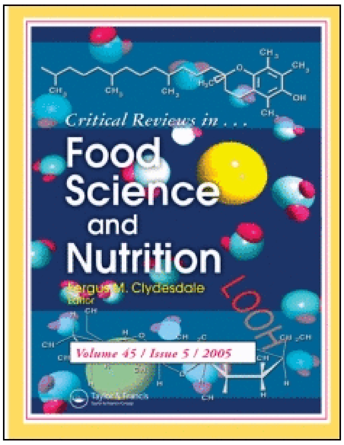

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Irradiation Applications in Vegetables and Fruits: A Review

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There is an increasing trend both in advanced countries and many developing countries to centrally process fresh fruits and vegetables, properly packaged, for distribution and marketing. Irradiation technology proved to be effective in reducing post-harvest losses, and controlling the stored product insects and the microorganisms. Gamma irradiation was employed to restrain potato sprouting and kill pests in grain. Irradiation proved to be extremely beneficial in terms of prolonging the fruit and vegetable shelf life by 3–5 times. In order not to expose fruits and vegetables to high irradiation doses another approach is to use the "hurdle technology," that is to apply more than one technology toward better quality and longer shelf life. This review summarizes a) all the obtained results in this field (either irradiation on its own or in conjunction with other technologies) on fruits and vegetables in 11 figures and eight (8) very comprehensive tables, and b) provides an insight in the various methods (EPR, TL, Comet assay among others) for detection of irradiated foods.

Keywords irradiation, γ-rays, fruits, vegetables, hurdle technology, shelf life, irradiation detection

INTRODUCTION

There is an increasing trend both in advanced countries and many developing countries to centrally process fresh fruits and vegetables, properly packaged, for distribution and marketing. Changes occurring in demographics, lifestyles, and eating habits have been cited as some of the reasons for the increasing demands for fresh cut or minimally processed fruits and vegetables. Sales of fresh-cut fruits and vegetables continue to flourish (IAEA, 2006). For that reason there is great interest focused on produce-associated foodborne illnesses (Thayer and Rajkowski, 1999). New tools to ensure the safety of fresh and fresh-cut produce are required and low dose irradiation is one of the most promising (Niemira and Fan, 2006). Food irradiation is a physical means of food processing that involves exposing the pre-packaged or bulk foodstuffs to gamma rays, X-rays, or electrons. Foodstuffs are generally irradiated with gamma radiation from a radioisotope source, or with electrons or X-rays generated using an electron accelerator (Barbosa-Canovas et al., 1998).

Due to the strong desire to reduce the use of chemicals applied to fruits and vegetables, the non-residual feature of ionizing radiation is an important advantage. Internationally, food irradiation has been considered a safe and effective technology by the World Health Organization (WHO), the Food & Agriculture Organization (FAO), and the International Atomic Energy Agency in Vienna (El-Samahy et al., 2000). The potential application of ionizing radiation in food processing is based mainly on the fact that ionizing radiations damage very effectively the DNA so that living cells become inactivated, therefore microorganisms, insect gametes, and plant meristems are prevented from reproducing, resulting in various preservative effects as a function of the absorbed radiation dose. At the same time, radiation-induced other chemical changes in food are minimal (Thayer, 1990). Furthermore, irradiation technology proved to be effective in reducing post-harvest losses, and controlling the stored product insects and the microorganisms (Ahmed, 1993). For instance, gamma irradiation was employed to restrain potato sprouting, kill pests in grain, modify some ingredients, and bring about changes in the physical-chemistry and sensitization of food (Wang and Chao, 2002). Gamma irradiation has long been employed for decontamination and/or sterilization of dehydrated vegetables (Guo et al., 1993; Zhou et al., 1996), fruits (Li and Hao, 1993; Yu et al., 1993; Zhang et al., 1993), seasonings (Chen et al., 1993), and animal feed (Yang et al., 1993).

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QUALITY AND SHELF LIFE EXTENSION OF IRRADIATED FRUITS

Basson et al. (1978) found that for mango, irradiated with 1kGy, the only compounds to undergo significant modifications are the 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%). Therefore, only carbohydrate degradation needs to be considered. Furthermore, carbohydrate reactivity tends to protect the other components from degradative changes.

D'innocenzo and Lajolo (2001) used irradiation treatment as an imposed stress to cause changes in firmness. Physiologically mature papaya fruits were irradiated (0.5 kGy) and allowed to ripen at 22°C and 90% RH. Irradiation caused a two-day delay on the onset of ripening time. The total soluble solids (°Brix) of both treated and control fruits, increased from 8% to 12% and were not affected by irradiation.

A study was conducted on early and late season "Rio Red." Fruit was treated with 0, 0.07, 0.2, 0.4, and 0.7 kGy and then stored under 10°C for 4 weeks followed by 1 week at 20°C with 90–95% relative humidity. It was demonstrated that irradiation doses of up to 0.7 kGy had no significant effect on the Vitamin C content of early-season grapefruit. Late season fruit exposed to irradiation greater than or equal to 0.2 kGy caused a marked reduction in Vitamin C content after 35 days of storage. Soluble solids (%) were not affected due to irradiation or storage of early-season fruit. On the other hand, late-season fruit had lower soluble solids (%) and acidity values than early-season fruit and the soluble solids/acid ratio after 35 days of storage were slightly higher than the initial ratios (Patil et al., 2004).

According to Assi et al. (1997) mature green and pink tomato (*Lycopersicon esculentum* Mill.) fruit were subjected to ionizing irradiation in the range of 0.7 to 2.2 kGy from gamma- or X-ray sources. Fruit irradiated at the mature-green stage softened during post-irradiation storage (20°C) but exhibited an apparently irreversible suppression in polygalacturonase activity, with levels remaining lower than 10% of those of non-irradiated fruit. Polygalacturonase activity was less strongly affected in irradiated pink fruit than in mature-green fruit, but activity remained reduced relative to the controls. Pectinmethylesterase and β-galactosidase activities were significantly enhanced in irradiated fruit of both ripening stages in the early period following irradiation, but reductions were noted after prolonged storage.

Wang et al. (2006) measured and analyzed the enzyme activity in Golden Empress cantaloupe juice after ^{60}Co irradiation. Enzyme activity determination revealed that lipoxygenase was the easiest one to be inactivated by irradiation, followed by polyphenoloxidase and peroxidase. However, all three enzymes remained active even at 5 kGy.

Fresh Tristar' strawberries were irradiated with electron beam irradiation at 0, 1, and 2 kGy. Fruit firmness decreased as irradiation dose increased. Water-soluble pectin increased and oxalate-soluble pectin decreased at 0 and 1 day after 1 and 2 kGy irradiation. Fruit firmness was correlated with oxalate-soluble pectin content. Total pectin and non-extractable pectin were not affected by irradiation. The oxalate-soluble pectin content and firmness of irradiated strawberries increased slightly at the beginning of 2°C storage and then decreased as storage time increased. No changes occurred in water-soluble pectin, non-extractable pectin, or total pectin during storage (Yu et al., 1996).

Susheela et al. (1997) found no significant loss of sugar and ascorbic acid contents in three-quarter ripe and fully ripe pineapple fruit (*Ananas comosus*) irradiated at 0.15 kGy.

Single-strength orange juice was exposed to 0, 0.89, 2.24, 4.23, and 8.71 kGy gamma radiation at 5°C, and then stored at 23°C for 6 days and 7°C for 21 days. Both ascorbic acid (AA) and dehydroascorbic acid (DAA) concentrations decreased with increased radiation dose. Juice irradiated at all doses had lower AA and TAA content than non-irradiated juice. TAA loss following irradiation treatment was less than half that of AA. The conversion of AA to DHA was promoted by irradiation. Both the concentration and the percentage of DHA increased linearly with increased radiation dose. Irradiation did not alter the non-AA antioxidant activity (Fan et al., 2002).

Paull et al. (1996) reported that papaya fruits (*Curica papaya* L.) treated with 0.25 kGy of γ-irradiation frequently softened more uniformly than non-irradiated fruit. Fruit with less than 25% of their surface colored yellow placed immediately into storage at 10°C after irradiation developed skin scald. This was prevented by delaying storage by 12 h. Fruits that were irradiated when 30% of the skin was yellowed softened at a slower rate than non-irradiated fruits. There was no difference in the softening rate between irradiated and non-irradiated fruits at the mature green stage. Fruit stored for 14 days at 10°C before returning to 25°C had a slightly slower rate of softening than fruit allowed ripening at 25°C without storage. Premature flesh softening occurred occasionally in fruit that had between 8 and 18% of the skin yellow and 70–90% flesh coloring when irradiated.

Wang and Chao (2003) investigated the irradiation effects on dehydration characteristics and quality of apples (Fuji apple). They found that the vitamin C content of apples, the dehydration rate, and the rehydration ratio were greatly affected by irradiation dose (1.5, 4.5, 5, and 6 kGy). It was shown that the greater the dose, the higher the dehydration rate, the less the vitamin C content, and the lower the rehydration ratio.

Rubio et al. (2001) studied the effects of irradiation (0.50, 0.75, and 1.00 kGy) on the vitamin C content of lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea*), and celery (*Apium graveolens*). There was a marked difference in the natural total ascorbic acid content of the vegetables studied with cabbage showing the highest. Irradiation did not decrease these initial concentrations, and in the case of cabbage, it actually increased them.

For lettuce, cabbage, and celery the initial ascorbic acid content was 2.357, 3.085, and 0.549 mg/100 g, respectively and after irradiation was 2.036, 5.018, and 0.616 mg/100 g, respectively irradiated with 1.00 kGy.

According to Drake and Neven (1998), irradiation can be applied to cherries, apricots, or peaches as a quarantine treatment at 0.3 kGy or less with little quality loss. Differences in stem condition and bruising were more evident for irradiated "Rainier" cherries than for methyl bromide (MeBr) treated "Rainier" cherries, but these differences were small. Use of irradiation resulted in some firmness loss, for "Bing" cherries when compared with MeBr, but irradiation treatment of cherries did not result in a loss of fruit and stem color, whereas the use of MeBr doses resulted in both fruit and stem color loss. Apricots ("Perfection" and "Rival") and peaches ("Regina") were tolerant to irradiation at 0.3 kGy with little quality loss. Loss of firmness, color changes, and increased internal breakdown were evident in both apricots and peaches at irradiation dose above 0.6 kGy.

Drake et al. (1999) found that titratable acidity (TA) of "Gala" apples was reduced at irradiation doses of 0.60 kGy and above. On the other hand no loss of TA due to the irradiation dose was evident, for "Fuji" or "Granny Smith" apples.

Vanamala et al. (2007) exposed grapefruits (*Citrus paradisi* c.v. Rio Red) to gamma irradiation at 0, 0.15, and 0.3 kGy and then stored at 10°C for 36 days, followed by additional 20 days at 20°C. Irradiation or storage did not result in considerable changes of the content of total soluble solids in grapefruits. However, there was a considerable decline in the acid content during storage. Fruits exposed to 0.3 kGy of irradiation had higher acidity compared to the control (0 Gy). Moreover, their results suggest that low-dose irradiation at 0.3 kGy enhanced or at least maintained the flavonoid content.

Alonso et al. (2007) found that X-ray irradiation doses of 0.195 and 0.395 kGy had minimal differences in juice yield between X-ray irradiated and cold-treated clementine mandarin fruits (*Citrus reticulate*), with no significant difference between the control and any irradiation treatment. Both acetaldehyde and ethanol contents of the irradiated fruit were higher along with both X-ray dosage and storage period (1.5°C for 14 days). A synoptical presentation of the effect of irradiation on quality improvement and shelf life extension is given in Table 1.

SENSORY PROPERTIES OF IRRADIATED FRUITS

Drake et al. (1999) studied the effect of irradiation on "Gala," "Fuji," and "Granny Smith" apples. Irradiation at doses between 0.30 and 0.90 kGy reduced apple firmness. Doses of <0.30 kGy had no effect on apple firmness. Firmness lost due to irradiation was cultivar dependent. Irradiation did not influence the external color of apples but change in the internal color of "Gala" and "Granny Smith" apples due to irradiation exposure was present. "Bosc" pears lost firmness due to irradiation, and the firmness loss was dose dependent. Both, "Anjou" and "Bosc" ripened normally after irradiation exposure. There was an increase in scald for "Anjou" directly proportional to the applied dose.

According to D'innocenzo and Lajolo (2001), irradiated (0.5 kGy) and non-irradiated papaya fruits, stored at 22°C and 90% RH, ripened normally with respect to sugar content, color change, firmness, and the general appearance of the fruit.

Patil et al. (2004) studied both early and late season "Rio Red" grapefruit. Sensory qualities such as appearance and flavor of early season grapefruit exposed to irradiation treatments at or below 0.4 kGy were comparable to the control after 35 days storage with the exception of the 0.7 kGy treatment, which was found to be detrimental. Appearance rather than flavor of grapefruit was found to be more sensitive to irradiation. Irradiation had no significant effect on the sensory qualities of late season grapefruit.

Assi et al. (1997) studied mature green and pink tomato (*Lycopersicon esculentum* Mill.) fruit that were subjected to ionizing irradiation in the range of 0.7 to 2.2 kGy from gamma- or X-ray sources. Irradiation-induced softening was evident in mature-green and pink fruit within hours following irradiation, and differences between irradiated and control fruit persisted throughout post-irradiation storage (at 20°C). Trends of firmness loss were more consistent and displayed much greater dose dependence on pericarp tissue than whole fruit.

Larrigaudière et al. (1990) reported that γ-irradiation of early climacteric (breaker) cherry tomatoes (*Lycopersicon pimpinellifollium* L.) caused a sharp burst in ethylene production during the first hour. The extent of ethylene production was dose dependent and its maximum was at about 3 kGy. The content of 1-aminocyclopropane-1-carboxylic acid (ACC), followed the same evolution as ethylene production, while malonyl ACC increased steadily with time in irradiated fruits. The burst in ethylene production was accompanied with a sharp stimulation of ACC synthase activity which began 15 minutes after irradiation. γ-Irradiation greatly inhibited the activity of ethylene-forming enzyme at doses higher than 1 kGy. Such sensitivity is in accordance with a highly integrated membrane-bound enzyme.

Wang et al. (2006), after having evaluated sensorially the cantaloupe juice, found that Golden Empress cantaloupe juice developed a slight irradiation off-odor after treatment at 1 kGy, and had strong off-odor at 2 kGy and above. Therefore, the dosage should be less than 1 kGy in order to keep the off-odor within the acceptable range.

Susheela et al. (1997) described the effect of gamma radiation on the three-quarter ripe and fully ripe pineapple fruit *Ananas comosus.* The latter after having been irradiated at 0.05, 0.1, and 0.15 kGy and stored at 25–29°C with 90–97% relative humidity was shown to maintain their texture better than the controls. The maximum tolerable dose was approximately 0.25 kGy.

Follett (2004) investigated the effect of irradiation and heat quarantine treatments on the external appearance of Lychee (*Litchi chinensis*) and Longan fruit (*Dimocarpus longan*). After eight days of storage, lychee fruit treated with hot water immersion was rated as significantly less acceptable than untreated (control) fruit for pericarp appearance when held at 2 or 5°C. Pericarp appearance was more acceptable in irradiated fruit compared to hot water immersion fruit at both storage temperatures but the results were not significant. In another experiment examining the rate of color loss, the pericarp appearance ratings for lychee fruit treated by hot water immersion at 49°C were highest (the least desirable) on all days. Fruit treated by hot water

Table 1 The effect of irradiation on quality improvement and shelf life extension of fruits

Species	Irradiation type/dose	Temperature (°C)	Shelf life	Quality	Refs
Mango	Gamma irradiation 1kGy	—	—	The only compounds to undergo significant modifications are the 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
Papaya	Gamma irradiation 0.5 kGy	22°C and 90% RH	—	Irradiation caused a two-day delay of the onset of ripening time. The total soluble solids (°Brix) of both treated and control fruits, increased from 8% to 12% and were not affected by irradiation.	D'innocenzo and Lajolo, 2001
Early season "Rio Red" grapefruit	Gamma irradiation 0.07, 0.2, 0.4, and 0.7 kGy	10°C for 4 weeks followed by 1 week at 20°C with 90–95% relative humidity for 35 days		Soluble solids (%) were not affected due to irradiation or storage of early season fruit. It was demonstrated that irradiation had no significant effect on Vitamin C content	Patil et al., 2004
Late season "Rio Red" grapefruit	Gamma irradiation 0.07, 0.2, 0.4, and 0.7 kGy	10°C for 4 weeks followed by 1 week at 20°C with 90–95% relative humidity for 35 days		Late season fruit exposed to irradiation greater than or equal to 0.2 kGy caused a marked reduction in Vitamin C content after 35 days of storage. Lower soluble solids (%) and acidity values than early season fruit and the soluble solids/acid ratio after 35 days of storage were slightly higher than the initial ratios	
Mature green and pink tomato (*Lycopersicon esculentum* Mill.) fruit	0.7 to 2.2 kGy from gamma-or X-ray sources	10°C		Polygalacturonase activity was less strongly affected in irradiated pink fruit than in mature-green fruit, but activity remained reduced relative to the controls. Pectinmethylesterase and β-galactosidase activities were significantly enhanced in irradiated fruit of both ripening stages in the early period following irradiation, but reductions were noted after prolonged storage. Irradiation enhanced electrolyte efflux in fruit of both maturity classes.	Assi et al., 1997
Golden Empress cantaloupe juice after	Gamma irradiation 5 kGy			Enzyme activity determination indicated that lipoxygenase was the easiest one to be inactivated by irradiation, followed by polyphenoloxidase and peroxidase, but the 3 enzymes still remained activities even at 5 kGy.	Wang et al., 2006
Fresh Tristar' strawberries	Electron beam irradiation 1, and 2 kGy	2°C		Water-soluble pectin increased and oxalate-soluble pectin decreased at 0 and 1 day after 1 and 2 kGy irradiation. Total pectin and nonextractable pectin were not affected by irradiation. The oxalate-soluble pectin content and firmness of irradiated strawberries increased slightly at the beginning of storage and then decreased as storage time increased. No changes occurred in water-soluble pectin, nonextractable pectin, or total pectin during storage.	Yu et al., 1996
Three-quarter ripe and fully ripe pineapple fruit (*Ananas comosus*)	0.05, 0.1, and 0.15 kGy	25–29°C with 90–97% relative humidity		Maintained their texture better than the controls. The maximum tolerable dose was about 0.25 kGy.	Susheela et al., 1997
Orange juice	0.89, 2.24, 4.23, and 8.71 kGy gamma radiation	23°C for 6 days and 7°C for 21 days		Both ascorbic acid (AA) and dehydroascorbic acid (DAA) concentrations decreased with increased radiation dose. Juice irradiated at all doses had lower AA and TAA content than nonirradiated juice. Irradiation did not alter non-AA antioxidant activity.	Fan et al., 2002
Apples (Fuji apple)	1.5, 4.5, 5, and 6 kGy	—		Vitamin C content of apples, dehydration rate, and rehydration ratio were greatly affected by irradiation dose. The greater the dose, the higher the dehydration rate, the less the vitamin C content, and the lower the rehydration ratio.	Wang and Chao, 2003

(*Continued on next page*)

Table 1 The effect of irradiation on quality improvement and shelf life extension of fruits (*Continued*)

Species	Irradiation type/dose	Temperature (°C)	Shelf life	Quality	Refs
Lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea*), and celery (*Apium grave* Pineapple (*Ananas comosus) olens*)	1.00 kGy			For lettuce, cabbage, and celery initial ascorbic acid content was 2.357, 3.085, and 0.549 mg/100 g, respectively and after irradiation was 2.036, 5.018, and 0.616 mg/100 g, respectively.	Rubio et al., 2001
Carrot (*Daucus carota L.*)	1 and 2 kGy	4°C	—	There was no significant difference in the vitamin C content and total carotenoids in samples and control samples. Variation in the content of vitamin C and carotenoids during storage also was not statistically significant from the control samples. The qualified test panelist could not differentiate between irradiated and non-irradiated samples.	Bandekar et al., 2006
Pre-climacteric mango (Mangifera indica L var. “Alphonso”)	200 Gy	Ambient temperature (28–32°C)	About 8–10 days	—	Janave and Sharma, 2005
Pre-climacteric mango (Mangifera indica L var. “Alphonso”)	100 Gy	Ambient temperature (28–32°C)	5–6 days	—	
“Gala” apples	0.3 and 0.9 kGy	—	—	Titratable acidity (TA) was reduced at irradiation doses of 0.60 kGy and above.	Drake et al., 1999
“Gala,” “Fuji,” and “Granny Smith” apples	0.3 and 0.9 kGy			No loss of TA due to the irradiation dose was evident	
Grapefruits (*Citrus paradisi* c.v. Rio Red)	0.15 kGy	10°C for 36 days, followed by an additional 20 days at 20°C	—	No considerable changes of the content of total soluble solids in grapefruits. However, there was a decline in acid content during storage.	Vanamala et al., 2007
Grapefruits (*Citrus paradisi* c.v. Rio Red)	0.3 kGy	10°C for 36 days, followed by an additional 20 days at 20°C	—	No considerable changes of the content of total soluble solids in grapefruits. However, there was a decline in acid content during storage. Fruits exposed to 0.3 kGy of irradiation had higher acidity compared to the control. Enhanced or maintained flavonoid content	
Clementine mandarin fruits (*Citrus reticulate*),	0.195 and 0.395 kGy X-ray irradiation	1.5°C for 14 days	—	Minimal differences in juice yield between X-ray irradiated and cold-treated. Both acetaldehyde and ethanol contents of the irradiated fruit were higher along with both X-ray dosage and storage period	Alonso et al., 2007

immersion at 49°C were rated as unacceptable after one day of storage at 4°C, whereas irradiated and untreated fruit were rated as acceptable after eight days storage at 4°C. After 14 and 21 days of storage, the external appearance of “Chompoo” longan fruit treated by hot water immersion was rated less acceptable than those treated by irradiation or left untreated. After 21 days of storage, the external appearance of “Biew Kiew” longan fruit treated with hot water immersion was rated significantly less acceptable than those treated with irradiation, and both were less acceptable than untreated control fruit.

Rubio et al. (2001) irradiated lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea*), and celery (*Apium graveolens*) at 0.50, 0.75, and 1.00 kGy. Non-irradiated samples were used as controls. The effect of irradiation was measured during 7-days storage under refrigeration at 5–10°C. Cabbage was the most radiation resistant of the vegetables, since it did not suffer changes in any quality attribute upon irradiation at the doses tested. The only significant differences detected between control and irradiated samples, i.e. in the appearance of lettuce and in the color of celery, were not judged by produce experts to have “commercial” significance. Moreover, all control and irradiated vegetables received good overall acceptability scores, not significantly different from non-irradiated samples.

The data of Bibi et al. (2006) on sensory evaluation of musk melons (*Cucumis melo*) revealed that a dose of 2.5 kGy and above can maintain the sensory qualities within acceptable limits during the seven days of storage (5°C). The firmness of the irradiated sample for 2.5 and 3.0 kGy were 0.8 and 0.7, respectively at the 14th day of storage and thus, a dose of up to 2.5 kGy could preserve the texture to some extent. Musk melons after radiation treatment (0.5–3.0 kGy) could not maintain their appearance and sensorial quality more than seven days at refrigerated temperature and were discarded due to soft texture and high microbial load. Sensory evaluation of apples (*Pyrus malus*), showed that fresh non-irradiated samples had the highest score while samples irradiated at 3.0 kGy and stored for 14 days (5°C) received the lowest scores. The hardness (kg-Force) of apples decreased with increasing dose levels as well as over storage.

The effects of gamma irradiation at 0, 0.4, and 0.6 kGy on the texture, color, and disease incidence in mangoes were investigated by Uthairatanakij et al. (2006). The mangoes cv. Nam Dokmai and Chok Anan were harvested at the 70% and 90% stages of maturity and assessed after ripening at 25°C. Ripened "Chok Anan" mangoes harvested at 70% and 90% maturity were softer than untreated fruits. In contrast, ripened irradiated "Nam Dokmai" mangoes appeared firmer compared to untreated fruits. Polygalacturonase activity in "Nam Dokmai" mangoes of 90% maturity was not affected by gamma irradiation. Gamma irradiation had no effect on skin or flesh color and soluble solids content of mangoes of both cultivars harvested at both maturity stages. It was concluded that gamma irradiation at doses up to 0.6 kGy had no adverse effects on ripening of the test mangoes harvested at both maturity stages.

Ten citrus cultivars grown in Florida, including the five orange [Citrus sinensis (L.) Osbeck] cultivars, Ambersweet, Hamlin, Navel, Pineapple, and Valencia, and the five mandarin hybrids (*Citrus reticulata* Blanco), "Fallglo," "Minneola," "Murcott," "Sunburst," and "Temple," were exposed to irradiation at 0, 0.15, 0.3, and 0.45 kGy, and stored for 14 days at 1°C or 5°C plus 3 days at 20°C, to determine dose tolerance based on fruit injury. Softening of "Valencia," "Minneola," "Murcott," and "Temple" was dose-dependent, but that of other cultivars was unaffected. The appearance of all cultivars was negatively affected by the loss of glossiness with the 0.45 kGy dose. Less than 1.0% of fruit decayed and irradiation treatment had no effect on decay (Miller et al., 2000).

Boylston et al. (2002) irradiated papayas, rambutans, and Kau oranges at 0 (control) and 0.75 kGy and stored for 2 and 9 days to determine the effect of X-irradiation on sensory quality attributes. The effects of irradiation and storage on specific sensory attributes were shown to depend on the specific fruit. Aroma and flavor tended to be more intense in the irradiated fruit. Although firmness decreased as a result of irradiation and storage, this decrease was significant only in rambutans. The color of the rambutans and oranges were considerably affected by irradiation (Table 2).

THE MICROFLORA OF IRRADIATED FRUITS

Gamma irradiation (doses of 0.75 and 1 kGy) reduced lesion size caused by *Colletotrichum gloeosporioides* and anthracnose incidence in papaya fruit (*Carica papaya*) 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. The fruits were stored at 25°C/80% RH for 7 days (Cia et al., 2007).

Wang et al. (2006) investigated microorganism survival in Golden Empress cantaloupe juice after ^{60}Co irradiation. Microorganism survival determination indicated that *Escherichia coli* was sensitive to irradiation, and could be reduced by 7 log-cycles at 1 kGy, whereas the total colony and target spore bacteria in the juice demonstrated stronger endurance to the irradiation, suggested by D_{10} values of 0.9908 and 1.1923 kGy, respectively. It was thereby concluded that both total colony and target spore bacteria were difficult to be inactivated as compared to *E. coli*. The study revealed that gamma irradiation can not completely inactivate a total colony, and target spore bacteria in cantaloupe juice on the premise of acceptable off-odor.

Susheela et al. (1997) found that the effect of gamma radiation at 0.05, 0.1, and 0.15 kGy and stored at 25–29°C with 90–97% relative humidity on the three-quarter ripe and fully ripe pineapple fruit (*Ananas comosus*) reduced the incidence of fungal infection, predominantly caused by *Ceratocystis paradoxa*.

Different doses of gamma irradiation (1, 2, 3, 4, 5, 6, 7, 8, 9, 10 kGy) were used by Bidawid et al. (2000) in order to investigate the inactivation of hepatitis A virus (HAV) inoculated onto strawberries at ambient temperature. The number of surviving viruses at a given dose of radiation was determined with a plaque assay. Data analysis with a linear model displayed that D_{10} value 2.97 ± 0.18 kGy was required to achieve a 1-log reduction in HAV titre in strawberries.

Lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea*), and celery (*Apium graveolens*), were artificially contaminated with *Vibrio cholerae* El Tor 01 Inaba, and irradiated at 0.50, 0.75, and 1.00 kGy. Non-irradiated samples were used as controls. The effect of irradiation was measured during 7-days storage under refrigeration (5–10°C) irradiation proved to be an effective technique to eliminate *V. cholerae* in fresh vegetables. Doses of less than 0.75 kGy were sufficient to eliminate an initial contamination of 10^5 cells/g of *V. cholerae* (Rubio et al., 2001).

Mohacsi-Farkas et al. (2006) found that for pre-cut cantaloupe samples (*Cucumis melo*), 1 kGy irradiation caused 2 log cycles reduction of *L. monocytogenes*, and about 5 log-cycles reduction of inoculated *E. coli* O157. 1 kGy irradiation had the same effect on pre-cut watermelon (*Citrullus lanatus)*, with initial pH of 5.5. After irradiation, the surviving cells of both pathogens examined were able to grow at 15°C, whereas *L. monocytogenes* grew even at 5°C.

According to Bibi et al. (2006) the total viable count for control samples of musk melons (*Cucumis melo*), increased from 4.8×10^5 to 6.7×10^7 CFU/g after seven days storage at refrigeration temperature (5°C). Very few colonies were recorded in the samples irradiated at the dose of 3.0 kGy, which increased to 3.9×10^2 CFU/g after seven days storage. A radiation dose of 1.0 kGy completely controlled fungal growth and coliform bacteria during seven days storage. After one week, all the samples,

Table 2 Sensory properties of irradiated fruits

Species	Irradiation type/dose (kGy)	Temperature (°C)	Sensory properties	Refs
Papaya	Gamma irradiation 0.5 kGy	22°C and 90% RH	Both irradiated and non-irradiated fruits ripened normally with respect to sugar content, color change, firmness, and general appearance of the fruit.	D'innocenzo and Lajolo, 2001
Early season 'Rio Red' grapefruit	—	10°C for 4 weeks followed by 1 week at 20°C with 90–95% relative humidity.	Sensory qualities such as appearance and flavor of early season grapefruit exposed to irradiation treatments at or below 0.4 kGy were comparable to the control after 35 days storage	Patil et al., 2004
Early season 'Rio Red' grapefruit	Gamma irradiation 0.07, 0.2, 0.4 kGy	10°C for 4 weeks followed by 1 week at 20°C with 90–95% relative humidity		
Late season 'Rio Red' grapefruit	Gamma irradiation 0.07, 0.2, 0.4, and 0.7 kGy	10°C for 4 weeks followed by 1 week at 20°C with 90–95% relative humidity	Irradiation had no considerable effect on the sensory qualities of late season grapefruit.	
Mature green and pink tomato (*Lycopersicon esculentum* Mill.) fruit	0.7 to 2.2 kGy from gamma-or X-ray sources	10°C	Irradiation-induced softening was evident in mature-green and pink fruit within hours following irradiation, and differences between irradiated and control fruit persisted throughout post-irradiation storage. Trends of firmness loss were much more consistent and showed much greater dose dependency in pericarp tissue than whole fruit.	Assi et al., 1997
Early climacteric (breaker) cherry tomatoes (*Lycopersicon pimpinellifollium* L.)	Gamma irradiation 3 kGy	—	The content of 1-aminocyclopropane-1-carboxylic acid (ACC), followed the same evolution as ethylene production, while malonyl ACC increased steadily with time in irradiated fruits. The burst in ethylene production was accompanied by a sharp stimulation of ACC synthase activity which began 15 minutes after irradiation.	Larrigaudie're et al. 1990
Golden Empress cantaloupe juice	Gamma irradiation 1 kGy		Slight irradiation off-odor after treatment at 1 kGy,	Wang et al., 2006
Golden Empress cantaloupe juice	Gamma irradiation 2 kGy		Had strong off-odor at 2 kGy and above	
Three-quarter ripe and fully ripe pineapple fruit (*Ananas comosus*)	Gamma irradiation 0.05, 0.1, and 0.15 kGy	25–29°C with 90–97% relative humidity	Maintained their texture better than the controls	Susheela et al., 1997
Lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea*) and celery (*Apium graveolens*)	Gamma irradiation 0.50, 0.75, and 1.00 kGy	5–10°C for 7 days	All control and irradiated vegetables received good overall acceptability scores, not significantly different from non-irradiated samples. Cabbage was the most irradiation resistant	Rubio et al., 2001
Melons (*Cucumis melo*)	Gamma irradiation 2.5 kGy	5°C for 14 days	Maintained the sensory qualities within acceptable limits	Bibi et al., 2006
Apples (*Pyrus malus*)	Gamma irradiation (0.5–3.0 kGy)	5°C for 14 days	Hardness of apples decreased with increasing dose levels as well as during storage	
Mangoes cv. Nam Dokmai	0.4 and 0.6 kGy	25°C (ripening)	Ripened irradiated "Nam Dokmai" mangoes appeared firmer compared to untreated fruits. Gamma irradiation had no effect on skin or flesh color	Uthairatanakij et al., 2006
Mangoes cv. Chok Anan	0.4 and 0.6 kGy	25°C (ripening)	Ripened irradiated "Chok Anan" mangoes harvested at 70% and 90% maturity were softer than untreated fruits. Gamma irradiation had no effect on skin or flesh color	
"Gala" apples	0.30–0.90 kGy	—	Irradiation at doses between 0.30 and 0.90 kGy reduced apple firmness. Doses of <0.30 kGy had no effect on apple firmness. Irradiation did not influence the external color of apples.	Drake et al., 1999

(*Continued on next page*)

Table 2 Sensory properties of irradiated fruits (*Continued*)

Species	Irradiation type/dose (kGy)	Temperature (°C)	Sensory properties	Refs
"Gala," "Fuji" and "Granny Smith" apples	0.30–0.90 kGy	—	Irradiation at doses between 0.30 and 0.90 kGy reduced apple firmness. Doses of <0.30 kGy had no effect on apple firmness. Irradiation did not influence the external color of apples.	
'Bosc' pears	0.30 – 0.90 kGy	—	Firmness loss due to irradiation, and the firmness loss was dose dependent	
Ten citrus cultivars, including the five orange (Citrus sinensis (Osbeck) cultivars, Ambersweet, Hamlin, Navel, Pineapple, and Valencia, and the five mandarin hybrids (*Citrus reticulata*), "Fallglo", "Minneola", "Murcott", "Sunburst" and "Temple"	0, 0.15, 0.3, and 0.,45 kGy,	Stored for 14 days at 1°C or 5°C plus 3 days at 20°C	Softening of 'Valencia', 'Minneola', 'Murcott', and 'Temple' was dose-dependent, but that of other cultivars was unaffected. The appearance of all cultivars was negatively affected by the loss of glossiness with the 0.45 kGy dose.	Miller et al., 2000
Papayas, rambutans, and Kau oranges	0.75 kGy	—	Aroma and flavor tended to be more intense in the irradiated fruit. Firmness decreased as a result of irradiation and storage, though it was significant only in rambutans	Boylston et al., 2002
One hundred random fruit samples	1.5 kGy	Refrigeration temperature (<10°C) 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
One hundred random fruit samples	3.5 kGy	Refrigeration temperature (<10°C) 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.	

irrespective of the treatment used, were spoiled and discarded. It was also found that irradiation treatments of minimally processed apple (*Pyrus malus*), lowered the bacterial load initially and by the end of the experiment and after 14 days storage, the TBC values increased to 3.7×10^4, 2.6×10^3, 8.5×10^2 and 4.0×10^2 for 1.0, 2.0, 2.5, and 3.0 kGy treated samples, respectively. Minimum TBC were recorded at 2.5 and 3.0 kGy treated minimally processed apples. In the case of coliform and fungal load samples treated with 2.0 kGy or more, they were found completely free of coliforms. These results suggested that the apples should be treated with a dose of 2.5 kGy to keep the minimally processed apples microbiologically acceptable (Figure 1).

Trigo et al. (2006a) investigated the effect of irradiation on blueberries (Vaccinium sp). The fruits were packed in polymeric film bags and sealed. Blueberry packages were irradiated at several doses (0 up to 3 kGy with intervals of 0.5 kGy). The blueberries were stored at 4°C. Shelf-life of 0.5 and 1 kGy irradiated blueberries was shorter compared with that of non-irradiated fruit. Inactivation of blueberry microbial load after irradiation, at doses mentioned, led to reduction by approximately 1.5 log for total counts and 5 log for coliforms.

Aziz and Moussa (2002) collected and analyzed one hundred random fruit samples, for mycotoxins and the effect of gamma-irradiation on the production of mycotoxins in fruits was investigated. The analysis of fruits revealed the occurrence of penicillic acid, patulin, cyclopiazonic acid (CPA), citrinin, ochratoxin A, and aflatoxin B1. Of the 100 samples examined, 60 were positive for one or more mycotoxins. Irradiation of

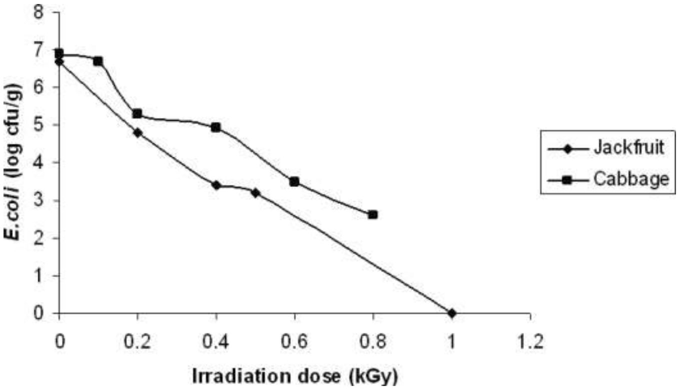

Figure 1 Effect of different irradiation doses on *E. coli* population in Jackfruit (*Artocarpus heterophyllus*) packed in a polypropylene rigid container (Faridah et al., 2006) and cabbage (*Lactuta sativa*, var. capitata) packed in polyethylene bag (Bibi et al., 2006).

fruits at doses of 1.5 and 3.5 kGy decreased significantly the total fungal counts compared with non-irradiated controls. After 28 days of storage at refrigeration temperature ($<10^\circ$C), the total fungal counts of 1.5 and 3.5 kGy irradiated fruit samples had an average of 4.88^*10^2 and 1.39^*10^1 per gram, respectively, whereas the fungal counts for the non-irradiated fruit samples increased up to about 6.05^*10^6 per gram.

Mycotoxin production in fruits decreased with increasing irradiation dose and was not detected at 5.0 kGy. Pillai et al. (2006) carried out studies using Poliovirus Type 1 and bacteriophage MS2 to determine whether electron beam irradiation (10 MeV) could be used to inactivate these viruses on cantaloupe *Cucumis melo reticulatus* surfaces. The D_{10} values of Poliovirus Type 1 and MS2 bacteriophage were found to be 4.76 and 4.54 kGy, respectively (Table 3).

IRRADIATION AND HURDLE TECHNOLOGY OF IRRADIATED FRUITS

Moreno et al. (2007) reported that no significant weight losses were induced to packaged fresh blueberries (*Vaccinium corymbosum* L.) by electron beam irradiation (1.1, 1.6, 3.2 kGy). Moisture content and water activity of the fruits ranged between 79.6 and 81.8 g/100 g and 0.87 to 0.92, respectively. These results indicated that exposure of blueberries to irradiation up to 3.2 kGy did not affect the juiciness of the fruits. Irradiating the blueberries up to 3.2 kGy did not affect their pH and the fruits had acceptable acidity levels that remained unchanged throughout storage time (at 5°C and 70.4% RH for 14 days). Only irradiation at doses higher than 1.6 kGy induced undesirable texture changes (i.e. softening) in the fruits. Blueberries exposed up to 1.6 kGy dose were found acceptable by the panelists in terms of overall quality, color, texture, and aroma.

According to El-Samahy et al. (2000) irradiation treatments (0.5, 0.75, 1.0, and 1.5 kGy) in conjunction with hot water-dipping (55°C/5 min) caused significant decrease in firmness values of mango fruits (*Mangifera indica* L.), variety "Zebda," either at zero time or during the storage (12 ± 1°C and 80–85% relative humidity). This decline in firmness was shown to be proportional to the radiation dose. The results clearly indicated that samples irradiated up 1.0 kGy were acceptable organoleptically until 50 days of storage at 12°C. After 60 days, mangoes were over-ripe with a buttery texture. Phenolic compounds and total content of carotenoids in mango significantly increased when the latter was subjected to irradiation. The increase in phenolic

Table 3 The effect of irradiation (type/dose) on fruit microflora

Species	Irradiation type/dose (kGy)	Temperature (°C)	Irradiation effect on microflora	Refs
Papaya fruit	Gamma irradiation 0.75 and 1 kGy	The fruit were stored at 25°C/80% RH for 7 days	Reduced lesion size caused by *Colletotrichum gloeosporioides* and anthracnose incidence in papaya fruit (*Carica papaya*) 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
Golden Empress cantaloupe juice after	1 kGy		7 log-cycles reduction of *Escherichia coli*, whereas total colony and target spore bacteria in the juice had stronger endurance to the irradiation, suggested by D_{10} values of 0.9908 and 1.1923 kGy, respectively.	Wang et al., 2006
Strawberries	Gamma irradiation (1, 2, 3, 4, 5, 6, 7, 8, 9, 10 kGy	Ambient temperature	D_{10} value 2.97 ± 0.18 kGy was required to achieve a 1-log reduction in HAV titre	Bidawid et al., 2000
Lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea*), and celery (*Apium graveolens*)	Gamma irradiation 0.75 kGy	5–10°C for 7 days	Elimination of an initial contamination of 10^5 cells/g of *V. cholerae*	Rubio et al., 2001
Cantaloupe	1 kGy	5°C	2 log cycles reduction of *L. monocytogenes*	Mohacsi-Farkas et al., 2006
Cantaloupe	1 kGy	5°C	5 log-cycles reduction of inoculated *E. coli* O157	
Melons (*Cucumis melo*)	3 kGy	5°C	Very few colonies remained	Bibi et al., 2006
Melons (*Cucumis melo*)	1 kGy	5°C	Completely controlled fungal growth and coliform bacteria during seven days storage	
Apple (*Pyrus malus*)	2.0 kGy	5°C	Completely controlled fungal growth and coliform bacteria during seven days storage	
Cantaloupe (*Cucumis melo reticulatus*)	4.76 kGy electron beam irradiation	—	D_{10} values of Poliovirus Type 1	Pillai et al., 2004
Cantaloupe (*Cucumis melo reticulatus*)	4.54 kGy electron beam irradiation	—	D_{10} values of MS2 bacteriophage	

compounds was proportional to the radiation dose used. Irradiation at 0.5–1.5 kGy caused a slight loss of vitamin C. This loss could be due to irradiation-induced oxidation of ascorbic acid. Substantial reduction in acidity was recorded in all treatments with prolongation of storage time. However, the percentage decrease in non-irradiated samples was higher than in irradiated samples.

The synergic effects of calcium ascorbate (CaA) and ionizing radiation on the quality of "Gala" apple slices under modified atmosphere packaging were investigated by Fan et al. (2005). "Gala" apple slices, treated with water or 7% CaA followed by either non-irradiation (0 kGy) or irradiation at 0.5 and 1.0 kGy, were stored at 10°C up to 3 weeks. Irradiation did not affect the titratable acidity and the pH of sliced apples. Fruit slices softened during irradiation and storage, but this decrease in firmness during storage was reduced by the CaA treatment. Although the ascorbic acid content of apple slices treated with CaA decreased rapidly during storage, the ascorbic acid content was always higher in CaA treated samples than in the apple slices treated with water. Irradiation decreased both L* and the hue values of apple slices. CaA increased L* and hue values of apple slices thereby suggesting that CaA reduced browning, even in irradiated samples. The microflora population of apples slices was not affected by CaA. The combination of CaA and irradiation enhanced the microbial food safety while maintaining the quality of fresh-cut apple slices.

The results reported by Faridah et al. (2006) showed that both *L. monocytogenes* and *E. coli* 0157 have different D_{10}-value in different fruits, aerobically packaged and stored at 5°C ± 2°C, when irradiated with gamma rays. *L. monocytogenes* is proven to be more radiation resistant than *E. coli* O157. D_{10}-values of *L. monocytogenes* were 0.15 kGy in pineapple (*Ananas comosus*), and 0.4 kGy in jackfruit (*Artocarpus heterophyllus*). D_{10}-values of *E. coli* 0157 were considerably lower; 0.08 kGy in pineapple, 0.16 kGy in jackfruit, and 0.14 kGy in mix fruit (pineapple and guava). Moreover, irradiation with 0.5 to 3 kGy induced 1–3 log cycles reduction in the aerobic plate count of the above fruits. However, depending on the applied dose, the growth of surviving microorganisms was observed on storage day 4 or 8. The total viable count was almost always lower when the radiation dose was higher. Moreover, for pineapple, after three days of storage, panelists gave the highest score to the irradiated sample (1.5 kGy) and on the eighth day of storage, the highest score was shared by the non-irradiated and irradiated sample (1.5 kGy).

Drake et al. (2003) exposed commercially-packed Fuji and Granny Smith apples and Anjou and Bosc pears to gamma irradiation treatments at doses of 150, 300, 600, and 900 Gy. After irradiation, apples were stored for 30, 60, and 90 days, while pears were stored for 30 and 90 days in ambient atmosphere at 1°C. Irradiation treatment did not influence the total carbohydrate or individual sucrose, glucose, fructose, or sorbitol concentrations in either apples or pears, regardless of the cultivar. Carbohydrate concentrations were altered in both apples and pears as storage time progressed and these changes were shown to be cultivar dependent. Total carbohydrates and glucose, fructose, and sorbitol concentrations increased, and sucrose decreased in apples as storage progressed. Total carbohydrates and fructose increased; whereas, sucrose, glucose, and sorbitol concentrations decreased in Anjou pears as storage progressed. Total and individual carbohydrate concentrations decreased in Bosc pears as storage progressed from 30 to 90 days.

Janave and Sharma (2005) reported that low dose gamma irradiation of pre-climacteric mango (*Mangifera indica L var.* "Alphonso") fruits at 100 Gy extended the shelf-life at ambient temperature (28–32°C) by 5–6 days. The extension of shelf-life was dose dependent, maximum being at 200 Gy by about 8–10 days. Wrapping the fruits in food grade Klin Wrap film resulted in greater number of fruits remaining in semi-ripe condition after 21 days of storage. Although the fruits retained about 40% of chlorophyll, unwrapped fruits were completely yellow. The physiological weight loss (PWL) was reduced by 50% in Klin film wrapped fruits as compared to that in unwrapped fruits. More than 70–80% fruits remained as marketable fruits by the end of the experiment whereas control fruits were slightly overripe. The shelf-life in Klin film wrapped irradiated mangoes was extended by about 10–15 days over irradiated unwrapped fruits thus resulting in total shelf-life of about 25–30 days at room temperature. In mangoes of the variety "Dasheri," gamma irradiation extended the shelf-life by 4–5 days, which could be increased by another 7–10 days by Klin wrap packaging. These fruits also remained green by the end of the experiment thereby confirming the observations reported with "Alphonso" mango.

The irradiation (0.5 and 1 kGy) of watermelon (*Citrullus lanatus*) caused a microbial reduction of 1–2 log in the total aerobic mesophilic counts and total aerobic psychrotrophic counts. The color was slightly darker after irradiation (1st day) but this difference lessened with storage time prolongation. Texture results pointed out no detectable differences after irradiation. Sensorial results of irradiated and non-irradiated watermelon also pointed out an extended shelf life for irradiated watermelon at

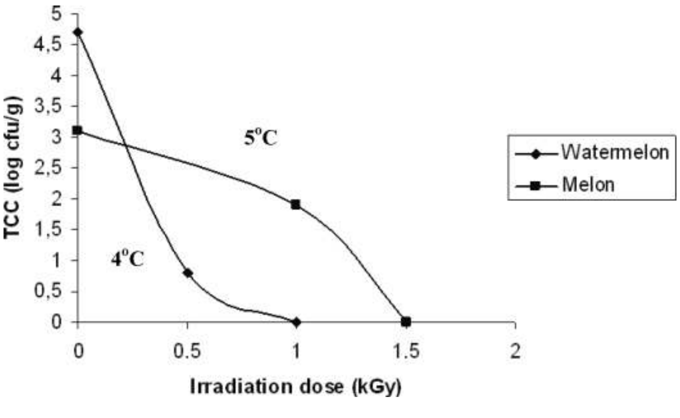

Figure 2 Effect of different irradiation doses on total coliform count (TCC) on watermelon (*Citrullus lanatus*) packed in polystyrene tray and then in polymeric film bags, and Melon (*Cucumis melo*) packed in polyethylene package at day 7 of storage, stored at 4°C (Trigo et al., 2006; Bibi et al., 2006).

Table 4 The effect of irradiation (type/dose) and hurdle technology on shelf life, sensory and physical properties of fruits

Species	Irradiation type/dose (kGy)	Other technology	Temperature (°C)	Shelf life	Sensory properties	Irradiation effect	Refs
Fresh blueberries (*Vaccinium corymbosum* L.)	Electron beam 1.1, 1.6, 3.2 kGy	Packaged (trays consisted of plastic clamshell containers)	5°C and 70.4% RH for 14 days		Only irradiation at doses greater than 1.6 kGy induced undesirable texture changes (i.e., softening) in the fruits. Blueberries exposed up to 1.6 kGy dose were found acceptable by the panelists in terms of overall quality, color, texture, and aroma.	Results indicate that exposure of blueberries to irradiation up to 3.2 kGy does not affect the juiciness of the fruits. Irradiating the blueberries up to 3.2 kGy did not affect their pH and the fruits had acceptable acidity levels that remained unchanged throughout storage time.	Moreno et al., 2007
Mango fruits (*Mangifera indica* L.) variety "Zebda "	—	Hot water-dipping (55°C/5 min)	12 ± 1°C and 80–85% relative humidity	25 days.	—	Phenolic compounds and total content of carotenoids in mango were significantly increased by exposure to irradiation. Irradiation caused a slight loss of vitamin C. Significant reduction in acidity was found in all treatments as storage time lengthened; however, the percentage decrease in unirradiated samples was higher than in irradiated samples. Irradiation treatments caused additional significant reductions in total bacterial counts.	El-Samahy et al., 2000
Mango fruits (*Mangifera indica* L.) variety "Zebda "	Gamma irradiation 0.5, 0.75, 1.0, and 1.5 kGy	Hot water-dipping (55°C/5 min)	12 ± 1°C and 80–85% relative humidity	50 days (1 kGy)	The results clearly indicated that samples irradiated up 1.0 kGy were acceptable organoleptically until 50 days of storage at 12°C. After 60 days, mangoes were over-ripe with a buttery texture.		
'Gala' apple slices	—	7% CaA	10°C for up to 3 weeks			The microflora population of apples slices was not affected by CaA.	Fan et al., 2005
'Gala' apple slices	0.5 and 1.0 kGy	7% CaA	10°C for up to 3 weeks		Irradiation decreased both L* and hue values of apple slices. CaA increased L* and hue values of apple slices, suggesting CaA reduced browning, even in irradiated samples.	Irradiation did not affect titratable acidity and pH of sliced apples. Fruit slices softened during irradiation and storage, but this decrease in firmness during storage was reduced by the CaA treatment. The combination of CaA and irradiation enhanced microbial food safety	
Jackfruit (*Artocarpus heterophyllus*)	0.4 kGy	Aerobically packaged	5°C ± 2°C	at least 8 days		*Listeria monocytogenes* (D10 = 0.4 kGy)	Faridah et al., 2006
Jackfruit (*Artocarpus heterophyllus*)	0.16 kGy	Aerobically packaged	5°C ± 2°C	at least 8 days		*E. coli* O157 (D10 = 0.16 kGy)	

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Table 4 The effect of irradiation (type/dose) and hurdle technology on shelf life, sensory and physical properties of fruits (*Continued*)

Species	Irradiation type/dose (kGy)	Other technology	Temperature (°C)	Shelf life	Sensory properties	Irradiation effect	Refs
Pineapple (*Ananas comosus*)	0.15 kGy	Aerobically packaged	5°C ± 2°C	at least 8 days		*Listeria monocytogenes* (D10 = 0.15 kGy)	
Pineapple (*Ananas comosus*)	0.08 kGy	Aerobically packaged	5°C ± 2°C	at least 8 days		*E. coli* O157 (D10 = 0.08 kGy)	
Mixed fruit (pineapple and guava (psidium guajava)	0.14 kGy	Aerobically packaged	5°C ± 2°C	at least 8 days		*E. coli* O157 (D10 = 0.14 kGy)	
Fuji and Granny Smith apples	150, 300, 600, and 900 Gy	Commercially packed	1°C	—	—	Irradiation treatment did not influence the total carbohydrate or individual sucrose, glucose, fructose, or sorbitol concentrations	Drake et al., 2003
Anjou and Bosc pears	150, 300, 600, and 900 Gy gamma irradiation	Commercially packed	1°C	—	—	Irradiation treatment did not influence the total carbohydrate or individual sucrose, glucose, fructose, or sorbitol concentrations	
Watermelon (*Citrullus lanatus*)	0.5 and 1 kGy	Packed in a Nutrip-PS (polystyrene) tray and then in polymeric film bags	4°C	9 days for 0.5 kGy (4 days for control and 3 days for1 kGy)	The color was a slightly darker after irradiation (1st day), nevertheless this difference lessened along storage time. Texture results point out for no detectable differences after irradiation.	1–2 log reduction in the total aerobic mesophilic counts and total aerobic psychrotrophic counts	Trigo et al., 2004
Melon (*Cucumis melo*)	0.5 and 1 kGy	Packed in a Nutrip-PS (polystyrene) tray and then in polymeric film bags	4°C	9 days similar to control	Color and texture results point out no detectable differences after irradiation, along storage time.	1–2 log reduction in the total aerobic mesophilic counts and total aerobic psychrotrophic counts	

0.5 kGy (up to 9 days) compared with the non-irradiated watermelon (4 days). The watermelon irradiated at 1 kGy exhibited a shorter shelf life (3 days). Furthermore, for melon (*Cucumis melo*), the irradiation (0.5 and 1 kGy) caused a microbial reduction of 1–2 log in the total aerobic mesophilic counts and total aerobic psychrotrophic counts. The color and texture results disclosed no detectable differences after irradiation versus storage time. Irradiated melon at 0.5 kGy and 1 kGy displayed similar shelf life (9 days) to non-irradiated ones. All fruit samples were packed in a Nutrip-PS (polystyrene) tray and then in polymeric film bags and stored at 4°C (Trigo et al., 2006b) (Figure 2, Table 4).

QUALITY AND SHELF LIFE EXTENSION OF IRRADIATED VEGETABLES

Fan and Sokorai (2005) assessed the radiation sensitivity of fresh-cut vegetables using electrolyte leakage measurement. Fresh-cut vegetables were gamma irradiated at doses up to 3 kGy at 0.5 kGy intervals. Electrolyte leakage increased linearly with higher radiation dose for all vegetables. Red cabbage, broccoli, and endive had the highest radiation resistance while celery, carrot, and green onion were the most sensitive to radiation. The radiation sensitivity was not necessarily correlated with endogenous antioxidant capacity or phenolics content of the vegetables, which displayed large variation among the test samples.

Song et al. (2006) investigated carrot and kale juice during a three-day storage period (10°C). They reported that the total phenolic contents of both vegetable juices were significantly higher in the irradiated (3 kGy) samples than in the non-irradiated control. The antioxidant capacity of the irradiated carrot juice was higher than that of the non-irradiated control. On the other hand, over the storage period, the antioxidant capacity decreased in spite of increase in the phenolic content of the kale juice.

Wang and Du (2005) found that the vitamin C content, and the rehydration ratio of dried potato was greatly affected by the irradiation dose (2, 4, 5, 6, 8, or 10 kGy). They claimed that the greater the dose, the lower the vitamin C content and the rehydration ratio.

The effects of cooking followed by irradiation (10 kGy) on vitamins B1 and C, and the antinutritional factors, phytic acid and nitrates, in a ready-to-eat meal of sorghum porridge and spinach-based relish were investigated by (Duodu et al., 1999). Cooking reduced vitamin B1 and C contents of the spinach relish, and irradiation caused further losses. Cooking did not alter vitamin B1 content (0.28 mg gr^{-1}) of the sorghum porridge but irradiation decreased it drastically (0.04 mg gr^{-1}). Cooking did not decrease phytic acid in the sorghum porridge whereas irradiation caused a significant decrease.

According to Mohacsi-Farkas et al. (2006) a radiation dose of 1 kGy had no significant effect on total carotenoid and vitamin C content of sliced tomatoes (*lycopersicon syn. L. esculentum*). However, this dose caused approximately 40% decrease in α-tocopherol.

Bandekar et al. (2006) studied the effect of radiation processing on vitamin C, total carotenoids, texture, and organoleptic properties of carrot and cucumber. No significant difference in the vitamin C content and total carotenoids in the radiation processed (1 and 2 kGy) samples and control samples was reported. Variation in the content of vitamin C and carotenoids during storage was not statistically significant from the control samples. The trained test panel could not differentiate between the irradiated and the non-irradiated samples.

In general, no substantial effect of irradiation on the sugar content of onions was observed (Thomas et al., 1986; Diehl, 1977; Guma and Rivetti, 1970). Furthermore, gas chromatography of silylated extracts displayed no changes in the levels of glucose, fructose, or malic acid in four onion cultivars grown in Germany when irradiated with 10 MeV electrons at doses of 0.05 or 0.10 kGy and stored at 10°C or 20°C. The sucrose level was about 2.2% of fresh weight at the beginning of the storage period and declined to 1.5% in irradiated as well as non-irradiated bulbs (Diehl, 1977; Grunewald, 1978). Similarly, doses of 0.05 to 0.5 kGy had no appreciable effect on the total free sugar content (sucrose, glucose, and fructose) in onion bulbs of 11 cultivars produced in different locations in Japan, though the sucrose content seemed to slightly increase by irradiation (Nishibori and Namiki, 1982).

The vitamin C content in three onion cultivars grown in Israel following irradiation to 0.07 kGy and 5 months storage at ambient temperature was essentially the same as in the non-irradiated controls (Molco and Padova, 1969). An increase in the ascorbic acid content with increasing dose from 0.03 to 0.18 kGy was observed in a study by Nandpuri et al.(1969) while, according to Salems (1974), a 18% reduction of ascorbic acid was reported by 0.08 kGy irradiation.

In a study on onion cultivars of Hungary, no significant differences in the vitamin C content of irradiated and non-irradiated samples were observed during a 10-month storage period and the vitamin C content of the irradiated samples seemed not to be influenced by the time of irradiation after harvest (Mahmoud et al., 1978). On the contrary, Guo et al. (1981) reported a drastic reduction in the vitamin C content of onions immediately after irradiation at 0.1 to 0.5 kGy. However, the decrease in vitamin C during the remaining eight months storage was much lower in irradiated than in control onions.

Regarding potatoes there have been many results reported in the literature on the effect of irradiation on sugar content of potatoes during storage. In Danish potato cultivars irradiated between 0.04 and 0.16 kGy, sucrose and glucose increased while fructose decreased. These changes were reversible and disappeared after storage for some months at 5°C (Jaarma, 1958).

Pre-storage of potatoes for 4 weeks at 2°C to 15.5°C prior to irradiation to 0.1 kGy affected the sugar content during post-irradiation storage. Pre-irradiation storage of tubers showed a marked temporary increase in sucrose, reaching a maximum after 3 to 7 days before decreasing to a level which was still higher than that of the non-irradiated tubers. Tubers stored at 2°C exhibited an immediate decrease in sucrose after irradiation, followed within 3 days by a rise to values not significantly different from the controls (Burton, 1975).

Moreover, in potatoes cultivars grown in the U.K., a marked increase was observed in sucrose in tubers irradiated with 0.1 kGy and stored at 10°C. The maximum content was reached 5 days after irradiation and decreased afterwards. It is remarkable that 26 days after irradiation, the sucrose content remained the same as in the non-irradiated tubers (Burton et al., 1959).

A comparison of sugar changes in 0.1 kGy treated potatoes during storage at 14°C and in non-irradiated potatoes at 4°C to 5°C for 6 months storage showed a 50% lower content of reducing and total sugars as well as 15% greater starch content in the irradiated tubers than in controls (Eisenberg et al., 1971). A similar study with several Indian potato cultivars revealed that sugar accumulation in non-irradiated tubers stored at 2° to 4°C progressed at a more rapid rate than in irradiated tubers at 15°C during a 6 month storage period (Joshi et al., 1990).

Adesuyi and Mackenzie (1973) reported that in yam tubers (*Dioscorea rotundata*) starch levels were almost identical in control and 0.15 kGy treated tubers after a storage period of 5 months under normal conditions (25° to 37°C; RH 50 to 85%). A decrease in starch level was recorded in tubers irradiated to 0.1 and 0.125 kGy but those exposed to 0.025, 0.05, and 0.075 kGy displayed higher starch content than 0.1 and 0.125 kGy treated samples.

Several workers have studied the stability of this vitamin in potatoes irradiated for sprout inhibition purposes. Irradiation with 0.07 to 1.0 kGy, two weeks after harvest, had no effect on vitamin C (Metlitsky et al., 1968). In another study, no immediate change in vitamin C content was observed after exposure to 0.1 to 1.0 kGy whereas after one week the levels decreased in proportion to the increasing dose (Gounelle et al., 1968). An immediate oxidation of vitamin C was observed following irradiation at 0.1 kGy but the difference in content between the irradiated and the non-irradiated tubers disappeared on prolonged storage (Salkova, 1957). In South African potato cultivars no detrimental effect on ascorbic acid was reported after exposure up to 0.15 kGy during 16 weeks of storage (Winchester and Visser, 1975).

Potatoes treated with X-rays to doses up to 0.09 kGy exhibited no effect on ascorbic acid but at 0.135 kGy a significant reduction occurred (Berger and Hansen, 1962). Studies with several Indian potato cultivars have shown that ascorbic acid levels decreased during the initial period of storage following irradiation with 0.1 kGy, regardless of the cultivar, when stored either at tropical ambient temperatures or at 15°C. However, on prolonged storage, ascorbic acid levels were equal to, or even higher than those of control samples. Irradiated tubers stored at 15°C recorded higher levels of ascorbic acid as compared to controls stored at 2° to 4°C for identical periods (Joshi et al., 1990; Thomas, 1984).

Studies with nine Indian potato cultivars displayed that irradiation at 0.1 kGy resulted in decreased levels of carotenoids in the tuber flesh, particularly at 15°C where 50% reduction in its content occurred after 6 months storage. A partial recovery of the carotenoids content occurred when such tubers were reconditioned at 34°–35°C for 6 to 12 days (Janave and Thomas, 1979).

In the Indian potato cultivar, up-to-date, aspartic acid, asparagine, threonine, serine, alanine, isoleucine, leucine, lysine, and arginine displayed an increase in 24 hr after irradiation at 0.1 kGy, while glutamic acid, proline, methionine, and phenylalanine decreased. The lysine content displayed a six-fold increase after 1 week storage, and at 1 month the concentration was still three times higher than the control values (Ussuf and Nair, 1972). Exposure of potatoes to 0.07 to 0.1 kGy doses two weeks after harvesting or later did not appreciably affect the nitrogenous substances except during the initial storage period when some of the non-protein nitrogen increased at the expense of decomposition of protein nitrogen. With prolonged storage, protein nitrogen and non-protein nitrogen were found to be equal in irradiated and control tubers (Metlitsky et al., 1968).

Although irradiation at 0.1 kGy had no effect on the total sulfur and thiosulfonate content of garlic bulbs during storage at 3 ± 1°C and 80 ± 5% RH for 10 months, the contents of both components exhibited a significant reduction in control and irradiated after 6 to 8 months storage compared to initial values (Kwon et al., 1989). Similarly, no appreciable changes were detected in either gas liquid chromatograms or visible and infra-red spectrographs of ether extracts of "red" garlic bulbs irradiated with 0.05 kGy and stored in a commercial warehouse (6 to 32°C, RH 58 to 86%) for 6 months (Curzio and Ceci, 1984).

A Canadian study revealed that the total weight loss due to sprouting and shrinkage of onion bulbs irradiated with 0.06 and 0.076 kGy was 5.7% as against 23.2% for the non-irradiated bulbs after 5 months storage at 12.8°C (Anon. 1962d). In the cv "Valenciana Sintética 14" grown in Argentina, the weight loss at the end of a 270 day test storage in a commercial warehouse (6 to 32°C, RH 50 to 90%) was found to be 43.3% in the control as against only 22.8% in 0.03 kGy treated samples (Curzio and Croci, 1983). In a pilot-scale study conducted in India the weight losses due to dehydration after 4.5 months storage at ambient temperature under commercial conditions (23° to 32°C, RH 60 to 80%) was 15.2% in irradiated (0.06 kGy) samples as against 27.7% in non-irradiated bulbs (Thomas et al., 1986).

In the garlic bulb cv "Red" the weight losses amounted to 55% and 24% in the control and irradiated (0.03 kGy); respectively at the end of 300 days storage at 6° to 32°C, RH 58–86% (Croci and Curzio, 1983).

In three Japanese potato cultivars the weight loss during storage at room temperature was reduced by 0.07 and 0.15 kGy but not during storage at 5°C (Umeda et al., 1969a, b). A commercial scale study involving five Japanese cultivars under varying storage regimes confirmed that irradiation prevented weight loss as compared to non-irradiated potatoes, especially at 7°C storage (Umeda, 1978; Matsuyama and Umeda, 1983).

In a semi-commercial experiment with two potato cultivars grown, the weight losses during 6 months storage at 20°C varied from 28 to 51% in non-irradiated as compared to 17 to 40% in samples irradiated at 0.1 kGy (Khan et al., 1986). A progressive reduction in weight losses in yams *(D. rotundata*) was reported with increasing doses from 0.025 to 0.15 kGy after 5 months storage in a yam barn (25° to 37°C, RH 50 to 85%), the loss being 39.7% in controls as compared to only 17.7% in 0.15 kGy irradiated (Adesuyi and Mackenzie, 1973). A dose between 0.05 to 0.20 kGy caused more than 50% reduction in weight loss in nine yam cultivars grown in Nigeria in comparison to controls (Adesuyi, 1976; 1978) (Table 5).

SENSORY PROPERTIES OF IRRADIATED VEGETABLES

Song et al. (2007) found that immediately after irradiation the overall sensory scores of the irradiated and non-irradiated carrot and kale juice were not considerably different. However, the sensory quality of the non-irradiated carrot and kale juice decreased with storage time. Panelists evaluated that the control could not be used for food after two-day storage because of the deterioration in quality due to spoilage. In the same study, no significant differences in the amino acid composition between the non-irradiated control and irradiated (3 and 5 kGy) carrot and kale juice were observed. During the storage period (10°C), total ascorbic acid, ascorbic acid, and dehydroascorbic acid contents were reduced, and the ascorbic acid of the irradiated carrot and kale juice were higher than that of the non-irradiated one at three days storage. Furthermore, irradiated samples stored for three days have similar or slightly higher levels of total ascorbic acid than their non-irradiated counterparts. Moreover, it was found that in the case of carrot and kale juice, radiation resulted in a dose-dependent reduction of the ascorbic acid content. However, the contents of the total ascorbic acid, including dehydroascorbic acid, were stable up to three kGy irradiation dose. Irradiation prolonged their shelf life up to three days whereas the shelf life of the non-irradiated control was limited only to one day.

At −20°C, radiation doses sufficient to achieve a 5-$\log_{10}$ kill (3.9 to 4.6 kGy) caused significant softening of peas and broccoli stems but not of corn or lima beans. Lower doses of comparable antimicrobial efficacy delivered at −5°C (2.5 to 3.1 kGy) did not lead to significant changes in texture in any of the studied vegetables. Color varied significantly among the dose-temperature combinations only for broccoli florets; this variation did not demonstrate a clear pattern of quality changes in response to irradiation (Niemira et al., 2002).

Bari et al. (2005) reported that the appearance, color, texture, taste, and overall acceptability of broccoli and mung bean sprouts, irradiated at 1.0 kGy, did not undergo significant changes after seven days of post-irradiation storage at 4°C, in comparison with control samples.

The L-color values of dried potato were greatly affected by the irradiation dose (2, 4, 5, 6, 8, or 10 kGy) according to Wang and Du (2005). The L-values of the dried-product under low dose irradiation were greater than for non-irradiation and at higher than 6 kGy, the higher the dose, the lower the value.

Segsarnviriya et al. (2005) conducted a sensory test in which overall appearance, color, odor, taste, texture, and the overall quality were scored by trained panelists on each vegetable at 1, 4, and 7 days after irradiation. The ten vegetables reported to be acceptable by the panelists up to 7 days of storage at 10 ± 1°C after irradiation, were okra, baby corn, chaom, bird pepper, goat pepper, brinjal, eggplant, bitter cucumber, asparagus, and basil.

Horak et al. (2006) investigated the following minimally processed conventional and organic vegetables: conventional and organic chicory (*Chicorium endive*), organic rugola (*Eruca sativa* Mill), soy sprouts (*Glycine max*), alfalfa sprouts (*Medicago sativa*), and a mixed salad composed of cherry tomatoes (*Solanum lycopersicum)*, carrots (*Daucus carota L.*), lettuce (*Lactuca sativa)*, and cabbage *(Brassica oleracea*). In the case of conventional chicory and soy sprouts, the sensorial evaluation showed that these products had a higher general acceptability after irradiation with at least twice the disinfection dose (1.2 and 2 kGy, respectively). This dose seemed to considerably improve the shelf life of these products. The sensorial evaluation of alfalfa sprouts, mixed salad, organic chicory, and organic rugola revealed that there were no significant modifications in all the characteristics evaluated.

Landgraf et al. (2006) examined the cubes of mango (*Mangifera indica*) cultivar Tommy Atkins were sensory accepted until day 4 when exposed to 1 kGy. This cultivar showed a better response to irradiation than the Haden cultivar. Pineapple (*Citrullus vulgaris*) and watermelon (*Citrullus vulgaris*) in cubes exposed to 1 and 2.5 kGy irradiation were sensorialy acceptable. Irradiation did not affect the watermelon sweetness or pineapple sourness.

The results of the sensory evaluation of carrot stored at room temperature for 3 days and 7 days indicated that irradiation with lower than 2.0 kGy had no significant effect on color, lightness, flavor, sweetness, odor, and taste. During storage, the overall acceptability of the control samples was not higher than the samples irradiated with doses below 2.0 kGy. The results of sensory evaluation of carrot stored at refrigerator temperature (4–7°C) for 4 and 10 days indicated that color, lightness, odor, taste, sweetness, and flavor of samples irradiated with lower than 2.0 kGy (included 2.0 kGy) were not considerably different than those of the non-irradiated ones. The overall acceptability of samples irradiated with doses lower than 2.0 kGy was higher than that of the non-irradiated samples. Furthermore, color, taste, sweetness, and flavor of tomato stored at room temperature irradiated with doses higher than 1.0 kGy were significantly lower than control samples and in particular, taste and flavor. The overall acceptability of the non-irradiated samples was higher than that of the irradiated samples. Samples irradiated with doses above 2.0 kGy were not sensorialy acceptable (Shurong et al., 2006).

Bandekar et al. (2006) reported that the dose of 2 kGy did not alter the organoleptic properties of carrot (*Daucus carota L.*)

Table 5 Quality and shelf life extension of irradiated vegetables

Species	Irradiation type/dose (kGy)	Temperature (°C)	Shelf life	Quality	Refs
Red cabbage, broccoli and endive	Gamma irradiation 0.48, 0.98, 1.46, 1.94, 2.49, 2.90 kGy			Highest radiation resistance. Electrolyte leakage increased linearly with higher radiation dose for all vegetables	Fan and Sokorai, 2005
Celery, carrot and green onion	Gamma irradiation 0.48, 0.98, 1.46, 1.94, 2.49, 2.90 kGy			Sensitive to radiation. Electrolyte leakage increased linearly with higher radiation dose for all vegetables	
Carrot and juice	Gamma irradiation 3 kGy	10°C for 3 days		Total phenolic contents were significantly higher in the irradiated samples than in the non-irradiated control. Antioxidant capacity increased	Song et al., 2006
Kale juice	Gamma irradiation 3 kGy	10°C for 3 days		Total phenolic contents were significantly higher in the irradiated samples than in the non-irradiated control. Antioxidant capacity decreased	
Carrot juice		10°C	1 days	Nonirradiated samples stored for 3 days had similar or slightly lower levels of total ascorbic acid than their irradiated ones.	Song et al., 2007
Kale juice		10°C	1 days		
Carrot juice	3 and 5 kGy	10°C	3 days	Dose-dependent reduction of the ascorbic acid content. The contents of the total ascorbic acid, including dehydroascorbic acid, were stable up to 3 kGy	
Kale juice	3 and 5 kGy	10°C	3 days	Dose dependent reduction of the ascorbic acid content. The contents of the total ascorbic acid, including dehydroascorbic acid, were stable up to 3 kGy	
Organic watercress	—	7	14.5 days		Landgraf et al., 2006
Organic watercress	1 kGy	7	16 days		
Sliced tomatoes (*lycopersicon syn. L. esculentum*)	1 kGy			No significant effect on total carotenoid and vitamin C content of sliced tomatoes (*lycopersicon syn. L. esculentum*), however, it caused approximately 40% decrease in α-tocopherol	Mohacsi-Farkas et al., 2006
Carrot (*Daucus carota L.*)	1 and 2 kGy	4°C		There was no significant difference in the vitamin C content and total carotenoids in samples and control samples. Variation in the content of vitamin C and carotenoids during storage also was not statistically significant from the control samples. The qualified test panelist could not differentiate between irradiated and unirradiated samples.	Bandekar et al., 2006
Cucumber (*Cucumis sativus L.*)	1 and 2 kGy	4°C			
Onion bulbs	0.05 to 0.5 kGy			No appreciable effects on the total free sugar content (sucrose, glucose, and fructose)	Nishibori and Namiki, 1982
Potatoes	0.1 kGy	at 10°C		Marked increase in sucrose Maximum content was reached 5 days after irradiation, after which it decreased; 26 days after irradiation it was about the same as in nonirradiated tubers	Burton et al., 1959
Yam tubers (*Dioscorea rotundata*)	—	25° to 37°C; RH 50 to 85%);		Starch levels were almost identical	Adesuyi and Mackenzie, 1973
Yam tubers (*Dioscorea rotundata*)	0.15 kGy	25° to 37°C; RH 50 to 85%);			
Onion	0.1 to 0.5 kGy			Drastic reduction in vitamin C content immediately after irradiation	Guo et al., 1981
Potatoes	0.1 kGy	Tropical ambient temperatures or at 15°C		Ascorbic acid levels decreased during the initial period of storage	Joshi et al., 1990; Thomas, 1984

(*Continued on next page*)

Table 5 Quality and shelf life extension of irradiated vegetables (*Continued*)

Species	Irradiation type/dose (kGy)	Temperature (oC)	Shelf life	Quality	Refs
Potatoes	0.1 kGy	15°C		Decreased levels of carotenoids in the tuber flesh, particularly at 15°C where 50% reduction in its content occurred after 6 months storage. A partial recovery of the carotenoids content occurred when such tubers were reconditioned at 34°–35°C for 6 to 12 days	Janave and Thomas, 1979
Potato	0.1 kGy			Aspartic acid, asparagine, threonine, serine, alanine, isoleucine, leucine, lysine, and arginine showed increases 24 h after irradiation while glutamic acid, proline, methionine, and phenylalanine decreased. Lysine content showed a six-fold increase after 1 week storage, and at 1 month the concentration was still three times higher than the control values	Ussuf and Nair, 1972
Garlic bulbs	0.1 kGy	3 ± 1°C and 80 ± 5% RH for 10 months		No influence on the total sulfur and thiosulfonate content	Kwon et al., 1989
"Red" garlic bulbs	0.05 kGy	6 to 32°C, RH 58 to 86% for 6 months		No appreciable changes were detected in etherial extracts of "Red" garlic bulbs	Curzio and Ceci, 1984
Onion bulbs	—	12.8°C for 5 months		Weight loss due to sprouting and shrinkage of onion bulbs was 23.2%	Anon., 1962
Onion bulbs	0.06 and 0.076 kGy	12.8°C for 5 months		Weight loss due to sprouting and shrinkage of onion bulbs was 5.7%	
Onion bulbs cv "Valenciana Sintética 14"	—	6 to 32°C, RH 50 to 90% for 270 days		Weight loss was found to be 43.3%	Curzio and Croci, 1983
Onion bulbs cv "Valenciana Sintética 14"	0.03 kGy	6 to 32°C, RH 50 to 90% for 270 days		Weight loss was found to be 22.8%	
Onion bulbs	—	23° to 32°C, RH 60 to 80% for 270 days 4.5 months		Weight loss was found to be 27.7%	Thomas et al., 1986
Onion bulbs	0.06 kGy	23°C to 32°C, RH 60 to 80% for 270 days 4.5 months		Weight loss was found to be 15.2%	
Japanese potato cultivars	0.07 and 0.15 kGy	Room temperature		Weight loss	Umeda et al., 1969a, b
Japanese potato cultivars	0.07 and 0.15 kGy	5°C		No weight loss	
Potato cultivars	—	20°C for 6 months		28 to 51% weight loss	Khan et al., 1986
Potato cultivars	0.1 kGy	20°C for 6 months		17 to 40% weight loss	

and cucumber (*Cucumis sativus L.*). The radiation processing did not affect the textural properties of the above-mentioned minimally processed produce. There was significant reduction in the firmness of the peripheral region of the carrot after exposure to gamma rays. However, the acceptability of the radiation processed carrot was not affected. In fact, there was a slight increase in the sweetness after irradiation and the taste panel preferred irradiated carrot over control. During storage, there was significant increase in the firmness of the peripheral region of both control and irradiated samples.

Studies employing gas liquid chromatography, thin layer chromatography, infrared spectroscopy, and sensory tests of head space gases showed no changes in the flavor components of Red Globe onions irradiated with doses of 0.06, 0.1, 0.2, and 0.5 kGy and stored at ambient temperature (25° to 30°C) up to 3 months (Bandyopadhyay et al., 1973). Moreover, no appreciable differences were reported in the pungency and flavor strength in irradiated (0.06 kGy) onions under commercial conditions (Thomas et al., 1986).

Enzymic pyruvate, closely related to flavor development in crushed garlic, increased in both control and irradiated bulbs during storage and the average values were higher in irradiated bulbs (Ceci et al., 1991).

Irradiation at doses of 0.06 to 0.5 kGy neither affected skin color nor influenced the rate of fading of bulb color over three month storage at ambient temperatures (25° to 30°C) in the cultivar "Nashik Red Globe" as evidenced by their anthocyanin content (Bandyopadhyay et al., 1973). Similar observations were reported for cultivar "Giza-6" exposed to 0.06 kGy (Salems, 1974).

Mohacsi-Farkas et al. (2006) performed a sensory testing of pre-cut, irradiated tomatoes (*lycopersicon syn. L. esculentum*), cantaloupe melon (*Cucumis melo*), and watermelon (*Citrullus lanatus*). Statistically significant differences in organoleptic properties (color, odor, taste, and texture) were reported only in case of watermelon, at doses higher than 1.5 kGy. Firmness of the samples showed statistically significant softening (tendering) only of watermelon cubes at radiation dose of two kGy.

Bibi et al. (2006) found that the appearance and flavor scores for tomatoes (*L. esculentum)* showed similar trends as that for cucumbers (*Cucumis sativus*) stored at 5°C. The appearance score was lower for non-irradiated samples than for 3.0 kGy treated samples. The flavor of tomatoes was enhanced with irradiation. The non-irradiated samples had a lower mean score than 3.0 kGy treated samples. Although the flavor deteriorated during storage, the data did not indicate a clear trend. The trend of changes in firmness of tomatoes was also similar to that of cucumbers. The firmness of 0.5 kGy treated samples was similar to that of control samples whereas the 3.0 kGy irradiated samples displayed the minimum firmness. Furthermore, it was determined that the appearance scores of minimally processed carrots (*Daucus carota*) were affected by radiation doses and the mean scores decreased from 7.6 (control) to 6.33 (3.0 kGy treated). This suggested that minimally processed carrots should not be irradiated at higher than 2.0 kGy dose for storage at low temperature (5°C). It is evident from this data that the appearance of irradiated minimally processed cabbage (*Lactuca sativa var. capitata*) was not affected significantly by the applied gamma radiation for doses from 0.5 up to 3.0 kGy (Table 6).

THE MICROFLORA OF IRRADIATED VEGETABLES

Bibi et al. (2006) reported that the initial bacterial load in control carrot samples (*Daucus carota*) was 6.3 × 10^2 CFU/g in control samples and reached 6.5 × 10^5 CFU/g after 14 days of storage. A dose of 1 kGy reduced the bioload down to 12.0 CFU/g, which were few colonies after 14 days storage. The samples receiving 2 kGy or higher doses were completely free of bacteria during 14 days refrigerated storage. The control samples showed 2.7 × 10^1 CFU/g fungal counts initially and increased to 1.2 × 10^4 CFU/g after 14 days of storage. The samples irradiated at a dose higher than 1 kGy were also completely fungi free during the two weeks storage at 5°C. Additionally, the initial total bacterial count (TBC) in cabbage (*Lactuca sativa var. capitata*) control samples increased from 1.0 × 10^3 to 1.0 × 10^5 CFU/g after 14 days of storage. In the case of irradiated samples the counts ranged from 7.1 × 10^1 to 6.3 × 10^3 CFU/g at 0-day and increased to 4.2 × 10^4, 2.4 × 10^4, 8.1 × 10^2, 1.5 × 10^2 CFU/g for 0.5, 1.0, 2.0, 2.5, and 3.0 kGy irradiated samples respectively, after 7 days of storage. The bacterial counts of 2 kGy irradiated samples were within the permissible limits. It was also noted that samples irradiated with a dose higher than 1 kGy were completely free of coliforms. Only few colonies were detected after 14 days storage of 1 kGy treated samples. In the case of fungal counts, a dose of 2.5 kGy gave samples completely free of viable fungal colonies up to 14 days of refrigerated storage.

Song et al. (2006) studied the effectiveness of gamma irradiation for inactivating *Salmonella typhimurium* and *Escherichia coli* in carrot and kale juice, stored at 10°C. Viable cells in the non-irradiated samples were 10^7 cfu/ml, but the irradiation at 3 kGy showed no viable cell growth of the test organisms at a detection limit of this study (10^1 cfu /ml). *E. coli* was more sensitive to radiation than *S. typhimurium*. The D_{10} values of *S. typhimurium* in the carrot and kale juice were 0.445 ± 0.004 and 0.441 ± 0.006 kGy, respectively, while those of *E. coli* were 0.301 ± 0.005 and 0.299 ± 0.006 kGy.

Song et al. (2007) reported that the initial populations of the total aerobic bacteria and coliform counts observed in the carrot juice were 10^6 CFU/ml, and those of the kale juice were 10^7 CFU/ml. All the aerobic bacteria and coliforms in the fresh carrot juice were eliminated with irradiation at 3 kGy and the D_{10} value of the microflora in the carrot juice was found to be approximately 0.5 kGy. However, a radiation dose up to 5 kGy could not completely eliminate the bacteria in the fresh kale juice. The D_{10} value was higher than 1.0 kGy in the kale juice. This result indicated that the microflora of the kale and carrot juice is fairly different.

Four frozen vegetables (broccoli, corn, lima beans, and peas) were gamma irradiated at subfreezing temperatures ranging from −5 to −20°C. The amounts of radiation necessary to reduce the bacterial population by 90% (D_{10}-values) for *Listeria monocytogenes* differed significantly among vegetables at each irradiation temperature. D_{10}values increased significantly with decreasing temperature for all vegetables, with each vegetable displaying a different response pattern. At an irradiation temperature of −5°C, D_{10} values ranged from 0.505 kGy for broccoli to 0.613 kGy for corn. At −20°C, D_{10} ranged from 0.767 kGy for lima beans up to 0.916 kGy for peas (Niemira et al., 2002).

Bari et al. (2005) found that irradiation of broccoli and mung bean sprouts at 1.0 kGy resulted in reductions of approximately 4.88 and 4.57 log CFU/g, respectively, of a five-strain cocktail of *L. monocytogenes.* Reductions of approximately 5.25 and 4.14 log CFU/g were reported for cabbage and tomato, respectively, at a similar dose. The appearance, color, texture, taste, and overall acceptability did not undergo considerable changes after seven days of post-irradiation storage at 4°C, in comparison with the control samples.

Kim et al. (2004) investigated the isolation of enteric bacteria in the fermentation process of Kimchi (Korean fermented vegetables) and its radicidation by gamma irradiation. Viable cell numbers of enteric bacteria were 10^4 CFU /g at the initiation of the fermentation process, gradually reducing during the fermentation period, and not detected after 10 days. The enteric bacteria in the early fermentation period of

Table 6 Effect of irradiation (type/dose) on shelf life and sensory properties of vegetables

Species	Irradiation type/dose (kGy)	Temperature (°C)	Shelf life	Sensory properties	Refs
Carrot juice	—	10°C	1 days	Overall sensory scores of the irradiated and non-irradiated carrot and kale juice were not significantly different. The color of the control samples became darker.	Song et al., 2007
Kale juice	—	10°C	1 days		
Carrot juice	Gamma irradiation 3 kGy	10°C	3 days	Overall sensory scores of the irradiated and non-irradiated carrot and kale juice were not significantly different.	
Kale juice	Gamma irradiation 3 kGy	10°C	3 days		
				The color of the irradiated samples maintained its original color over time, whereas the color of the control samples became darker.	
Broccoli, corn, lima beans, and peas	2.5 to 3.1 kGy	−5°C		Did not cause significant changes in texture	Niemira et al., 2002
Broccoli, corn, lima beans, and peas	3.9 to 4.6 kGy	−20°C		Caused significant softening of peas and broccoli stems but not of corn or lima beans	
Broccoli and mung bean sprouts	1 kGy	4°C		The appearance, color, texture, taste, and overall acceptability did not undergo significant changes after 7 days of postirradiation storage	Bari et al., 2005
Okra, baby corn, chaom, bird pepper, goat pepper, brinjal, egg plant, bitter cucumber, asparagus, and basil	Gamma irradiation 0.3, 0.6, 0.9 kGy	10 ± 1°C		Organoleptically acceptable after 7 days storage	Segsarnviriya et al., 2005
Conventional chicory	1.2 kGy	4°C		Sensorial evaluation showed that they had a better general acceptability when were irradiated with at least twice the disinfection dose (1.2 and 2 kGy, respectively).	Horak et al., 2006
Conventional soy sprouts	2 kGy	4°C			
Alfalfa sprouts	2 kGy	4°C		No significant modifications in all the characteristics evaluated	
Mixed salad composed of cherry tomatoes	1.2 kGy	4°C			
Organic chicory	1.3 kGy	4°C			
Organic rugola	1.4 kGy	4°C			
Pineapple (*Citrullus vulgaris*) in cubes	1 and 2.5 kGy			Irradiation did not influence the pineapple sourness.	Landgraf et al., 2006
Watermelon (*Citrullus vulgaris*) in cubes	1 and 2.5 kGy			Irradiation did not influence the watermelon sweetness	
Carrot	<2.0 kGy	Room temperature		No significant effect on color, lightness, flavor, sweetness, odor, taste. During storage, overall acceptability of control samples was not higher than samples irradiated with doses below 2.0 kGy.	Shurong et al., 2006
Carrot	<2.0 kGy	4–7°C		No significant effect on color, lightness, flavor, sweetness, odor, taste. Overall acceptability of samples irradiated with doses lower than 2.0 kGy was higher than that of nonirradiated samples	
Tomato	>1.5 kGy	4–7°C		Negative effect on color and lightness	
Tomato	>1 kGy	4–7°C		Negative effect on the taste, sweetness and flavor	
Tomato	>1 kGy	Room temperature		Color, taste, sweetness and flavor significantly lower than control samples, especially, taste, and flavor	
Tomato	>2 kGy	Room temperature		Samples not accepted	
Tomato (*lycopersicon syn. L. esculentum*),	>1.5 kGy			Statistically significant differences in colour, odour, taste and texture were determined only in case of watermelon. Rank sums of pre-cut tomato and cantaloupe cubes were not significantly different.	Mohacsi-Farkas et al., 2006

(*continued on next page*)

Table 6 Effect of irradiation (type/dose) on shelf life and sensory properties of vegetables (*Continued*)

Species	Irradiation type/dose (kGy)	Temperature (°C)	Shelf life	Sensory properties	Refs
Melon (*Cucumis melo*)	>1.5 kGy				
Watermelon (*Citrullus lanatus*)	>1.5 kGy				
Tomatoes (*lycopersicon syn. L. esculentum*),	2 kGy			Firmness of the samples showed statistically significant softening (tendering) only of watermelon cubes.	
Melon (*Cucumis melo*)	2 kGy				
Watermelon (*Citrullus lanatus*)	2 kGy				
Carrot (*Daucus carota L.*)	2 kGy			No change the organoleptic properties, and no effect on the textural properties. a slight increase in the sweetness after irradiation	Bandekar et al., 2006
Cucumber (*Cucumis sativus L.*)	2 kGy			No change the organoleptic properties and no effect on the textural properties	
Carrots (*Daucus carota*)	3 kGy	5°C		Appearance scores were lower for irradiated samples than for controls	Bibi et al., 2006
Tomatoes (*L. esculentum*	3.0 kGy	5°C		The appearance score was lower for non-irradiated samples than irradiated samples.	
Tomatoes (*L. esculentum*	3.0 kGy	0.5 kGy		The non-irradiated samples had a lower mean flavor score than 3.0 irradiated samples.	
Tomatoes (*L. esculentum*	0.5 kGy	0.5 kGy		Firmness similar to that of control samples	
Tomatoes (*L. esculentum*	3 kGy	3 kGy		Samples had the minimum firmness	
Cabbage (*Lactuca sativa var. capitata*)	0.5 up to 3.0 kGy	5°C for 14 days		that the appearance of irradiated minimally processed cabbage (*Lactuca sativa var. capitata*), was not affected significantly	

Kimchi were eliminated by 2–3 kGy of gamma irradiation, but *Lactobacillus* spp. survived and fermentation was maintained. The D_{10} values of total enteric group and *Latobacillus* spp. were about 0.32 and 0.87 kGy, respectively. The three typical enteric bacteria were identified as *Enterobacter agglomerans*, *Salmonella typhimurium*, and *Alcaligenes xylosoxydans*, and the D_{10} values were 0.38, 0.54, and 0.47 kGy, respectively (Figure 3).

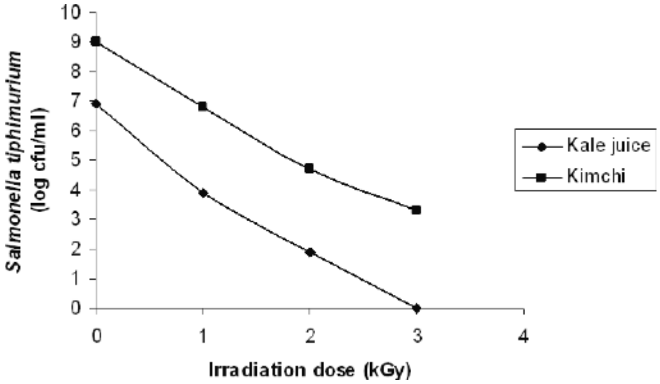

Figure 3 Effect of different irradiation doses on total *Salmonella tiphimurium* population of Kale (*Brassica oleracea* var. acephala) juice and Kimchi (Korean fermented vegetables) (Song et al., 2006; Kim et al., 2004).

Lee et al. (2006) studied the effects of an irradiation treatment for eliminating pathogens on cucumber, blanched and seasoned spinach, and seasoned burdock. The pathogens tested were *Salmonella Typhimurium*, *Escherichia coli*, *Staphylococcus aureus*, and *Listeria ivanovii*. Inoculated viable cells of *S. Typhimurium* and *L. ivanovii* into cucumber and blanched and seasoned spinach were reduced by about 4 decimal points with 2 kGy and that of *S. aureus* inoculated into burdock displayed 4-decimal point reduction with 1 kGy. *E. coli* inoculated into burdock was not detected with 1 kGy. All the bacterial contents of test pathogens into the samples were reduced to lower than the detection limit with 3 kGy irradiation. The range of the D_{10} value was 0.28–0.42 among the four above-mentioned pathogens.

Doses of gamma irradiation ranging between 1 and 10 kGy were used to investigate the inactivation of hepatitis A virus (HAV) inoculated onto lettuce at ambient temperature. Data analysis with a linear model indicated that a D_{10} value of 2.72 ± 0.05 was required to achieve a 1-log reduction in HAV titre in lettuce (Bidawid et al., 2000).

Horak et al. (2006) studied the effect of irradiation on conventional and organic chicory (*Chicorium endive*), organic rugola (*Eruca sativa* Mill), soy sprouts (*Glycine max*), alfalfa sprouts (*Medicago sativa*), and a mixed salad composed of cherry tomatoes (*Solanum lycopersicum*), carrots (*Daucus carota L.*), lettuce

(*Lactuca sativa*), and cabbage *(Brassica oleracea*) stored at 4°C. The investigated microorganisms were *Listeria monocytogenes* ATCC 15313, *Salmonella Enteritidis* ATCC 13076, and *Staphylococcus aureus* ATCC 6538P. The most radiation-resistant microorganism in the products was *Listeria monocytogenes* in organic chicory and rugola, conventional chicory, alfalfa and soy sprouts, and *Staphylococcus aureus* in mixed salad. Based on the application of five times the D_{10} determined value, the minimum disinfection doses proposed for the products were 1.2 kGy for chicory and mixed salad, 1.3 kGy for organic chicory, 1.4 kGy for rucula, and around 2 kGy for soy and alfalfa sprouts.

Storage at refrigeration temperature was found not to be sufficient to control the growth of survived cells of *L. monocytogenes* on irradiated organic watercress (Landgraf et al. 2006). Doses of 1, 2, and 3 kGy reduced the population by ca. 4, 5, and 6 logs, respectively. The non-irradiated samples displayed increasing counts during storage time at 7°C. Similar behavior was reported for samples exposed to 1 kGy. Samples irradiated with 2 kGy and 3 kGy maintained the same population throughout their shelf-life. *Salmonella* population displayed the same pattern as *L. monocytogenes* when inoculated on organic watercress and exposed to 1, 2, and 3 kGy. The population of *Salmonella* on the non-irradiated sample presented a small increase between 14 and 16 days of storage at 7°C but the population was already very high. It was also found that the D_{10} value for *L. monocytogenes* in arugala varied from 0.37 to 0.48 kGy. Furthermore, they reported that for shredded iceberg lettuce the D_{10} values for *Escherichia coli* O157:H7 and *Salmonella spp.* were 0.11–0.12 and 0.16–0.23 kGy, respectively (Figures 4 and 5).

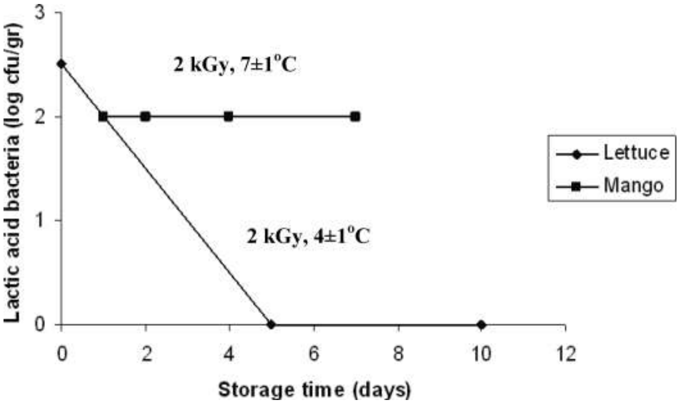

Figure 5 Effect of irradiation (2 kGy) on lactic acid bacteria population in lettuce (*Lactuta sativa*) and mango, cultivar Haden, (*Mangifera indica)* (Hammad et al., 2006; Landgraf et al., 2006).

Lopez et al. (2006) determined similar the D_{10} values for two different strains of *E. coli* (an ATTC and a wild type), in celery (*Apium graveolens*) and cabbage (*Lactuca sativa var. capitata*) (0,18–0,23 kGy). The same situation was observed for *Listeria innocua* in carrots (*Daucus carota L.*), iceberg lettuce (*Lactuca sativa* var. *capitata*), Toscana (containing chopped iceberg lettuce) and, Four Seasons salads (containing a mixture of chopped romaine lettuce, iceberg lettuce, Butterhead lettuce and spinach) (0.19–0.22 kGy). However, a higher D_{10} value was obtained for the same microorganism, when inoculated in spinach (*Spinacia oleracea*) (0.32 kGy). *E. coli* O157:H7 displayed a greater radio sensibility, presenting a D_{10} value of 0.09 ± 0.01 kGy in both mixed salads (Figure 6).

Shurong et al. (2006) determined the D_{10}-values of *E. coli* 0157:H7, *Listeria innocua* and *Salmonella Enteritidis*. D_{10}-values of *E. coli* O157:H7 inoculated in cherry tomato and fresh pre-cut carrot were 0.08 kGy and 0.13 kGy, respectively; D_{10}-values of *Salmonella Enteritidis* inoculated in cherry tomato, fresh pre-cut carrot, a mixture of blanched celery, and peanut were in the range of 0.24 kGy to 0.33 kGy. Irradiation with doses less than 2.0 kGy dose could ensure a 5 log reduction of the most resistant examined pathogen, *Salmonella Enteritidis*. Moreover, irradiation could effectively control the growth of pathogens during storage period.

The effects of low-dose irradiation on the microbiota of pre-cut tomato (*lycopersicon syn. L. esculentum)* was investigated by Mohacsi-Farkas et al. (2006). Challenge testing with pathogens such as *E. coli* O157:H7 and *L. monocytogenes* were also carried out. Doses of 1–3 kGy were able to reduce considerably the microbiological contamination of tomato. The low-dose

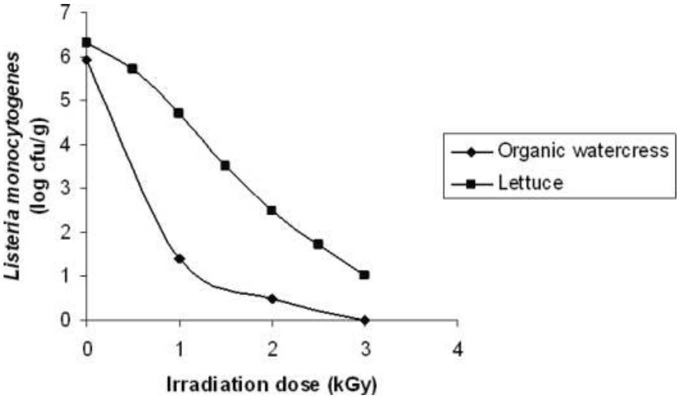

Figure 4 Effect of different irradiation doses on *Listeria monocytogenes* population of organic watercress (*Nasturtium officinale*) (Landgraf et al., 2006) and Lettuce (*Lactuta sativa*) (Hammad et al., 2006).

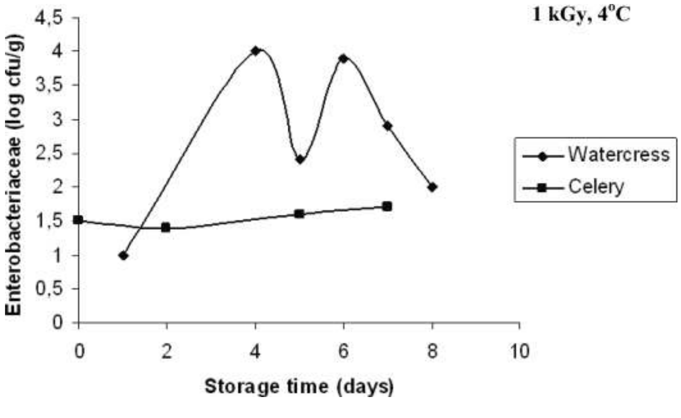

Figure 6 Effect of irradiation (1 kGy) on Enterobacteriaceae population in watercress (*Nasturtium officinale*) and celery (*Apium gravedens*) stored at 4°C (Trigo et al., 2006; Lopez et al., 2006).

irradiation reduced the viable cell count of *Listeria monocytogenes* by 2 log-cycles. A dose of 1 kGy reduced the viable cell number by more than 5 log-cycles. *E. coli* was able to grow on tomatoes only at 15°C, even survivors of radiation treatment, after three days of storage. At refrigeration temperature (5°C) the number of *E. coli* remained stable during seven days of storage. Faridah et al. (2006) found that D_{10}-value of *L. monocytogenes* was 0.23 kGy both in onion (*Allium cepa*) and cucumber (*Cucumus sativus*), aerobically packaged at 5°C ± 2°C. The D_{10}-values of *E. coli* 0157 were lower (0.11 kGy in onion and 0.06 in cucumber) compared to the D_{10}-values of *L. monocytogenes* in these vegetables. Generally, the total viable count in both onion and cucumber increased during storage. However, the microbial count was lower in the irradiated samples (0.5, 1.5, 3.0 kGy) compared to the non-irradiated samples. The shelf-life of onion and cucumber was at least 14 and 8 days, respectively. Data demonstrated that the hardness of onion was not affected by the irradiation in the range of 0.5 to 3.0 kGy. Furthermore, data displayed that the hardness of cucumber was not affected by the irradiation in the range of 0.5 to 3.0 kGy. The results also exhibited that storage of onion and cucumber for 15 days did not affect this parameter. In addition, irradiation was shown to hardly affect the color (lightness, redness, and greenness) of the minimally processed onion and cucumber (Figure 7). The effect of irradiation on vegetable microflora is summarized in Table 7.

IRRADIATION AND HURDLE TECHNOLOGY OF IRRADIATED VEGETABLES

Lacroix and Lafortune (2004) inoculated grated carrots (*Daucus carota*) with *Escherichia coli* (10^6CFU/g) and packed under air or under MAP condition (60% O_2, 30% CO_2, and 10% N_2). The packages were then, gamma-irradiated at doses varying from 0.15 to 0.9 kGy and stored at 4 ± 1°C. *E. coli* counts were periodically evaluated during 50 days of storage. Results showed that at day 1, an irradiation treatment at a dose of 0.15 kGy reduced by 3 and 4 log the microbial level representing a level of 3 and 2 log CFU/g when samples were irradiated under air and under MAP respectively. However, a level of 3 log CFU/g was detected in both treated samples after 7 days of storage. When samples were irradiated at doses 0.3 kGy no *E.coli* was detected during the whole storage in samples treated under MAP. However, when samples were treated under air, a level of 1–2 log CFU/g of *E.coli* was detected after 5 days of storage.

A series of experiments to examine the effects of gamma irradiation (1, 2, and 3 kGy) on coriander leaves (*Coriandrum sativum* L.) stored in polyethylene sachets at 8–10°C was performed by Kamat et al. (2003). The initial total bacterial and mold counts observed in coriander leaves ranged between 10^6 to 10^8 cfu/g and 10^3–10^4 cfu/g, respectively. All the samples contained Listeria, Yersinia, and fecal coliforms prior to irradiation. Dose of 1 kGy resulted in three log cycles reduction of bacteria, 1 log kill of yeast and mould and reduction of coliform to 43 cfu/g. The Listeria and Yersinia present in the product were eliminated by such a low-dose treatment. The total chlorophyll contents as well its components, chlorophyll a and b did not change significantly on irradiation (1, 2, and 3 kGy) and subsequent storage. Similarly, the total carotenoid levels remained unaffected by exposure to 1 kGy dose; however, a dose-dependent enhancement in their extractability was observed in irradiated leaves. No significant quantitative changes in the constituents of the major aroma compounds obtained from these two samples were reported (Figure 8).

Landgraf et al. (2006) performed a sensory evaluation for exudate, odor, texture, and color for minimally processed iceberg lettuce aerobically packed in polyethylene bags exposed to radiation doses of 0.0 (control), 0.7, 0.9, and 1.1 kGy. It was reported that doses of 0.7 and 0.9, kGy did not affect the iceberg lettuce attributes. However, a significant difference in the texture was observed with the dose of 1.1 kGy. Therefore, above this dose, irradiation treatment would not be suitable for iceberg lettuce. Furthermore, on day 0 and 2, irradiated and non-irradiated packaged watercress were similarly assessed even for samples

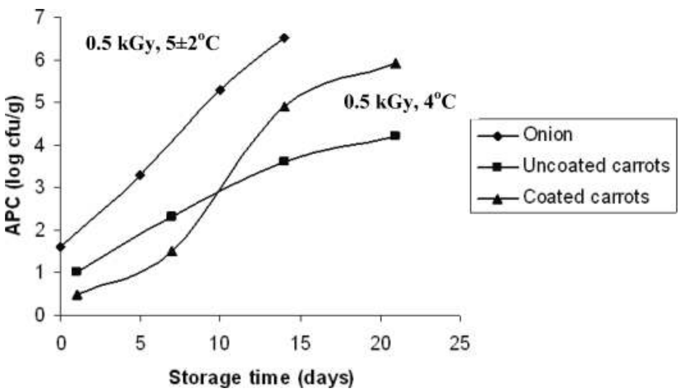

Figure 7 Effect of irradiation (0.5 kGy) on the aerobic plate count of different products; onions (*Allium cepa*) packed in polypropylene bag, (Faridah et al., 2006) and coated (caseinate based coating) and uncoated peeled carrots (*Daucus carota*) (Lacroix et al., 2006).

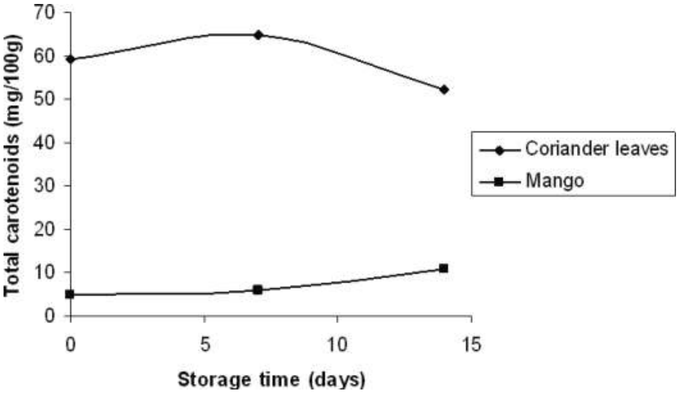

Figure 8 Effect of irradiation (1kGy) on total carotenoids content of mango fruits, (*Mangifera indica*) variety "Zebda" (mg/100 g pulp), and Coriander leaves (*Coriandrum sativum*) (mg/100 g tissue) (El-Samahy et al., 2000; Kamat et al., 2003).

exposed to 3 and 4 kGy. This feature continued up to day 5, when the 4 kGy sample obtained the lowest acceptability on the hedonic scale. From the seventh day onwards, the acceptability of all samples decreased, although only on days 9 and 12 significant differences were observed with respect to 3 and 4 kGy irradiated samples. The acceptability of non-irradiated and 1 kGy irradiated watercress was higher, compared to higher doses, and did not differ significantly over all the rest of the days of the study.

Lacroix et al. (2006) studied carrots *(Daucus carota* L.) stored under MAP: (60% O_2; 30% CO_2; 10% N_2) with an edible coating based on caseinate and whey protein in conjunction with gamma irradiation. Carrots were irradiated at 0.5 or 1 kGy and stored at $4 \pm 1°C$ for 21 days. Results showed that gamma irradiation did not affect significantly the physico-chemical properties of the carrots. Coating and irradiation treatment at 1 kGy were also able to protect the firmness during storage under air. MAP retarded whitening of uncoated carrots, but this treatment had a detrimental effect on the firmness. Microbiological analysis revealed that for uncoated carrots a dose of 0.5 and 1 kGy applied under air and MAP reduced, respectively, by 3.5 and 4 log CFU/g and by 4 and 4.5 log CFU/g the content in aerobic plate count (APC). For coated carrots a dose of 0.5 and 1 kGy applied under air and MAP reduced, respectively, by 4 and 4.5 log CFU/g and by 3 and 4.25 log CFU/g the content of APC. Processed carrots were also coated with caseinate based coating containing spice extracts or of antimicrobial compounds present in spices and irradiated at doses from 0.07 to 2.4 kGy to evaluate the radiosensitization of *Listeria monocytogenes* HPB 2812 serovar $^1/_2$a (10^6 CFU/g). The dose (D_{10}) required to reduce *L. monocytogenes* population by 1 log was 0.36 kGy for samples packed under air and 0.17 kGy for those packed under MAP. The effect of an antimicrobial edible coating containing *trans*-cinnamaldehyde combined with MAP and gamma irradiation showed that the coating was able to reduce by 1.29 logs CFU/g the content of *L. innocua* in carrots packed under air after 21 days of storage whereas when packed under MAP, a 1.08 log CFU/g reduction was observed only after seven days of storage. Moreover, after seven days of storage, no *L. innocua* was detected in samples treated at 0.5 kGy under air or in samples treated at 0.25 kGy under MAP. A complete inhibition of *L. innocua* was also observed during all storage period in uncoated and coated samples treated at 0.5 kGy under MAP (Figure 9).

Irradiation treatment with 0.5 to 2 kGy on lettuce (*Lactuca sativa)* caused a reduction of 3.13 to 4 log in mesophilic and psycrotrophic counts, respectively. In the case of turnip (*Brassica campestris*) there was a 4.2 log reduction (Trigo et al. 2006b). The irradiation treatment in parsley (*Petroselinum crispum*) caused a reduction of 3–4 log cycles in mesophilic and psycrotrophic counts. As regards watercress (*Nasturtium officinale*) there was a 4.69 log reduction. A dose of 0.5 kGy resulted in reductions of 2.23 and 2.68 log of mesophilic bacterial counts in coriander (*Coriandrum sativum*) and mint (*Mentha spicata*), respectively. With 1 kGy there was a 3.67 and 2.70 log reduction. A dose of 0.5 kGy in coriander resulted in reductions of 1.52 and 1.72 log for coliforms and *Enterobacteriaceae*. In mint, the reduction was 3.57 and 3.66 log. Radiation caused a reduction in coliforms and *Enterobacteriaceae* of 5 to 7 log in lettuce and 4 log in turnip. During the trial period this difference remained constant. Radiation caused a reduction in coliforms and *Enterobacteriaceae* of 5.69 log in parsley and 6.2 log in watercress.

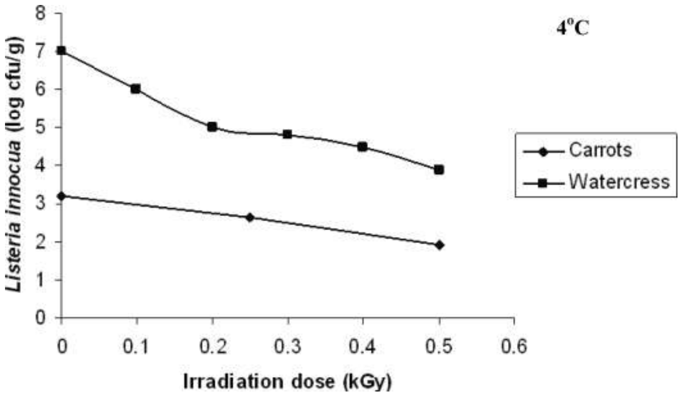

Figure 9 Effect of different doses of irradiation on the *Listeria innocua* population in Carrots (*Daucus carota*) (Lacroix et al., 2006) and watercress packed in polymeric bags (Trigo et al., 2006) stored at 4°C.

Basbayraktar et al. (2006) concluded that a dose of 1.0 kGy is sufficient to reduce the non-pathogenic and the pathogenic bioload of minimally processed carrots without affecting the sensorial quality. D_{10}-values for *L. monocytogenes* and *E. coli* were determined as 0.29 kGy and 0.29 kGy, respectively. At 1.0 kGy irradiation, approximately 4-log reduction in *E. coli* and *L. monocytogenes* counts. Furthermore, no *Listeria* and *E. coli* were recovered from any sample during the storage periods. Treatment with 1 kGy was effective to reduce the pathogens in the shredded carrots. While irradiation had an effect only on pH but no effect on the appearance and texture of sliced-carrot samples. Panelists observed that storage affected the sensory quality of the samples. Panelists preferred the irradiated to the non-irradiated sliced-carrot samples regarding the odor, taste, and general acceptability. All samples were packed in sterile polyethylene bags. Moreover, it was found that a dose of 1.5 kGy is sufficient to maintain the sensorial quality and the reduction of pathogenic bioload of minimally processed mixed salad. The five-log reduction in *S. Enteritidis* counts and 4 log reduction in *L. monocytogenes* counts and lack of adverse effects on sensory attributes revealed that low dose irradiation can improve food safety of mixed salad (Figures 10 and 11).

Patterson et al. (2006) determined that irradiation (2 kGy) treatment alone or in combination with a decontamination wash (using calcium hypochlorite, eugenol (oil of clove), or oregano oil) did not considerably affect the quality of alfalfa seeds during sprouting. Irradiation (2 kGy) and oregano oil (0.1%) did result in significantly lower total counts during storage of the sprouts for 5 days at 5°C. However, the microbial counts in all cases were higher than log 8 by day 5 of storage and all the samples appeared spoiled. *Pantoea* spp. was the dominant bacterium

Table 7 The effect of irradiation on vegetable microflora

Species	Irradiation type/dose (kGy)	Temperature (°C)	Irradiation effect	Refs
Carrot juice	Gamma irradiation 3 kGy	10°C	No viable cell growth of *Salmonella typhimurium* and *Escherichia coli* (reduced from 10^7 cfu/ ml)	Song et al., 2006
Kale juice	Gamma irradiation 3 kGy	10°C	No viable cell growth of *Salmonella typhimurium* and *Escherichia coli* (reduced from 10^7 cfu/ ml)	
Carrot juice	Gamma irradiation 3 kGy	10°C	All the aerobic bacteria and coliform in the fresh carrot juice were eliminated (population before irradiation 10^6 CFU/ml)	Song et al., 2007
Kale juice	Gamma irradiation 5 kGy	10°C	Incomplete elimination of bacteria (population before irradiation 10^7 CFU/ml)	
Broccoli	0.505 kGy	Irradiated at −5°C	Reduce the bacterial population by 90% (D_{10}-values) for *Listeria monocytogenes*	Niemira et al., 2002
Corn	0.613 kGy	Irradiated at −5°C		
Lima beans	0.767 kGy	Irradiated at −20°C		
Peas	0.916 kGy	Irradiated at −20°C		
Broccoli sprouts	1.0 kGy	4°C	4.88 log CFU/g, of a five-strain cocktail of *L. monocytogenes*	Bari et al., 2005
Mung bean sprouts	1.0 kGy	4°C	4.57 log CFU/g of a five-strain cocktail of *L. monocytogenes*	
Kimchi (Korean fermented vegetables)	0.38 kGy		D_{10} value of *Enterobacter agglomerans*,	Kim et al., 2004
Kimchi (Korean fermented vegetables)	0.54 kGy		D_{10} value of *Salmonella typhimurium*	
Kimchi (Korean fermented vegetables)	0.47 kGy		D_{10} value of *Alcaligenes xylosoxydans*	
Kimchi (Korean fermented vegetables)	0.32 kGy		D_{10} value of total enteric group	
Kimchi (Korean fermented vegetables)	0.87 kGy		D_{10} values of *Latobacillus* spp	
Cucumber, blanched and seasoned spinach, and seasoned burdock	Gamma irradiation 1 kGy		Reduction of about 3 log CFU/g of *Salmonella* Typhimurium	Lee et al., 2006
Cucumber	Gamma irradiation 2 kGy		4 log reduction of *S. aureus*	
Blanched and seasoned spinach	Gamma irradiation 2 kGy		4 log reduction of S. aureus	
Seasoned burdock	Gamma irradiation 1 kGy		4 log reduction of *S. aureus*	
Cucumber	Gamma irradiation 2 kGy		S.Typhimurium was reduced by about 4 lof CFU/g	
Blanched and seasoned spinach	Gamma irradiation 2 kGy		S. Typhimurium was not detected	
Seasoned burdock	Gamma irradiation 2 kGy		S. Typhimurium was not detected	
Cucumber	Gamma irradiation 2 kGy		*Escherichia coli* decreased about 4 log cfu/g	
Blanched and seasoned spinach	Gamma irradiation 2 kGy		*Escherichia coli* decreased about 4 log cfu/g	
Cucumber	Gamma irradiation 1 kGy		3 log CFU/g reduction of the *L. ivanovii*	
Blanched and seasoned spinach	Gamma irradiation 2 kGy		By about 4 log cfu/g reduction of the *L. ivanovii*	
Seasoned burdock	Gamma irradiation 3 kGy		*L. ivanovii* not detected	
Cucumber, blanched and seasoned spinach, and seasoned burdock	Gamma irradiation 3 kGy		All the bacterial contents of*Salmonella* Typhimurium, *Escherichia coli*, *Staphylococcus aureus*, and *Listeria ivanovii* were reduced to below the limit of detection	
Lettuce	Gamma irradiation 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 kGy	Ambient temperature	D_{10} values of 2.72 ± 0.05 was required to achieve a 1-log reduction in HAV titre	Bidawid et al., 2000
Soy sprouts (*Glycine max*)	2 kGy	4°C	5 log cycles reduction of *L. monocytogenes*	Horak et al., 2006
Alfalfa sprouts (*Medicago sativa*)	1.85 kGy	4°C	5 log cycles reduction of *L. monocytogenes*	
Mixed salad composed of cherry tomatoes (*Solanum lycopersicum*)	1.2 kGy	4°C	5 log cycles reduction of *S. aureus*	
Chicory (*Chicorium endive*)	1.2 kGy	4°C	5 log cycles of *L. monocytogenes*	

(*Continued on next page*)

Table 7 The effect of irradiation on vegetable microflora (*Continued*)

Species	Irradiation type/dose (kGy)	Temperature (°C)	Irradiation effect	Refs
Organic watercress	1 kGy	7°C	Reduced the of *L. monocytogenes* population by ca. 4 logs	Landgraf et al., 2006
Organic watercress	2 kGy	7°C	Reduced of *L. monocytogenes* population by ca. 5 logs	
Organic watercress	3 kGy	7°C	Reduced of *L. monocytogenes* population by ca. 6 logs	
Arugala	0.37 to 0.48 kGy	7°C	D_{10} value for *L. monocytogenes*	
Shredded iceberg lettuce	0.11 – 0.12 kGy	7°C	D_{10} value for *Escherichia coli* O157:H7	
Shredded iceberg lettuce	0.16 – 0.23 kGy	7°C	D_{10} value for Salmonella spp.	
Celery (*Apium graveolens*)	0.18 ± 0.01 kGy	4°C	D_{10} value for *E. coli* ATCC	Lopez et al., 2006
Cabbage (*Lactuca sativa var. capitata*)	0.22 ± 0.03 kGy	4°C	D_{10} value for *E. coli* ATCC	
Iceberg lettuce (*Lactuca sativa* var. *capitata*),	0.22 ± 0.03 kGy	4°C	D_{10} value for *L. innocua*	
Carrots (*Daucus carota L.*)	0.20 ± 0.02 kGy	4°C	D_{10} value for *L. innocua*	
Spinach (*Spinacia oleracea*)	0.32 ± 0.01 kGy	4°C	D_{10} value for *L. innocua*	
Toscana Salad (containing chopped iceberg lettuce)	0.19 ± 0.01 kGy	4°C	D_{10} value for *L. innocua*	
Four Seasons Salad (containing a mixture of chopped romaine lettuce, iceberg lettuce, Butterhead lettuce, and spinach)	0.21 ± 0.03 kGy	4°C	D_{10} value for *L. innocua*	
Cherry tomato	0.08 kGy		D_{10}-value of *E. coli* O157:H7	Shurong et al., 2006
Carrot	0.13 kGy		D_{10}-value of *E. coli* O157:H7	
Cherry tomato	0.24 kGy to 0.33 kGy		D_{10}-values of *Salmonella* Enteritidis	
Carrot	0.24 kGy to 0.33 kGy		D_{10}-values of *Salmonella* Enteritidis	
Mixture of blanched celery and peanut	0.24 kGy to 0.33 kGy		D_{10}-values of *Salmonella* Enteritidis	
Tomato (*lycopersicon syn. L. esculentum*)	1 kGy		Reduction of the viable cell number by more than 5 log-cycles	Mohacsi-Farkas et al., 2006
Tomato (*lycopersicon syn. L. esculentum*)	1 kGy		Reduction of*Listeria monocytogenes* by 2 log-cycles	
Carrot samples (*Daucus carota*)	1 kGy	5°C for 14 days	From 6.3×10^2 CFU/g to 12.0 CFU/g	Bibi et al., 2006
Carrot samples (*Daucus carota*)	2 kGy	5°C for 14 days	From 6.3×10^2 CFU/g to 0 bacteria during storage	
Carrot samples (*Daucus carota*)	2 kGy	5°C for 14 days	The control samples had 2.7 × 10CFU/g fungal counts to complete elimination of any fungi during storage	
cabbage (*Lactuca sativa var. capitata*)	1 kGy	5°C for 14 days	Completely free of coliforms. Few colonies were detected after 14 days storage of 1 kGy treated samples	
Cabbage (*Lactuca sativa var. capitata*)	2.5 kGy	5°C for 14 days	Free of viable fungal colonies during storage	

present in all samples. These results suggested that even if the initial microbial quality of the seeds is good (<1 log/g) sufficient microorganisms are present to grow rapidly during the sprouting process, resulting in sprouts with high total counts (Table 8).

IDENTIFICATION OF IRRADIATED FRUITS AND VEGETABLES

The trade and acceptance of foods treated with ionizing radiation, gamma radiation, or X-rays, require appropriate means of control. A foolproof test to detect whether or not food has been irradiated, and eventually to quantify the amount of radiation, is vital to verify the labeling and enforce legislation. Such an assay also provides the information for avoiding repeated irradiations which are likely to degrade the food in terms of organoleptic acceptability and nutritional quality (Rosenthal, 1993).

Labeling of irradiated foods will ensure the consumer's freedom of choice. Thus, both for the general consumer acceptance but also in order to control international trade of irradiated foods, it may be advantageous to have available analytical detection methods to be applied directly on the food product itself

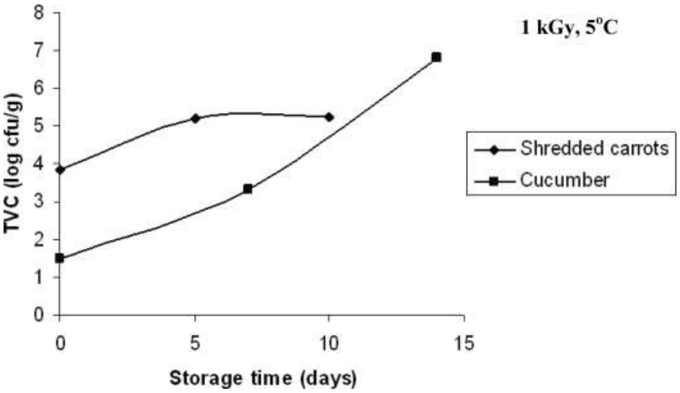

Figure 10 Effect of irradiation (1kGy) on total viable count (TVC) in shredded carrots *(Daucus carota)* packed in polyethylene bags and cucumber*(Cucumis sativus)* stored at 5°C (Basbayraktar et al., 2006; Bibi et al., 2006).

(Delincee, 1998a). The analytical detection methods should be simple, rapid, applicable to a wide range of foodstuffs, and should preferably have low cost and a minimum of false results (Haire et al., 1997; McMurray et al., 1996; Stewart, 2001). For quite a lot of foodstuffs, a radiation treatment can be detected. Nevertheless, some composite irradiated foods or foods with only a low amount of an irradiated ingredient in an otherwise non-irradiated food cannot be identified easily (Delincee, 1998a). Detection methods for irradiated foods may be classified in three basic categories; chemical, physical, and biological (Bayram and Delincee, 2004).

IDENTIFICATION TECHNIQUES

Physical Methods

Electron Spin Resonance

Measurement of the ESR spectra of the dry, outer skin of onion, red onion, garlic, and shallot before and after irradiation at doses from 0.052 to 0.2 kGy displayed increase in the intensity of the signal, which was one already present in non-irradiated items. However, the radiation-induced signal, due to the absorbed dose, decayed with time (100 hours). It was, therefore, concluded that the outer skin of these foods are not suitable as a long-term post irradiation monitor (Desrosiers and McLaughlin, 1989, 1990).

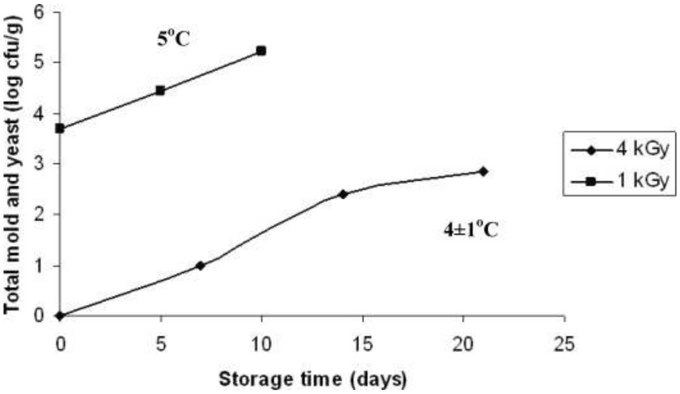

Figure 11 Effect of different irradiation doses on the total mold and yeast population of carrots (*Daucus carota*) irradiated with 4 kGy, (Hammad et al., 2006) and shredded carrots irradiated with 1 kGy and packed in polyethylene bags (Basbayraktar et al., 2006).

Raffi and Agnel (1989) investigated the application of electron spin resonance (ESR) on achenes, pips, stalks, and stones from irradiated fruits (strawberry, raspberry, red currant, bilberry, apple, pear, fig, French prune, kiwi, water-melon, and cherry). It was reported that, just after γ-treatment, a weak triplet ($a_h \sim 30$ G) always appeared due to the presence of a cellulose radical. Its left line (lower field) can be effectively used as an identification test of irradiation, at least for strawberries, raspberries, red currants, or bilberries irradiated in order to improve their storage time.

Luminescence

Irradiation with very low doses used to inhibit the sprouting of potatoes, onions, and garlic was clearly detected by TL analysis in routine control without the requirement for non-irradiated control samples for comparison (Schreiber et al., 1993b). The TL effect was attributed to the minerals adhering to the bulbs and tubers. Since mineral contamination is so heavy in potatoes, onions, and garlic, it is not difficult to separate identifiable mineral grains for analysis. If the soil where potatoes are grown contains feldspars, sprout inhibition treatment with 0.1 to 0.2 kGy doses can be detected for up to one year (Autio and Pinnioja, 1990). According to Sanderson et al. (2003a) an interlaboratory trial was conducted to validate photostimulated luminescence (PSL) methods for herbs, spices, and seasonings. Forty products (11 herbs, 17 spices, and 12 seasonings). All samples were irradiated with 10 kGy. Eight sets of screening data and 5 sets of calibrated data were returned by participants. Of the 840 samples sent, 1593 screening measurements and 788 calibrated measurements were received from 662 samples. In screening mode, participants reached definitive conclusions in 87% of cases, 99% of which were correct. Of the remaining 13%, calibration to identify low-sensitivity resolved 60% of cases. Overall, 94% of samples were correctly identified either by screening alone, or screening plus calibration; 6% remained unclassified and therefore required further investigation by thermoluminescence. The results confirm the validity of the PSL method for herbs, spices, seasonings, and blends, and emphasize the need for calibration to identify low-sensitivity samples.

An international interlaboratory trial was conducted to validate thermoluminescence (TL) methods for detecting irradiated fruits and vegetables. Five products were used in this study. Blind results were returned by 9 participants in the form of first and second glow integrals and glow ratios for all samples and a qualitative classification for each product. Of the 387 results reported, 327 valid results were obtained from participants. Where valid data were obtained, and correct qualitative

Table 8 Effect of irradiation (type/dose) and hurdle technology on shelf life, and sensory and physical properties of ivegetables

Species	Irradiation type/dose (kGy)	Other technology	Temperature (°C)	Shelf life	Sensory properties	Irradiation effect	Refs
Grated carrots (*Daucus carota*)	Gamma irradiated 0.15 kGy	Packaged in air	4 ± 1°C for 50 days	—	—	3 log CFU/g reduction of *E. coli* (from 10^6 log CFU/g) at day 1	Lacroix and Lafortune, 2004
Grated carrots (*Daucus carota*)	Gamma irradiated 0.15 kGy	Packaged in MAP condition (60% O_2, 30% CO_2, and 10% N_2)	4 ± 1°C for 50 days	—	—	4 log CFU/g reduction of *E. coli* (from 10^6 log CFU/g) at day 1	
Grated carrots (*Daucus carota*)	Gamma irradiated 0.3 kGy	Packaged in air	4 ± 1°C for 50 days	—	—	1–2 log CFU/g of *E.coli* was detected after 5 days of storage	
Grated carrots (*Daucus carota*)	Gamma irradiated 0.3 kGy	Packaged in MAP condition (60% O_2, 30% CO_2, and 10% N_2)	4 ± 1°C for 50 days		—	No *E.coli* were detected during the whole storage	
Sorghum porridge	Gamma irradiation 10 kGy	Cooking (before irradiation)			—	Cooking did not alter vitamin B1 content (0.28 mg/gr^{-1}) of the sorghum porridge but irradiation decreased it drastically (0.04 mg/gr^{-1}). Cooking did not decrease phytic acid in the sorghum porridge, but irradiation caused a significant decrease.	Duodu et al., 1999
Spinach-based relish	Gamma irradiation 10 kGy	Cooking (before irradiation)			—	Cooking reduced vitamin B1 and C contents of the spinach relish, and irradiation caused further losses. Cooking did not decrease phytic acid in the sorghum porridge, but irradiation caused a significant decrease.	
Coriander leaves (*Coriandrum sativum* L.)	Gamma irradiation 1 kGy	Packaged in polyethylene sachets	8–10°C		The leaves irradiated at 1 kGy and stored for two weeks showed 7–8% yellowing as against 12–15% in unirradiated ones	3 log cycles reduction of bacteria, 1 log kill of yeast and mold and reduction of coliform to 43 cfu/g. The Listeria and Yersinia present in the product were eliminated by such a low dose treatment. The initial total bacterial and mold counts observed in coriander leaves ranged between 10^6 to 10^8 cfu/g and 10^3–10^4 cfu/g, respectively. The total carotenoid levels remained unaffected by exposure to 1 kGy dose.	Kamat et al., 2003

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Table 8 Effect of irradiation (type/dose) and hurdle technology on shelf life, and sensory and physical properties of ivegetables (*Continued*)

Species	Irradiation type/dose (kGy)	Other technology	Temperature (°C)	Shelf life	Sensory properties	Irradiation effect	Refs
Shredded iceberg lettuce	0.7 kGy	Aerobically packed in polyethylene bags	—	—	Did not affect exudate, odor, texture, and color	—	Landgraf et al., 2006
Shredded iceberg lettuce	0.9 kGy	Aerobically packed in polyethylene bags	—	—	Did not affect exudate, odor, texture, and color	—	
Shredded iceberg lettuce	1.1 kGy	Aerobically packed in polyethylene bags	—	—	A significant difference in the texture	—	
Watercress	—	Packed	—	—	The acceptability of non-irradiated and 1 kGy irradiated watercress was higher	—	
Watercress	1 kGy	Packed	—	—		—	
Watercress	3 kGy	Packed	—	—		—	
Watercress	4 kGy	Packed	—	—		—	
Carrots (*Daucus carota* L.)	0.5 or 1 kGy	MAP: (60% O_2; 30% CO_2; 10% N_2) with an edible coating based on caseinate and whey protein	4 ± 1°C for 21 days		Results showed that gamma irradiation did not affect significantly the physico-chemical properties of the carrots	—	Lacroix et al., 2006
Carrots (*Daucus carota* L.)	0.5 or 1 kGy	Under air with edible coating based on caseinate and whey protein	4 ± 1°C for 21 days	—	Protection of firmness		
Carrots (*Daucus carota* L.)	0.5 kGy	Under air	4 ± 1°C for 21 days	—	—	3.5 log CFU/g reduction in the content in aerobic plate count (APC)	
Carrots (*Daucus carota* L.)	0.5 kGy	MAP: (60% O_2; 30% CO_2; 10% N_2)	4 ± 1°C for 21 days	—	—	4 log CFU/g reduction in the content in aerobic plate count (APC)	
Carrots (*Daucus carota* L.)	1 kGy	Under air	4 ± 1°C for 21 days	—	—	4 log CFU/g reduction in the content in aerobic plate count (APC)	
Carrots (*Daucus carota* L.)	1 kGy	MAP: (60% O_2; 30% CO_2; 10% N_2)	4 ± 1°C for 21 days	—	—	4.5 log CFU/g reduction in the content in aerobic plate count (APC)	
Carrots (*Daucus carota* L.)	0.5 kGy	Under air with edible coating based on caseinate and whey protein	4 ± 1°C for 21 days	—	—	4 log CFU/g reduction in the content in aerobic plate count (APC)	
Carrots (*Daucus carota* L.)	0.5 kGy	MAP: (60% O_2; 30% CO_2; 10% N_2) with an edible coating based on caseinate and whey protein	4 ± 1°C for 21 days	—	—	3 log CFU/g reduction in the content in aerobic plate count (APC)	
Carrots (*Daucus carota* L.)	1 kGy	Under air with edible coating based on caseinate and whey protein	4 ± 1°C for 21 days	—	—	4.5 log CFU/g reduction in the content in aerobic plate count (APC)	

Carrots (*Daucus carota* L.)	1 kGy	MAP: (60% O_2; 30% CO_2; 10% N_2) with an edible coating based on caseinate and whey protein	4 ± 1°C for 21 days	—	—	4.25 log CFU/g reduction in the content in aerobic plate count (APC)	
Onion (*Allium cepa*)	0.23 kGy)	Aerobically packaged	5°C ± 2°C	At least 14 days,	Hardness not affected by doses up to 3 kGy	*Listeria monocytogenes* (D10 = 0.23 kGy)	Faridah et al., 2006
Onion (*Allium cepa*)	0.11 kGy	Aerobically packaged	5°C ± 2°C	At least 14 days	Hardness not affected by doses up to 3 kGy	*E. coli* O157 (D10 = 0.11 kGy)	
Cucumber (*Cucumus sativus*)	0.23 kGy	Aerobically packaged	5°C ± 2°C	Shelf-life 8 days	—	*Listeria monocytogenes* (D10 = 0.23 kGy)	
Cucumber (*Cucumus sativus*)	0.06 kGy	Aerobically packaged	5°C ± 2°C	Shelf-life 8 days	—	*E. coli* O157 (D10 = 0.06 kGy)	
Lettuce (*Lactuca sativa)*	0.5 to 2 kGy	Packed in polymeric film bags	4°C	Shelf-life 12 days for 0.5 and 1 kGy (control 8 days)	3.13 to 4 log in mesophilic and psycrotrophic counts, respectively	—	Trigo et al., 2004
Turnip (*Brassica campestris*)	0.5 to 2 kGy	Packed in polymeric film bags	4°C	Shelf-life 15 days for 0.5 and 1 kGy (control 12 days)	4.2 log reduction in mesophilic and psycrotrophic counts	—	
Parsley (*Petroselinum crispum*)	0.5 to 2 kGy	Packed in polymeric film bags	4°C	—	Reduction of 3–4 log cycles in mesophilic and psycrotrophic counts	—	
Watercress (*Nasturtium officinale*)	0.5 to 2 kGy	Packed in polymeric film bags	4°C	Shelf-life 7 days (control 6 days)	4.69 log reduction in mesophilic and psycrotrophic counts	—	
Coriander (*Coriandrum sativum*)	0.5 kGy	Packed in polymeric film bags	4°C	Shelf life 9 days (control 7 days)	2.23 log reduction of mesophilic bacterial counts	—	
Mint (*Mentha spicata*)	0.5 kGy	Packed in polymeric film bags	4°C	Shelf life 7 days	2.68 log reduction of mesophilic bacterial counts	—	
Coriander (*Coriandrum sativum*)	0.5 kGy	Packed in polymeric film bags	4°C	Shelf life 9 days	1.52 and 1.72 log reduction for coliforms and *Enterobacteriaceae*, respectively		
Mint (*Mentha spicata*)	0.5 kGy	Packed in polymeric film bags	4°C	—	3.57 and 3.66 log reduction for coliforms and *Enterobacteriaceae*, respectively		
Lettuce (*Lactuca sativa)*	0.5 kGy	Packed in polymeric film bags	4°C	—	5 to7 log for reduction coliforms and *Enterobacteriaceae*, respectively		
Turnip (*Brassica campestris*)	0.5 kGy	Packed in polymeric film bags	4°C	—	4 log reduction in coliforms and *Enterobacteriaceae*		

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Table 8 Effect of irradiation (type/dose) and hurdle technology on shelf life, and sensory and physical properties of ivegetables (*Continued*)

Species	Irradiation type/dose (kGy)	Other technology	Temperature (°C)	Shelf life	Sensory properties	Irradiation effect	Refs
Shredded carrots	1.0 kGy	Packed in sterile polyethylene bags	5°C for 10 days	—	Panelists preferred the irradiated to the nonirradiated sliced-carrot samples regarding the odor, taste, and general acceptability	4-log reduction in *E. coli* and *L. monocytogenes* counts. In addition, *Listeria* and *E. coli* were not recovered from any sample during the storage periods. irradiation had an effect only on pH but no effect on the appearance and texture of sliced-carrot samples	Basbayraktar et al., 2004
Mixed salad (Radicchio, Butterhead lettuce, red lettuce, and green lettuce)	1.5 kGy	Commercially packaged samples	5°C for 10 days	—	No adverse effects on sensory attributes	Five-log reduction in *S.* Enteritidis counts and 4 log reduction in *L. monocytogenes*	
Soybean sprout	1.0 kGy	Commercially packaged samples	5°C for 10 days	—	Irradiation had no effect on the organoleptic properties	1.0 kGy dose decreased Vitamin C content approximately by 1/3. *Salmonella* spp. was eliminated	
Alfalfa seeds	2 kGy	Oregano oil (0.1%)	5°C for 5 days	—	—	Resulted in significantly lower total counts	Patterson et al., 2004

identifications were made by participants in all cases. Participants' results and homogeneity testing both confirmed the validity of the TL method for detecting irradiated fruits and vegetables (Sanderson et al., 2003b).

A survey for irradiation of 106 herbal food supplements was carried out. The results from three methods, two screening methods, and a specific method, were compared: Direct epifluorescent filter technique aerobic plate count (DEFT/APC), photostimulated luminescence (PSL) and thermoluminescence (TL) standardized by CEN. Forty samples were screened positive with the DEFT/APC method. However, the TL method could only confirm irradiation of 15 samples, 11 samples wholly irradiated, and 4 samples with a minor irradiated ingredient. Thus, the DEFT/APC method led to a large number of false positive results, although the number of false negative results probably was very low. Only 7 out of the 15 confirmed irradiated samples screened positive with the PSL screening method, the samples with low photon counts escaping detection. For 10% of the samples the TL method was also lacking in sensitivity, as not enough minerals could be isolated to get a signal over the minimum detection level. For such clean herbal food supplements no suitable method exists among the CEN standardized methods for irradiation detection (Leth et al., 2006).

Bayram and Delincee (2004) investigated different kinds of dried fruits, among other foodstuffs, to find whether a radiation treatment could be identified using various methods. Dried fruits were exposed to 0.5, 1, 3, 5 kGy doses. The foodstuffs were at first analyzed applying Photostimulated Luminescence (PSL) as a rapid screening method. As a second rapid method, ESR spectroscopy was applied. Finally, TL analysis was applied when silicate minerals could be isolated in an adequate amount from the foodstuffs. A successful application of the rapid methods was dependent on the nature of samples and processing conditions. The most reliable method was found to be TL, though it was the most time consuming and cumbersome method.

Electron Paramagnetic Resonance

Jesus et al. (1999) used paramagnetic defects induced by radiation in the fruit pulp to identify gamma-irradiated kiwi, papaya and tomato. Pulp without seed, peels, or stalks were treated with alcoholic extraction in order to remove water, soluble fractions, and solid residue. The ESR spectra of pulp samples of irradiated fruit consisted of species A ($g = 2.0045$) and species C ($g = 2.0201$ and $g = 1.9851$) which are also observed in irradiated stalks and skins. In comparison with samples not submitted to alcoholic extraction, species C is stable enough to be used as a dose marker. Furthermore, the species C signal can be detected perfectly even in pulp samples irradiated with doses as low as 200 Gy. Irradiation doses of fruit, exposed to 200–900 Gy of gamma rays, were estimated with an overall uncertainty of 15% using dried pulp samples. These results indicated that radicals induced in pulp had the potential to be used in the identification and absorbed-dose determination of irradiated fruit.

Electron paramagnetic resonance (EPR) and TL signals induced by gamma irradiation in some herbs, spices, and fruits (parsley, thyme, savory, sage, rosemary, origanum, fennel, almond, pistachio, walnut, hazelnut, and apricot) were systematically studied in order to detect the treatment. Due to the good stability of the radiation-induced signals, TL measured on silicates was always considered as unambiguous proof for radiation processing of plants. EPR is a very useful tool for unambiguous identification of radiation treatment for stone or shell containing fruits for more than a 1 year period. EPR can be used as a proof for radiation treatment for herbs and spices, but only for a limited period of time (70–90 days) because the radiation induced-radicals disappear with time storage (Raffi et al., 2000). According to Yordanov and Aleksieva (2007), the shape and time stability of the electron paramagnetic resonance (EPR) spectra of non- and γ-irradiated papaya, melon, cherry, and fig samples dehydrated via osmosis are reported. It was shown that non-irradiated samples are generally EPR silent whereas γ-irradiated exhibit "sugar-like" EPR spectra. The results displayed that 210 days after irradiation the intensity of radiation-induced EPR signal of papaya and melon decreases to ca. 10% from its initial magnitude. At the same time, the EPR signals of cherry and fig gradually decreased by 50% and 80%. Thus, even 210 days after irradiation the radiation-induced EPR signals in the studied fruits were easily recorded.

Ionizing radiation treatment of the Mexican spices black pepper, oregano, chilli guajillo, and chilli morron, produces free radicals that can be detected by EPR spectroscopy. In all the non-irradiated spices tested, the same single line signal at $g = 2.0041$ (native signal) was registered. Irradiation induced at least two EPR signals overlapping the native signal: an intense singlet and, with the exclusion of oregano, a weak triplet with hyperfine splitting of 3 mT due to cellulose free radicals. The radiation doses used were 1, 5, 10, 15, and 30 kGy (Bortolin et al., 2006).

DNA Comet Assay

Marin-Huachaca et al. (2004) evaluated the applicability of the DNA Comet Assay for distinguishing irradiated papaya, melon, and watermelon. The samples were treated in a ^{60}Co facility at dose levels of 0.0, 0.5, 0.75, and 1.0 kGy. The irradiated samples exhibited typical DNA fragmentation whereas cells from the non-irradiated ones appeared intact.

Marin-Huachaca et al. (2002) used three detection methods to identify irradiated fruits: DNA Comet Assay, the half-embryo test, and ESR. Both electron-beam (e-beam) and gamma rays were applied in order to compare the response with these two different kinds of radiation. Fresh fruits such as oranges, lemons, apples, watermelons, and tomatoes were irradiated with doses in the range 0, 0.50, 0.75, 1.0, 2.0, and 4.0 kGy and the seeds of the fruits were tested for irradiation. Both DNA Comet Assay and the half-embryo test enabled an easy identification of the radiation treatment whereas the ESR method was not satisfactory.

Delincee (1998b) studied grapefruit seeds that were exposed to radiation doses of 0, 0.1, 0.2, 0.3, 0.4, and 0.5 kGy covering the range of potential commercial irradiation for insect disinfestation and quarantine purposes. Seeds were isolated, crushed, and the cells embedded in an agarose layer. After lysis of cells, they were subjected to microgel electrophoresis for 2.5 minutes, and then stained. Fruits irradiated with 0.2 kGy and higher doses displayed typical DNA fragmentation. The DNA fragments, stretching or migrating out of the cell, forming a tall towards the anode, thereby giving the damaged cells an appearance of a comet. With increasing dose a longer extension of the DNA from the nucleus towards the anode was observed. Undamaged cells appeared as intact nuclei without tails.

Chemical and Biochemical Methods

Flow cytometry (FCM) as a detection method for radiation-induced changes in DNA of onion meristem tissues, in combination with fluorescent dyes which bind specifically to double strand regions, was examined. Nuclei from irradiated (0.06 to 0.09 kGy) onions exhibited a broader DNA distribution profile appearing as a wide coefficient of variation (cv 4.78%) of the Go/G_1 peak as compared to non-irradiated samples (cv, 2.39%). The DNA index (DI) of the diploid cells in control onions was 1 as against 0.74 in irradiated samples thereby suggesting the presence of Go/G_1, cells with abnormal DNA content in the meristem tissue of irradiated onions. These differences were detected even after 150 days storage at ambient conditions. These results indicated the potential of the FCM technique for differentiating irradiated from non-irradiated bulbs (Selvan and Thomas, 1994).

Natarajan et al. (1969) reported that irradiated strawberries can be identified by means of cytological studies on the primary root cells. A high incidence of bridges in anaphase cells revealed that the strawberries were irradiated with pasteurization doses, i.e. 150–250 krad. Due to the long delay between sampling and evaluation this identification method can only be used to investigate samples already marketed and consumed.

Biological Methods

Changes in Histological and Morphological Characteristics. Histological and cytological methods seem to be more effective and reliable when performed under optimal conditions. Since irradiation at sprout-inhibiting dose levels irreversibly inhibits cell division and multiplication of not only the bud tissues but also the cells of parenchyma, the lack of cell division in tissue cultures (Sandret et el., 1974), or the formation of wound periderm (Matano et al., 1972; Thomas, 1982) can be used as a reliable practical method for the identification of irradiated potatoes.

In onions, the absence of rooting or the rate of root elongation when immersed in water, provides a means for detection of irradiation treatment (Hori et al., 1964; Munzner, 1976). The discoloration of inner buds of onions and garlic bulbs can be also helpful to detect the irradiation treatment.

D'Oca et al. (2007) aplied the TL analysis to oregano as identification method of an irradiation treatment, even at the lowest dose (0.5 kGy), typically used for the commercial irradiation of spices and herbs. The TL ratio was indeed higher than 0.5 for all irradiated samples. Moreover, the TL ratio method allowed to distinguish between irradiated and non-irradiated oregano, even after seven months of storage in not controlled conditions.

Microorganisms. Oh et al. (2003) tried to develop detection methods for irradiated foods based on the microbial populations of irradiated foods. The method used in this study was a direct epifluorescent filter technique/aerobic plate count (DEFT/APC), which is based on the difference between DEFT counts and APC counts. The samples were imported spices (whole black pepper, powdered black pepper, powdered white pepper, marjoram, and thyme) and domestic spices (red pepper powder, garlic powder, onion powder, and ginger powder) produced in Korea. These samples were irradiated at 1.0, 3.0, 5.0, 7.0, and 10 kGy to reduce the spoilage organisms. Irradiation doses of 3.0 kGy or over eliminated viable microorganisms effectively, and the logDEFT/APC ratio gradually increased with dose increment in all samples. It could be suggested that if the logDEFT/APC ratio is 2.5 or over for peppers in Korea, the samples can be suspected as irradiated at a dose level of at least 3.0 kGy.

Seedling Growth Test. A seedling growth test for the identification of gamma-irradiated edible vegetable seeds was described. Seven different irradiated edible vegetable seeds as: rice (*Oryza sativa)*, peanut (*Arachis hypogaea*), maize (*Zeamays*), soybean (*Glycine max*), red bean (*Phaseolus angularis*), mung bean (*Phaseolus aureus*), and catjang cowpea (*Vigna cylindrica*) were tested by using the method of seedling growth. All of the edible vegetable seeds were exposed to gamma radiation on different doses 0, 0.5, 1.0, 1.5, 2.0, 3.0, 5.0 kGy. After treatment with the above 1.0 kGy dose to the seeds, the seedling rate was less than 50% compared with the control. Although the seedling rate of rice seeds can reach 58%, the seedling growth was not normal and the seedling leaves appeared deformed. The results obtained with this method were quite effective toward identifying gamma treatment of the edible vegetable seeds with above 1.0 kGy dose (Liu et al., 1993).

A collaborative study on the use of the half-embryo test for the detection of irradiated citrus fruit was undertaken by Kawamura et al. (1996). Seed samples removed from citrus fruit, irradiated with doses of 0, 0.2, and 0.5 kGy, were examined by 12 participating laboratories. The percentage of correct identifications, whether irradiated or non-irradiated, was 92% of 48 samples after 4 days incubation and 98% after 7 days incubation. Only one sample, irradiated with 0.2 kGy, was incorrectly identified. This collaborative study revealed that irradiated citrus fruit could be identified using the half-embryo test and this test can be effectively applied in practice.

Conclusions. Although irradiation appears to be one of the most promising novel technologies towards killing microorganisms, its wide range application has been strongly obstructed, mainly in EU, because of consumers' reserve and/or negative opinion vis-a-vis irradiation. However, as statistics has clearly shown in the US, both government and consumers are more positively inclined to irradiation and, as a result, the latter has found many applications in raw foods both of animal and plant origin. Foods being in the vanguard of irradiation applications are the ones of animal origin like meat (bovine, pork, sheep), poultry (chicken, duck, game meat), followed by juices, tomato, carrot, cabbage, celery, orange, strawberry, grapefruit, pepper, and oregano. In general, the irradiation advantages were: shelf life prolongation and no change in physical and organoleptic properties in conjunction with its lower cost (almost 50% lower costs) compared to other widely employed conventional methods. On the other hand, detection of irradiation is an important issue that will have to be properly addressed by a variety of methods (TL, EPR, FCM, and Comet assay among others) so that all the irradiated foods are properly labelled in compliance with the respective EU legislation.

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