) examined the efficiency of combined irradiation and a 1% calcium chloride dip to reduce the population of *Salmonella enterica* strains on diced tomatoes. Tomatoes were contaminated with nalidixic acid-resistant strains of *Salmonella* Hartford, *Salmonella* Montevideo, or a mixture of 5 strains and then irradiated at various doses up to 0.9 kGy from an e-beam source to conduct a D-value study. Surviving *Salmonella* populations were detected by standard and recovery plating methods. D-value results ranged from 0.26 to 0.39 kGy, indicating that a 5 log CFU/g reduction in *Salmonella* spp. in diced tomatoes would require a dose of 1.3-1.95 kGy.

Effect of Irradiation on Physico-chemical Quality Characteristics of Fresh Fruits

Irradiation can affect the quality attributes and shelf life of fresh fruits (Table 4), where a sensory profile is the key characteristic for consumer acceptance of any processed commodity (Table 5). Maria et al. (2007) reported the effect of e-beam irradiation on the quality properties of packaged fresh blueberries at doses greater than 1.0 kGy. Irradiation at doses higher than 1.1 kGy affected the texture of the blueberries and the fruits became considerably softer and less acceptable throughout storage. Blueberries exposed to 3.2 kGy were found unacceptable by the sensory panelists. However, irradiation at medium dose levels (1.0ï 3.2 kGy) did not affect the density, pH, water activity, moisture content, acidity and juiciness of the fruits, and a dose of 1.6 kGy was a feasible decontamination treatment that maintained acceptable fruit quality attributes. Kang et al. (2012) investigated the effect of X-ray irradiation (0.2ï 1.0 kGy) on the physical and chemical quality characteristics of fresh grapes. They found that irradiation by 0.2 and 0.4 kGy could reduce the respiration rate and extend the shelf life. No significant effect from irradiation was observed on the other physical and chemical qualities of grapes, including weight loss, total soluble solids, titratable acidity, protein, minerals, taste, etc. The irradiated fruits also had a better appearance than the control grapes after 14 days. They concluded that irradiation as a quarantine treatment for fresh grapes is possible.

Basfar et al. (2012) investigated the role of gamma irradiation with different doses on the removal of pesticide residues in different vegetables and fruits. They concluded that ionizing radiation at a specific dose could be helpful in reducing some but not all residues to below their maximum residue limits. Singh and Pal (2009) investigated the potential of ionizing radiation to improve the physiological responses, quality, and storage time of fresh guava fruits. Irradiation suppressed the respiration and ethylene production rates and thus retarded the process of fruit ripening during storage. It also retarded the physical and biochemical changes associated with ripening such as ýrmness, titratable acidity, soluble solids content, and vitamin C during storage, but the vitamin C content decreased at doses higher than 0.25 kGy. The treatment of guava fruit with 0.25 kGy dose increased the postharvest life by 3ï 4 days, maintained the quality of the fruit, and reduced the decay incidence. Moreover, the optimal dose (0.25 kGy) for postharvest life

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extension of guava fruits may be exploited to provide phytosanitary security against many insect pests including fruit þies.

The effect of e-beam irradiation on the quality attributes of packaged fresh blueberries at doses greater than 1.0 kGy was assessed by Moreno et al. (2007). Irradiation at doses higher than 1.1 kGy did affect the texture of blueberries as the fruits became considerably softer and less acceptable throughout storage. Fruits exposed to 3.2 kGy were found unacceptable by sensory panelists in terms of overall quality, texture, and aroma. However, irradiation at dose levels used in this study did not affect the density, pH, water activity, moisture content, acidity and juiciness of blueberries. It was concluded that e-beam irradiation of blueberries up to 1.6 kGy is a feasible decontamination treatment that maintains the overall fruit quality attributes.

Pimentel and Walder (2004) studied the effect of gamma irradiation in papayas, harvested at three degrees of maturation, to enhance their shelf life. Papayas were harvested in perfect quality conditions and divided into three distinct degrees of maturation by skin coloration. They were irradiated with 0.75 kGy and analyzed in four periods of conservation. The papaya maturation degree at harvest did not influence the irradiation effect. There was no effect from irradiation on papaya weight loss, occurrence of diseases, pH and total soluble solids contents. Irradiation maintained the firmness of the papaya and therefore, delayed ripening. Irradiation can induce softening, uneven ripening or surface damage in mango fruit, where irradiation dose, cultivar, and fruit maturity stage are important factors for the quality of irradiated mango fruit (Sivakumar et al., 2011).

Physicochemical, textural, respiration rates, micro structural, and sensory characteristics of ñTommy Atkinsò mangoes irradiated at 1.0, 1.5, and 3.1 kGy using a 10 MeV (10 kW) linear accelerator were determined by Moreno et al. (2006). The fruits were stored at 12°C and 62.7% RH for 21 days and evaluated at days 0, 5, 10, and 21. Irradiation affected the textural characteristics of the mangoes at doses higher than 1.0 kGy. Mangoes exposed to 1.5 and 3.1 kGy were softer and less firm throughout storage. Only the fruits irradiated at 3.1 kGy were unacceptable to the sensory panelists in terms of overall quality, texture, and aroma. Therefore, 1.0 kGy was the recommended dose for ñTommy Atkinsò mangoes to maintain the overall fruit quality attributes.

Zaman et al. (2007) studied the effect of gamma radiation on the shelf life extension of bananas. The bananas were treated with three gamma radiation doses of 0.3 kGy, 0.4 kGy and 0.5 kGy and stored in a dry place under room conditions. The shelf life of the irradiated bananas was extended by 20 days compared to the control bananas thereby delaying ripening. The chemical constituents of the irradiated bananas were the same and no major changes were observed in the nutritional and organoleptic qualities except a minor change in the ascorbic acid content. Therefore, irradiation can be used for the shelf life extension of bananas without any adverse effects.

Egea et al. (2005) studied the possibility of extending the postharvest life of apricots by applying e-beams at 0.5 and 1.0 kGy. A decrease in ethylene production and an increase in peroxidase activity in the apricots were observed when irradiated at 1.0 kGy, which may enhance the protection of fruit tissues against some possible damages associated with degenerative processes, such as carotenoid degradation. The other physico-chemical and nutritional properties of the apricots showed no significant changes upon irradiation when compared with those of the control, the non-irradiated fruit.

Harder et al. (2009) studied the effect of gamma radiation at doses of 0, 0.5, 1.0 and 2.0 kGy on a fruit drink comprised of kiwifruit nectar to evaluate the changes in the physical and chemical quality characteristics. No signiýcant differences were observed between the treatments compared to the control. They concluded that the irradiation did not induce signiýcant alterations in the physiochemical and sensorial characteristics of the kiwifruit nectar except for the total ascorbic acid at doses of 1.0 and 2.0 kGy.

Lee and Kader (2000) studied different pre-harvest and postharvest factors that influenced the vitamin C content of different horticultural produces. They reported that low doses (1 kGy or lower) of irradiation treatment have no significant effects on the vitamin C content of fruits and vegetables. Kilcast (1994) reported that some vitamins are sensitive and degrade upon irradiation, in which vitamin C and B_1 are the most sensitive water-soluble vitamins. Similarly, vitamin E and A were found to be the most sensitive fat-soluble vitamins. Castell-Perez et al. (2004) studied the effects of e-beam irradiation on the product quality of cantaloupes after the food-borne illness outbreaks related to their consumption in the United States and other countries. Whole and fresh-cut packaged cantaloupes were irradiated with e-beam irradiation with doses of 1.0, 1.5 and 3.1 kGy and stored at 10°C for 0, 4, 8 and 12 days along with the control (non-irradiated) samples. An irradiation dose up to 1.0 kGy caused no significant changes in the physical and sensory quality attributes of the fruit but higher doses had an undesirable effect on product quality. The carotene content slightly increased as the irradiation dose increased.

McDonald et al. (2012) determined the sensitivity of peaches to irradiation treatment. He studied the effect of commercial scale irradiation treatment on shelf life, overall quality and consumer liking on six varieties of peaches. No dose effects were observed on TA, Brix and weight loss due to irradiation. Irradiation did not adversely affect the shelf life but did enhance ripening which was perceived as a positive change by consumers. Overall, the acceptability of the irradiated peaches by consumers was higher than that of the untreated peaches. Basfar et al. (2012) investigated the role of gamma irradiation with different doses on the removal of pesticide residues in different vegetables and fruits. They concluded that ionizing radiation at a specific dose could be helpful in reducing some but not all residues to below their maximum residue limits.

Drake et al. (1999) investigated the effect of irradiation (0.3 and 0.9 kGy) on whole apples and pears. Irradiation did not influence the external color of apples but a change in the internal color of some apple varieties was observed. There was an increase in superficial scald (a physiological skin disorder) for pears directly related to applied irradiation dose. Fan and Mattheis (2001) observed that some apple fruits irradiated up to 1.3 kGy and stored at 20°C for a period of 3 weeks developed internal browning.

Wall and Khan (2008) evaluated the effect of different doses of x-ray irradiation (0, 0.2, 0.4, 0.6, and 0.8 kGy) on three dragon fruit clones (*Hylocereus* spp.) followed by storage for 12 days at 10°C. The effect of irradiation was clone dependent as surface color, peel injury, and bract appearance differed among the three clones with irradiation treatment but, in all cases, visible changes were minor. Irradiation treatment of dragon fruit at 0.8 kGy would ensure visual and compositional quality while adding quarantine security.

The color of rambutans and oranges were also affected by 0.75 kGy radiation. The color of irradiated fruit tended to be more intense than the control fruit (Boylston et al. 2002). Miller et

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al. (2000) irradiated ten citrus cultivars grown in Florida and observed that the appearance of all cultivars was negatively affected by a loss of glossiness when treated with 0.45 kGy radiation. Al-Bachir (1999) studied the effect of different doses of gamma irradiation (0, 0.5, 1.0 and 1.5 kGy) on the two apple varieties, Golden Delicious and Starking, for different storage periods. Irradiation significantly decreased the firmness, changed the color from green to yellow and significantly decreased the pH value of the juice in both apple varieties immediately after treatment. The effect of irradiation was more pronounced after the storage time of 45 days. Miller and McDonald (1995) reported a decline in flavor and texture of ósharpblueô blueberries irradiated with electron beam at 0, 0.25, 0.5, 0.75, and 1.0 kGy. The decline was linear with the dose increment after 7 days storage period. However, the other quality parameters such as skin color, waxy bloom, weight loss, decay, soluble solids concentration, acidity, pH were not affected by dosage or storage.

Dinnocenzo and Lajolo (2001) observed that low dose gamma-irradiation (0.5 kGy) had no direct effect on firmness of papaya fruit; however, it delayed several indices of fruit ripening, such as skin color, sugars and firmness. Kim and Yook (2009) investigated the effect of gamma-irradiation (0, 1, 2, and 3 kGy) on kiwifruits. Fruits exposed to 3-kGy irradiation showed negative effects on vitamin C content, antioxidant activity, and textural property but it positively contributed to improve sensory quality. Irradiation treatment also induced softness in fruits but the color and organic acid content were not much affected. Akter and Khan (2012) tested the combination of irradiation treatment (250, 500, and 750 Gy) and storage temperature (4, 12, and 25°C) to control annual post-harvest losses of BARI Hybrid-3 tomatoes in Bangladesh. Radiation did not affect color of tomato and it did not differ significantly with dose as well.

Instant firmness loss was detected in irradiated tomatoes stored at 25°C and firmness decreased more in 500 and 750 Gy treated fruits. Considering overall quality parameters, a dose of 750 Gy combined with 12°C storage temperature found ideal for this variety to reduce post-harvest losses.

Combination Technologies for Improved Quality of Irradiated Fresh Fruits

Combined preservation treatments can be advantageous for improving quality due to their synergistic effects (Raso et al., 2003). Lacroix and Ouattara (2000) reported that the use of combined treatments with irradiation had a synergistic effect on reducing the microorganism load and the irradiation dose required to eliminate pathogenic bacteria. The use of edible coatings in combination with gamma irradiation has been proven effective for increasing the shelf life of many foods. Vachon et al. (2003) reported that irradiation used in combination with modified atmosphere packaging (MAP) or edible coatings proved to be effective in maintaining the safety of fruits and vegetables and extending their shelf life. Irradiation reduced the numbers of existing microbial populations while MAP suppressed the growth of the surviving microorganisms during the subsequent storage.

Fan et al. (2005) investigated the effects of calcium ascorbate and ionizing radiation on the quality of óGalaô apple slices under modified atmosphere packaging. Different irradiation doses and calcium ascorbate treatments were used and the samples were stored for 3 weeks. Irradiation did not affect the titratable acidity and pH of the sliced apples. Fruit slices softened during irradiation and storage, but this decrease in firmness during storage was reduced by the calcium ascorbate treatment. The combination of ascorbate and irradiation enhanced microbial food safety while maintaining the quality of the fresh-cut apple slices.

The use of edible coatings in combination with gamma irradiation has been proven effective for increasing the shelf life and maintaining the quality of fresh strawberries. A treatment of 1.5 kGy applied to strawberries coated with a cross-linked edible film was useful in reducing water loss and mold growth; it also extended the shelf life by more than 15 days during storage at 4°C (Vachon et al., 2003). Hussain et al. (2010; 2012) also found similar results using carboxymethyl cellulose coating for gamma-irradiated pear and strawberry during refrigerated storage.

Farkas (1990) reported that the use of irradiation in combination with heat had also synergistic effects that included the destruction of vegetative bacteria and bacterial spores. Moreover, when irradiation was carried out in the absence of air, enhanced bactericidal effects were observed during heat treatment. This combined treatment offers potential for delayed ripening and reduction of microbial spoilage in mangoes, tomatoes, and other fruits and vegetables. Similarly, the combination of an edible coating and irradiation treatment has also been found effective in maintaining the quality of fresh strawberries. A treatment of 1.5 kGy applied to strawberries coated with a cross-linked edible film was useful in reducing water loss and mould growth; it also extended the shelf life by more than 15 days during storage at 4°C. Wani et al. (2008) described the effect of different gamma-irradiation doses (0.8ï 2.0 kGy), alone and in combination with refrigeration, for extending the shelf life of pears. Mature green pears were irradiated with different doses and stored under ambient temperature or refrigerated conditions. Irradiation doses of 1.5ï 1.7 kGy significantly inhibited the decaying of pears up to 16 days in ambient storage. In addition, irradiation in combination with refrigeration prevented

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the decaying of the pears up to 45 days, while 35% decay was observed in the non-irradiated samples.

Gagnon et al. (1993) and Lacroix et al. (1991 and 1993) reported the possibility of using ionizing radiation in combination with a hot water dip treatment to enhance the shelf life of fresh mangoes. Their results showed that after 30 days of storage, the percentages of rotten fruits were 100% for the controls, 80% for samples irradiated at 1.0 kGy, and 20% for samples treated with the hot water dip in combination with irradiation at 1.0 kGy. No adverse effects were observed on the nutritional and chemical qualities of the mangoes from the use of this combined treatment. This combined treatment also delayed the changes in color. Similar combination treatment studies were conducted on Moroccan citrus fruits at the Canadian Irradiation Center. Results from this study indicated that washing with warm water and waxing caused a great loss due to spoilage in the citrus fruits during storage. In contrast, the fruits irradiated at 0.3 kGy and stored at 3ºC for a period of 8 weeks had less than 11% losses. Sensory evaluation statistics showed that the organoleptic quality was maintained throughout the entire storage period in the irradiated fruits. It also observed that the vitamin C content in irradiated clementines was significantly higher (Abdellaoui et al., 1995).

Consumer Acceptance and Labeling of Irradiated Fresh Fruits

The consumer acceptance of fresh-cut produces includes a combination of attributes, such as appearance, texture, and flavor, as well as nutritional and safety aspects (Fancis et al., 2012). Food Irradiation is encountering a variety of challenges related to consumersô perceptions, acceptance and purchasing behavior along with the need to maintain the physical, nutritional and sensory qualities of the treated food while ensuring the food safety (Cardello, 2003). Despite the fact that irradiated foods and the process of food irradiation have been carefully tested and the greater quality of the treated products has been recognized, the quantity of irradiated foods in the global food trade is not significant (Farkas and Mohacsi-Farkas, 2011)

Deliza et al. (2010) studied the consumer perception of irradiated fruit (papaya) among Brazilian consumers and assessed the joint influence of product appearance, price and information about the use of irradiation. The participants in this study did not reject irradiated papaya; however, it was found the product appearance, as a proxy for product quality, was the most influencing factor to purchase papaya. Likewise the research carried out in the U.S.A. and elsewhere, Deliza et al. (2010) also concluded that the rate of acceptance of irradiated fruit increased with the provision of appropriate information. In a similar study, Martins et al. (2008) showed that irradiated watermelon and pineapple with doses up to 2.5 kGy were acceptable for consumers.

Many consumers have misconceptions about the technology and get confused, when failing to differentiate between irradiated and radioactive foods. Public education related to the health benefits of safe food production and the role of irradiation could promote the acceptance of this technology (Arvanitoyannis, 2010). It has been observed in some countries that when consumers are provided with sufficient information, they come to realize the benefits of irradiated foods. In the states of Michigan and Florida, public education efforts have gained some success in changing peoplesô attitudes towards irradiated foods. In addition, one storeôs efforts have also been proven successful in selling a variety of irradiated produce including grapefruits, oranges, onions, tomatoes, mushrooms and blackberries. Studies have revealed that consumers could be positively inclined toward the irradiation process when knowing that it can eliminate harmful microbes and reduce the threat posed by foodborne diseases (Lacroix and Vigneault, 2007).

Behrens et al. (2009) studied the consumer attitude towards food irradiation in São Paulo, Brazil. Both irradiated and non-irradiated food samples were served during sessions to 30 consumers that were divided in three groups. Differences between the irradiated and the non-irradiated samples were hardly perceived by any of the groups. Even when provided with positive information about irradiation and its benefits to foodstuffs and human health, many people still remained suspicious about the safety of the technology. Risk perception seemed to be related to unease and lack of knowledge about nuclear power and its non-defense use. The participants wanted more transparency in communication about the risks and benefits of irradiated foodstuffs on human health, especially with respect to its continued consumption. However, new findings and developments related to issues on health, environmental protection, international trade, quarantine and legislation have come to the forefront, and perceptions about food irradiation are changing rapidly, especially with respect to the potential that the technology offers for solving some of the most vital problems in these areas (Arvanitoyannis et al., 2009). Advertising trials of irradiated foodstuffs have been conducted over the past several years in countries such as France, Hungary, USA, Holland, Belgium, Argentina, Chile, China, Poland, Thailand, Indonesia, Bangladesh, India, Pakistan and the Philippines, all with favorable outcomes (Mostafavi et al., 2010). Junqueira-Gonc-alves et al. (2011) conducted a survey on the knowledge and acceptance level of food irradiation in Santiago, Chile. A total of 497 persons were interviewed. The statistics revealed that consumers were interested in new technologies but they needed enough information and knowledge about these technologies before deciding to accept them. Among the interviewed people, 76.5% did not know that irradiation could be used as a method for food preservation; 46% expressed their belief that irradiated foods meant the same as radioactive foods. Nevertheless, 91% claimed that they would become consumers of irradiated foodstuffs if they knew that óóirradiatedôô is not óóradioactiveôô and that proper irradiation could enhance food safety; 95.8% of the interviewed consumers were not familiar with the óóRaduraôô symbol. However, 55.8% expressed their opinion that they would buy irradiated food because of the symbol, affirming that the óóRaduraôô symbol transmits a sensation of confidence and safety. Therefore, an extensive effort is required in order to provide consumers with scientific and accredited information about food irradiation since the lack of information and understanding are the main obstacles for the general acceptability of this technology.

The European Union has adopted framework Directive 1999/2/EC and implemented Directive 1999/3/EC for the uniform application of regulations regarding irradiated foods. Authenticated identification methods confirming the irradiation status of fruits could play a very important role to ensure the right of choice by consumers. Due to mandatory labeling requirements, the proper monitoring of the irradiation process and traceability of irradiated products in the market, the need for effective and reliable detection methods has become more crucial. Serious efforts were made in this regard by the Research Coordination Program on Analytical Detection Methods for Irradiation Treatment of Foods (ADMIT) in the late 1980s and early 1990s (Stewart, 2010). The European Union (EU) also played a leading role in the standardization of the available identification methods, conducting more than 30 interlaboratory blind trials to validate the proposed methods. Currently, the European Union has standardized 10 different methods, which are also endorsed by the Codex Alimentarius. The identification techniques can be categorized as physical (photostimulated luminescence, thermoluminescence, and electron spin resonance analysis), chemical (gas chromatographic analysis of radiation-induced hydrocarbons and 2-alkylcyclobutanones), and biological methods (DNA comet assay, microbial screening using direct epifluorescent filter technique/aerobic plate count, and the LAL/GNB procedure) depending on the basic principles of the related techniques. These methods are also classified as screening and confirmatory techniques depending on their specificity, reliability, reproducibility, and ease of use (Chauhan et al., 2009). Recently, Akram et al. (2012) wrote a comprehensive book chapter containing the details on the applications, limitations, and comparisons of these detection methods.

CONCLUSIONS

Food irradiation is an effective food preservation technique that can be used to ensure the better quality of fresh fruits with an extended shelf-life. The risks of food-borne diseases can also be minimized using this technology. The proper selection of the applied dose alone or in combination with other useful preservation methods can greatly increase the potential of the irradiation process for fresh commodities. The studies on combined techniques involving the use of irradiation along with other preservation methods presented in this review show considerably beneficial effects to reduce microbial population, enhance shelf-life, and improve the quality of fruits. Consumer acceptance of irradiated fruits is a matter of proper education with research-oriented scientific facts. Validated methods that identify irradiated foods have been devised to verify compliance with existing regulations on irradiated foods.

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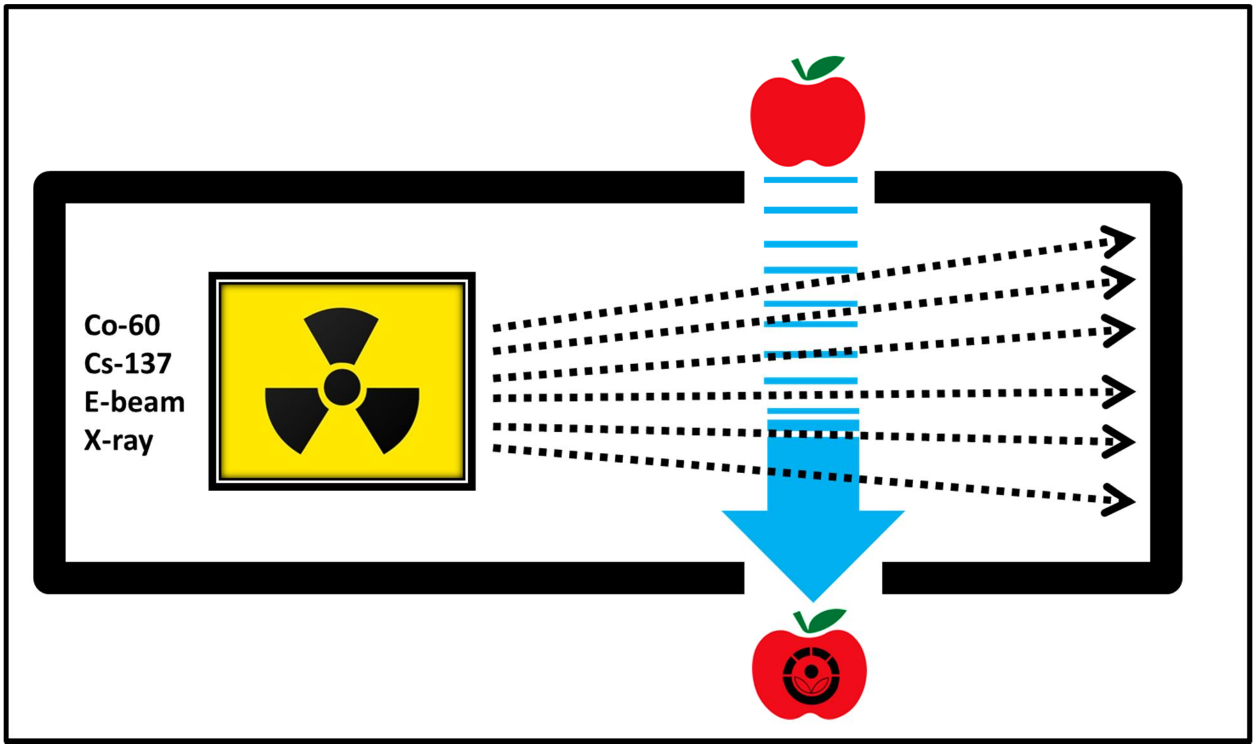

Figure 1 Process for the irradiation of fruits (Blackburn, 2011).

Table 1 Approved use of ionizing radiations for fruits in different countries

Objectives	Fresh Fruits	Country	Date	Dose
Delay ripening/ physiological growth	Any	Algeria	2005-04-11	Medium absorbed dose of 10 kGy
	Any	Bangladesh	2005-06-01	1.00 (max)
	Mangoes	Chile	1982-12-29	1.00 (max)
	Any	Croatia	1994-06-21	3.00 (max)
	Avocados	Cuba	1992-08-01	0.25 (max)
	Mangoes		1992-07-01	0.75 (max)
	Any	Brazil	2001-01-30	Not specific
	Any	Ghana	1997-01-15	1.00 (max)
	Mangoes	India	1998-04-06	1998-04-06
	Any	Israel	1987-02-17	1.00 average
	Any	Mexico	2005-09-06	10.00 (max)
	Any	Paraguay	2000-01-31	1.00 (max)
	Any	Peru	2001-12-05	1.00 (max)
	Any	Russian Federation	1964-07-11	0.03 (max)
	Any	Saudi Arabia	2002-01-07	Not specific
	Any	South Africa	2002-10-29	Not specific
	Any	Syrian Arab Republic	1996-08-02	1.00 (max)
	Papaya, Mangoes	Thailand	1986-12-04	1.00 (max)
	Any	Turkey	1999-11-06	1.00 (max)
	Any	United States of America	1986-04-18	1.00 (max)
	Any	Vietnam	1999-11-06	1.00 (max)
	Any	Zambia	-	1.00 (max)
	Any	Algeria	2005-04-11	Medium absorbed dose of 10 kGy
	Any	Bangladesh	Not available	1.00 (max)
	Any	Brazil	2001-01-30	Not specific
	Date, Papaya, Mangoes	Chile	2001-01-30	1.00 (max)
	Dates, papaya,	Costa Rica	1994-07-07	1.00 (max)

	Mangoes			
	Any	Croatia	1994-06-21	3.00 (max)
	Any	Czech Republic	2004-03-12	1.00 (max)
	Any	Ghana	1997-01-15	1.00 (max)
	Mango	India	1998-04-06	0.75 (max)
	Any	Israil	1987-02-17	1.00 average
	Any	Mexico	2005-09-06	10.00 (max)
	Any	Paraguay	2000-01-31	1.00 (max)
	Any	Peru	2001-12-05	1.00 (max)
	Any	Russian Federation	1964-07-11	0.03 (max)
	Any	Saudi Arabia	2002-01-07	Not specific
	Any	South Africa	2002-10-29	Not specific
	Any	Turkey	1999-11-06	1.00 (max)
	Any	Ukraine	1964-07-11	0.03 (max)
	Any	United States of America	1986-04-18	1.00 (max)
	Any	Vietnam	1999-11-06	1.00 (max)
	Any	Zambia	Not available	1.00 (max)
Shelf-life extension	Any	Algeria	2005-04-11	Medium absorbed dose of 10 kGy
	Strawberries	Argentina	1989-04-03	2.50 (max)
	Any	Bangladesh	Not available	2.50 (max)
	Strawberries	Belgium	2004-06-08	2.00 (max)
		Brazil	2001-01-30	Not specific
	Mango Strawberry	Chile	1982-12-29	1.00 (max) 3.00 (max)
	Any (fresh fruits)	China	1997-06-10	1.50 (max)
	Mango Strawberry	Costa Rica	1994-07-07	1.0 (max) 3.00 (max)
	Any	Czech Republic	2004-03-12	2.00 (max)
	Any	Ghana	1997-01-15	2.50 (max)
	Any	Mexico	2005-09-06	10.00 (max)
	Any	Paraguay	2000-01-31	2.00 (max)
	Any	Peru	2001-12-05	2.50 (max)
	Any	Philippines	2004-03-01	1.00 (max)

	Any	Russian Federation	1964-07-11	0.03 (max)
	Any	Saudi Arabia	2002-01-07	Not specific
	Any	South Africa	2002-10-29	Not specific
	Any	Syrian Arab Republic	1996-08-02	2.50 (max)
	Any	Turkey	1999-11-06	1.00 (max)
	Any	Ukraine	1964-07-11	0.03 (max)
	Any	Vietnam	1999-11-06	1.00 (max)
	Any	Zambia		2.50 (max)
Quarantine control	Any	Algeria	2005-04-11	Medium absorbed dose of 10 kGy
	Breadfruit, Longan, Litchi, Mango, Mangosteen, Rambutan, papaya (paw paw)	Australia	2003-02-27	0.15 (min)- 1.00 (max)
	Any	Bangladesh	2005-06-01	1.0 (max)
	Any	Brazil	2001-01-30	Not specific
	Any	Croatia	1994-06-21	3.00 (max)
	Any	Czech Republic	2004-03-12	1.00 (max)
	Any	Ghana	1997-01-15	1.00 (max)
	Any	Mexico	2005-09-06	10.00 (max)
	Carambola, Custard apple, Longan, Litchi, Mangoes, Mangosteen, Papaya, Rambutan	New Zealand	2003-02-27	0.15 (min)- 1.00 (max)
	Any	Peru	2001-12-05	1.00 (max)
	Any	Philippines	2004-03-01	1.00 (max)
	Any	Russian Federation	1964-07-11	0.03 (max)
	Any	Saudi Arabia	2002-01-07	Not specific
	Any	South Africa	2002-10-29	Not specific
	Any	Syrian Arab Republic	1996-08-02	1.00 (max)
	Any	Turkey	1999-11-06	1.00 (max)
	Any	Ukraine	1964-07-11	0.03 (max)
	Any	United States of	1986-04-18	1.00 (max)

	America		
Any	Vietnam	1999-11-06	1.00 (max)
Any	Zambia	Not available	1.00 (max)

Adapted from IAEA online database (http://nucleus.iaea.org/ifa/FoodAuthorisationDisplay.aspx)

last accessed on October 14, 2012.

Table 2 Recommended irradiation doses for the quarantine treatment of fresh fruits (IAEA, 2002)

Fruit commodity	Common name of insect	Scientific name of insect	Irradiation dose (Gy)	
			To inhibit development of immatures	To sterilize adults
Pome, stone fruits	Oriental fruit moth	*Grapholita molesta* (Lepidoptera: Tortricidae)	-[a]	200
Pomegranate	Mite	*Tenuipalpus granati* (Acari: Tenuipalpidae)	-	400
Apples, pears, walnuts, quince	Codling moth	*Cydia pomonella* (Lepidoptera: Tortricidae)	200	-
Tomato	Tomato fruit borer	*Phyllocopreuta oleivora* (Acari: Eriophyidae)	400	300
Citrus	Citrus rust mite	*Phyllocopreuta oleivora* (Acari: Eriophyidae)	-	350
Avocados	Mediterranean fruit fly	*Ceratitis capitata* (Diptera: Tephritidae)		100
Pome, stone fruits	Plum curculio	*Conotrachelus nenuphar* (Coleoptera: Curculionidae)	-	92
Sweet potato	Sweetpotato weevil	*Cylas formicarius* elegantulus (Coleoptera: Curculionidae)	-	165
Mango	Mango seed weevil	*Sternochetus mangifera* (Coleoptra: Curculionidae)	-	300
Litchi, longan, rambutan, macadamia	Koa seedworm	*Cryptophlebia illepida* (Lepidoptera: Tortricidae)	250	125
Litchi, longan, rambutan, macadamia	Litchi fruit moth	*Cryptophlebia ombrodelta* (Lepidoptera: Tortricidae)	250	125

[a]Not applied or not available

Table 3 Effect of ionizing radiations on the microbial load of fresh fruits

Commodity	Irradiation dose/type	Storage temperature /conditions	Effect on microbial quality	Reference
Strawberries	1-10 kGy ɔ-rays	Ambient temperature	D10 value 2.97 ± 0.18 kGy was required to achieve a 1-log reduction in HAV titre	Bidawid et al. (2000)
Melons (*Cucumis melo*)	1 and 3 kGy	5ºC	Fungal growth and coliform bacteria completely controlled during seven days storage at 1 kGy treatment	Bibi et al. (2006)
Apple (*Pyrus malus*)	2.0 kGy	5ºC	Fully controlled fungal growth and coliform bacteria during seven days storage	Bibi et al. (2006)
Papaya *(Carica papaya)*	0.7 and 1 kGy ɔ-rays	25ºC and RH 80% for 7days	Reduced lesion size caused by *Colletotrichum gloeosporioides* and anthracnose incidence in papaya fruit when applied after fruit inoculation, but did not protect the fruit when applied 24, 48, or 72 h before inoculation. These doses inhibited *Colletotrichum gloeosporioides* conidial germination and mycelial growth, but stimulated fungal sporulation	Cia et al. (2007)
Roma tomatoes	0.1, 0.5, 0.75, 1.0, and 1.5 kGy X-ray	20 days at 22ºC	Approximately 4.2, 2.3, 3.7 and 3.6 log CFU reduction of *E. coli* O157:H7, *L. monocytogenes*, *S. enterica* and *S. flexneri* per tomato were achieved by treatment with 0.75 kGy X-ray, respectively. More than a 5 log CFU reduction per tomato was achieved at 1.0 or 1.5 kGy X-ray for all tested pathogens	Mahmoud (2010)
Tomato	Combined e-beam irradiation (up to 0.9 kGy) and 1% calcium		D-value results ranged from 0.26 to 0.39 kGy, indicating that a 5 log (10) CFU/g reduction in *Salmonella* spp. in diced tomatoes would require a dose of 1.3-1.95 kGy	Prakash et al. (2007)

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	chloride			
Cantaloupe (*Cucumis melo reticulatus*)	4.54 and 4.76 kGy e-beam		D10 values of Poliovirus Type 1 with 4.54 kGy. D10 values of MS2 bacteriophage with 4.76 kGy	Pillai et al. (2004)
One hundred random fruit samples	1.5 kGy	<10ºC for 28 days	Initial viable population of fungi ranged from $4.8*10^4$ to $6.8*10^5$ per gram and decreased to $4.88*10^2$ after storage	Aziz and Moussa (2002)
Mix fruits (100 samples)	3.5 kGy	<10ºC for 28 days	Initial viable population of fungi ranged from $4.8*10^4$ to $6.8*10^5$ cfu/g and decreased to $1.39*10^1$ cfu/g after storage	Aziz and Moussa (2002)
Pears	1.5ï 1.7 kGy ɔ-rays	Refrigerated conditions (37±1ºC, RH 80%)	Synergistic effect of gamma irradiation and refrigeration delayed the physiological processes and inhibited microbial proliferation which resulted in delayed decaying of pears and enhanced the shelf life by30 days	Wani et al (2008)

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Table 4 Effect of ionizing radiations on the quality attributes and shelf-life of fresh fruits

Commodity	Irradiation dose/type	Storage period/ temperature	Quality attributes	Shelf-life extension	Reference
Apples (Gala)	0.3 and 0.9 kGy ɔ-rays		Titratable acidity (TA) reduced at irradiation levels of 0.60 kGy and above		Drake et al. (1999)
Apples (Fuji)	1.5, 4.5, 5, and 6 kGy ɔ-rays		Highly affected the Vitamin C content, dehydration rate and rehydration ratio. The greater the dose, the higher the dehydration rate, the less the vitamin C content, and the lower the re-hydration ratio		Wang and Chao (2003)
Mango (Tommy Atkins)	1.0, 1.5, and 3.1 kGy e-beams	12°C and 62.7% Relative Humidity (RH) for 21 days	No effect on textural characteristics at doses higher than 1.0 kGy. Mangoes exposed to 1.5 and 3.1 kGy were softer and less stiff throughout storage. Therefore, 1.0 kGy is the recommended treatment to maintain the overall fruit quality attributes		Moreno et al. (2006)
Mango (Alphonso, Dasheri & Langra)	0.05ï 0.3 kGy ɔ-rays in combination with different types of food grade packaging materials	28-32ºC	Delayed ripening, as indicated by higher retention of fruit color and reduction of Physiological weight loss	10-15 days	Janave and Sharma (2005)
Mango (Alphonso)	0.1 kGy ɔ-rays	28-32ºC		5-6 days	Janave and Sharma (2005)

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Mango (Pre-climacteric) Pears	0.2 kGy ɔ-rays 1.5ï 1.7 kGy ɔ-rays	 25±2ºC and RH 70%	 Firmness and acidity showed declined trend with storage. Overall acceptability based on color, texture and taste was signiýcantly higher in irradiated pears than control non-irradiated ones	8-10 days 14 days	Janave and Sharma (2005) Wani et al. (2008)
Grapefruits (*Citrus paradisi* c.v. Rio Red)	0.15 and 0.3 kGy ɔ-rays	36 days at 10ºC followed by an additional 20 days at 20ºC	Irradiation or storage had no considerable effect on total soluble solids; however, acidity decreased		Vanamala et al. (2007)
Bananas	0.30, 0.40 and 0.50 kGy ɔ-rays	Dry place under room conditions	Chemical constituents of the irradiated banana were the same and no major changes were observed in the nutritional and organolaptic qualities except a minor change in the ascorbic acid content	20 days	Zaman et al. (2007)
grapes (America red globe)	0.2, 0.4, 0.6 and 1.0 kGy X-rays	1.5°C & RH 70% for 22 days	No significant effect of irradiation on other physical and chemical quality of grapes (weight loss, total soluble solids, titratable acidity, protein, mineral, sweet and taste)		Kang et al. (2012)
Papaya	0.5 kGy ɔ-rays	22ºC and RH 90%	2 days delay to the onset of ripening time by irradiation. The total soluble solids of both treated and control fruits increased from 8% to 12% and were not affected by irradiation		Dinnocenzo and Lajolo (2001)

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Papaya	0.75 kGy ͻ-rays	4 different periods of storage	Irradiation maintained firmness of papaya and, therefore, delayed ripening. No effect of irradiation in fruit weight loss, occurrence of diseases, pH and total soluble solids contents	Pimentel and Walder (2004)
Strawberries (Fresh Tristar)	1and 2 kGy e-beams	2ºC	Water-soluble pectin increased and oxalate-soluble pectin decreased at 0 and 1 day after 1 and 2 kGy irradiation. Total pectin and non- extractable pectin were not affected by irradiation	Yu et al. (1996)
Blueberries	1.0 ï 3.2 kGy e-beams	5°C and 70.4% RH for 14 days	Medium dose levels (1.0ï 3.2 kGy) did not affect the density, pH, water activity, moisture content, acidity and juiciness of fruits. However, blueberries exposed to 3.2 kGy were found unacceptable by the sensory panelists	Maria et al. (2007)
Blueberries	1.0ï 2.0 kGy e-beams	5°C and 70.4% RH for 14 days and tested at days 0, 3, 7 and 14	1.6 kGy is a feasible decontamination treatment that maintains the overall fruit quality attributes. Fruits became considerably softer and less acceptable throughout storage at irradiation doses higher than 1.1 kGy	Moreno et al. (2007)

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Guava (*Psidium guajava* L.) (Lucknow-49 and Allahabad Safeda)	0.25, 0.5, and 1.0 kGy ɔ-rays	0.25 kGy dose increased the postharvest life of fruit by 3ï 4 days, maintained fruit quality, and reduced the decay incidence Ionizing radiation with low-temperature storage (10ºC) did not have much synergistic effect on storage life and quality of guava fruit	3-4 days	Singh and Pal (2009)

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Table 5 Effect of ionizing radiations on the sensory properties of fresh fruits

Commodity	Irradiation dose/type	Storage period/ temperature	Sensory properties	Reference
Pears (Bosc)	0.30 ï 0.90 kGy ɔ-rays		Firmness loss due to irradiation and it was dose dependent.	Drake et al. (1999)
Apples (Fuji & Granny Smith)	0.15, 0.3, 0.6 and 0.9 kGy ɔ-rays	30, 60 and 90 days ambient atmosphere at 1ºC	No quality losses reported at irradiation doses of 0.3 kGy or less. No loss of either total or individual carbohydrates was associated with irradiation treatment	Drake et al. (2003)
Apples *(Pyrus malus)*	0.5ï 3.0 kGy ɔ-rays		Hardness of apples decreased with increasing dose levels as well as during storage	Bibi et al. (2006)
Papaya	0.5 kGy ɔ-rays	22ºC and 90% RH	Both irradiated and non-irradiated fruits ripened normally with respect to sugar content, color, change, ýrmness, and general appearance of the fruit	Dôinnocenzo and Lajolo (2001)
Cantaloupes	1.0, 1.5 and 3.1 kGy e-beam		No significant changes on the fruitôs physical and nutritional quality attributes up to 1.0 kGy but higher doses had an undesirable effect on product quality	Castell-Perez et al. (2004)
Peaches (*Prunus persica*)	0.29, 0.49, 0.69 and 0.90 kGy ɔ-rays		Irradiation did not adversely affect shelf life but was seen to enhance ripening which was perceived as a positive change by consumers. Overall, consumers rated the acceptability of irradiated peaches higher than untreated peaches	McDonald et al. (2012)
Mangoes (Chok	0.4 and 0.6 kGy		Irradiation had no effect on skin or þesh color. Ripened irradiated ñChok Ananò mangoes harvested at 70% and	Uthairatanakij et al. (2006)

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Anan)	ɔ-rays		90% maturity were softer than untreated fruits	
Pineapple *(Ananas comosus)* 3/4 ripe and fully ripe	0.05, 0.1, and 0.15 kGy ɔ-rays	25-29ºC and 90-97% RH	Maintained their texture better than the controls	Susheela et al. (1997)
Melons *(Cucumis melo)*	2.5 kGy ɔ-rays	5ºC for 14 days	Maintained the sensory qualities within acceptable limits	Bibi et al. (2006)
Mango	1 kGy ɔ-rays		Significant modiýcations were observed in sugars which account for nearly 99% of the reactions. The other components which are slightly reactive are starch (0.2%), protein (0.2%), phenol (0.4%) and ascorbic acid (0.2%)	Basson et al. (1978)
Pears (Anjou and Bosc)	0.15, 0.3, 0.6 and 0.9 kGy ɔ-rays	30 and 90 days in ambient atmosphere at 1ºC	No quality losses reported at irradiation doses of 0.3 Gy or less. No loss of either total or individual carbohydrates was associated with irradiation treatment	Drake et al. (2003)
Papayas, rambutans, and Kau oranges	0.75 kGy X-rays		Aroma and þavor tended to be more intense in the irradiated fruit. Firmness decreased as a result of irradiation and storage, though it was signiýcant only in rambutans	Boylston et al. (2002)
Clementine mandarin fruits (*Citrus reticulate*)	0.195 and 0.395 kGy X-ray irradiation	1.5ºC for 14 days	Acetaldehyde and ethanol contents of the irradiated fruit were higher along with both X-ray dosage and storage period. Nominal differences in juice yield between X-ray irradiated and cold-treated fruits	Alonso et al. (2007)

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