Potential Applications of Ionizing Radiation in Postharvest Handling of Fresh Fruits and Vegetables

Ionizing energy has potential applications to fresh fruits and vegetables, but also some limitations which may affect its future use

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☐ THE FORMS OF IONIZING ENERGY (ionizing radiation) which may be used in food processing include gamma rays (from cobalt-60 or cesium-137), X-rays, and accelerated electrons (electron beams). Ionizing energy has recently been approved in the United States for certain applications in food preservation and processing. In April 1986, these applications were expanded to include treatment of fresh fruits and vegetables at doses up to 1 kGy (100 krad).

Extensive research has been done during the past 30 years on the effects of ionizing energy on foods, and more than 1,152 reports on fresh fruits and vegetables have been published (Abdel-Kader and Maxie, 1967; Kader and Heintz, 1983). Numerous reviews of this research have been published, including those dealing with food irradiation in general (Urbain, 1978; Diehl, 1983; IFT, 1983; Josephson, 1983) and others focusing on fresh fruits and vegetables (Maxie and Abdel-Kader, 1966; Romani, 1966; Clarke, 1971; Staden, 1973; Dennison and Ahmed, 1975; Moy, 1983; Kader et al., 1984). The accumulated data so far indicate that ionizing energy has some potential applications to fresh fruits and vegetables, but also has many limitations. Thus, this technology will not solve all the problems of postharvest deterioration of fresh produce. Rather, it should be considered as a possible supplement to refrigeration and other postharvest technology procedures aimed at reducing postharvest losses in fresh fruits and vegetables.

Factors Influencing Response

Harvested fresh fruits and vegetables, as living tissues, differ from other food groups in their optimum postharvest requirements, which are designed to slow down their respiration rates without terminating their living status. Fresh fruits and vegetables are highly sensitive to various stresses such as those induced by: wounding, bruising, or other types of physical damage; exposure to higher or lower than the optimum temperature for each commodity; water loss; exposure to oxygen and/or carbon dioxide levels beyond the concentrations which are tolerated by each commodity; and/or treatment with ionizing energy at doses above those tolerated by the commodity. Increased rates of respiration and ethylene production are among the general responses of fresh fruits and vegetables to various types of stress. The detrimental effects of these stresses are additive.

Several factors related to characteristics of each commodity or to irradiation procedures influence the response of fresh fruits and vegetables to ionizing energy treatments (Table 1). Also, preharvest factors such as climatic conditions and cultural practices affect composition and quality of these commodities, which may influence their response to ionizing energy–induced stress.

During ionization resulting from treating foods with ionizing energy, free radicals are produced. These free radicals react with various food constituents and may cause injury to the cells. Since fresh fruits and vegetables contain 80–95% water and their intercellular spaces (about 20% of total volume) contain oxygen, the most common free radicals are those of water and oxygen. Consequently, treating fresh fruits and vegetables with ionizing energy in nitrogen atmosphere can reduce the amount of free radicals and possible injuries to the plant tissue. However, this will also reduce the treatment's effectiveness in killing insects and inhibiting growth of fungi which may be present.

Potential Applications

The effects of ionizing radiation at various doses on fresh fruits and vegetables are summarized in Table 2. Following is a brief review of each of these effects in relation to potential applications:

• **Inhibition of Sprouting of Tuber, Bulb, and Root Vegetables.** When tubers and bulbs are treated with ionizing energy, remarkable morphological and histological changes in dormant buds are induced to develop the deformed buds and necrosis at growing points during subsequent storage. The extent and area of radiation-induced necrosis in growing points and

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their adjacent cells varies with irradiation dose (Matsuyama and Umeda, 1983). Treatment with ionizing energy at 0.05–0.15 kGy has been shown to inhibit sprouting of potato, yam, Jerusalem artichoke, sweet potato, ginger, sugar beet, table beet, turnip, carrot, onion, and garlic. The treatment is most effective when applied during dormancy, i.e., before sprouting has been initiated.

Irradiation doses below 0.15 kGy have minor effects on quality attributes of these vegetables. Doses above 0.15 kGy may induce undesirable side effects, such as decreased wound-healing ability (e.g., periderm formation on potato tubers), tissue darkening, increased sugar content in potatoes, decreased vitamin content, and increased susceptibility to postharvest pathogens (Matsuyama and Umeda, 1983; Thomas 1984a; b).

Although ionizing radiation at doses up to 0.15 kGy has been approved for commercial use on potatoes and onions in many countries, its application has been largely limited to Japan and the USSR. Potential use in the U.S. will depend upon extent of need to store these commodities and availability of alternative treatments. Chemicals such as maleic hydrazide (for preharvest treatment of onions and potatoes) and chloroisopropyl carbamate (for postharvest treatment of potatoes) are currently used for sprout inhibition when needed. The continued availability of these chemicals will greatly influence the potential use of ionizing energy in the future for inhibition of sprouting of tuber, bulb, and root vegetables.

Table 1—**Factors Influencing the Response** *of fresh fruits and vegetables to ionizing-radiation stress*

Commodity Factors

Type of commodity and cultivar
Production area and season
Maturity at harvest
Initial quality
Postharvest handling procedures

Irradiation Procedures

Dose
Dose rate
Environmental conditions during irradiation
  Temperature
  Atmospheric composition

Table 2—**Effects of Ionizing Radiation** *on fresh fruits and vegetables*

Dose (kGy[a])	Observed effects
0.05–0.15	Sprout inhibition in tuber, bulb, and root vegetables; inhibition of growth in asparagus and mushrooms
0.15–0.75	Insect disinfestation
0.25–0.50	Delayed ripening of some tropical fruits such as banana, mango, and papaya
>1.75	Control of postharvest disease
1.00–3.00	Accelerated softening; development of off-flavors in some commodities
>3.00	Excessive softening; abnormal ripening; incidence of some physiological disorders; impaired flavor

[a] 1 kilogray (kGy) = 1,000 Gray (Gy), which is the SI unit of energy absorbed (1 joule/kg) from ionizing radiation. 1 Gy = 100 rad (1 rad = 100 erg/g), and 1 kGy = 100 krad

• **Inhibition of Postharvest Growth of Asparagus.** Subjecting asparagus spears to ionizing energy at 0.05–0.15 kGy inhibits their elongation and curvature, but higher doses are detrimental to quality and storage life. It is not likely that ionizing energy will be used for control of postharvest growth of asparagus, since currently used practices of vertical packing and refrigeration are effective for this purpose. If additional treatments are needed for long-distance transport, modified atmospheres (10–15% carbon dioxide added to air) can be used to maintain asparagus quality.

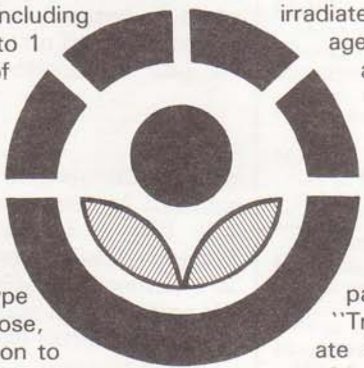
• **Inhibition of Postharvest Growth of Mushrooms.** Ionizing radiation at 0.06–0.5 kGy has been shown to inhibit cap opening and stalk elongation, reduce surface molds and darkening of the gills, and maintain the fresh appearance of mushrooms. Above 0.5 kGy, some undesirable changes in appearance and taste of mushrooms before and after canning have been reported. Since quick cooling and maintenance of mushroom temperature as close to 0°C as possible are very effective in slowing down growth, discoloration, and other causes of deterioration, such practices should be used before application of ionizing radiation is considered.

• **Insect Disinfestation.** A large number of insects can be carried by fresh fruits and vegetables during postharvest handling. Many of these insect species, especially the fruit flies of the family Tephritidae (e.g., Mediterranean fruit fly, Oriental fruit fly, Mexican fruit fly, Caribbean fruit fly), can seriously disrupt trade among countries and among states within the U.S. Consequently, effective insect-disinfestation treat-

Table 3—**Relative Tolerance** *of fresh fruits and vegetables to ionizing-radiation stress at doses <1 kGy*

Relative tolerance	Commodities
High	Apple, cherry, date, guava, longan, mango, muskmelon, nectarine, papaya, peach, rambutan, raspberry, strawberry, tamarillo, tomato
Moderate	Apricot, banana, cherimoya, fig, grapefruit, kumquat, loquat, lychee, orange, passion fruit, pear, pineapple, plum, tangelo, tangerine
Low	Avocado, cucumber, grape, green bean, lemon, lime, olive, pepper, sapodilla, soursop, summer squash, leafy vegetables, broccoli, cauliflower

FOOD IRRADIATION REGULATION ISSUED



The Food and Drug Administration has issued a final regulation, effective April 18, 1986, permitting the irradiation of fresh foods, including fruits and vegetables, at doses up to 1 kGy (100 krad) for the inhibition of growth and maturation and for insect disinfestation.

Irradiated products sold in retail packages must be labeled with the logo shown here and the statement, "Treated with radiation" (or "irradiation"). The statement may also describe the type of radiation used, as well as its purpose, e.g., "Treated with gamma radiation to extend shelf life." Additional information, such as "This treatment does not induce radioactivity," may also be included for educational purposes. For irradiated products not sold in retail packages, the logo and statement must appear on either the individual item, the bulk container, or a sign at point of purchase. After two years, the statement will no longer be required, only the logo.

The labeling and invoices or bills of lading for products shipped for further processing, labeling, or packaging must bear the statement, "Treated with radiation—do not irradiate again." Details are in the *Federal Register* of April 18, 1986.

ments which are not harmful to the consumer, the workers, or the commodity are essential for allowing unrestricted distribution of fresh fruits and vegetables. In areas where one or more of the quarantinable insect species are endemic (such as Hawaii and Florida), the need for insect-disinfestation treatments is continuous. In other areas, such as California, the need is for a stand-by treatment that can be used if infestations of tropical fruit flies, such as happened in 1980 with the Medfly (Couey, 1983), occurs in the future. Currently, a few California commodities require treatment for insect disinfestation when exported to certain countries; these commodities include stone fruits for codling moth control, citrus fruits for red scale control, and strawberries for thrips control.

Since the removal of ethylene dibromide (EDB) from the list of approved chemicals by the Environmental Protection Agency in September 1984, alternative treatments have been investigated, and some are now in commercial use, such as hot-water treatment for papayas in Hawaii and cold-air treatments for grapefruit in Florida. However, these alternatives have resulted in some problems, such as ripening disorders due to heat in payayas and chilling injury in cold-treated grapefruit.

The currently approved quarantine treatments include certification of insect-free areas, use of chemicals (methyl bromide, phosphine, hydrogen cyanide), cold treatments, heat treatments, and some combinations of these treatments. However, each of these treatments is usable on a limited number of commodities because of phytotoxic effects on others. Cold treatments (10 days at 0°C to 16 days at 2.2°C or below) are approved quarantine treatments for control of some of the fruit flies. While such treatments can be used on some commodities (e.g., apple, pear, grape, orange, kiwifruit, persimmon, pomegranate), they are not usable for highly perishable commodities (e.g., strawberry, bush berries, fig, apricot, cherry) or for chilling-sensitive commodities (e.g., grapefruit, lemon, avocado, papaya, mango, tomato, pepper). Thus, the search continues for alternative treatments such as modified atmospheres, ultrasound, microwave radiation, and insecticides.

The possible use of ionizing energy for insect disinfestation is one of its most promising applications (Burditt, 1982; Tilton and Burditt, 1983; Moy et al., 1983; Moy, 1985). Irradiation at doses below 1 kGy is an effective insect-disinfestation treatment against various species of fruit flies, mango seed weevil, navel orange worm, potato tuber moth, codling moth, spider mites, scale insects, and other insect species of quarantine significance in marketing fresh fruits and vegetables. Most insects are sterilized at doses of 0.05–0.75 kGy; some adult moths will survive 1 kGy, but their progeny are sterile. In general, eggs are the most sensitive to ionizing radiation, followed by larvae, then pupae. Moy et al. (1983) reported the minimum mortality dose on mature Medfly eggs on peaches to be 0.4 kGy, while 0.45–0.50 kGy is required on nectarines.

An absorbed dose of 0.25 kGy has been suggested as an effective quarantine treatment for fresh fruits and vegetables against the fruit flies, because it stops reproduction. This, however, will require a change in current quarantine regulations, which state that all living stages of pest species in commodities must be killed for a quarantine treatment to be acceptable. The criteria for efficacy of irradiation for quarantine treatment should be based on the ability to reproduce rather than on mortality of the insects, because irradiation dose levels that kill egg and larval stages and/or induce sterility or other abnormalities in the emerging adults are effective in stopping reproduction.

Most fresh fruits and vegetables will tolerate ionizing radiation at 0.25 kGy with minimal detrimental effects on quality. At doses between 0.25 and 1.0 kGy, some commodities can be damaged. A summary of the relative tolerance of fresh fruits and vegetables to ionizing radiation at doses below 1 kGy is presented in Table 3. As noted earlier, the relative tolerance of each commodity is influenced by many factors; consequently, its position in this classification may vary according to production area, season, and handling procedures. For example, the relative tolerance of citrus fruits to ionizing radiation has varied greatly among published reports (Moy, 1983; Hatton et al., 1984; O'Mahony et al., 1985; Nagai and Moy, 1985). It is not likely that ionizing radiation or any of the other treatments for insect disinfestation will provide a single acceptable quarantine treatment for all fresh fruits and vegetables.

- **Alteration of Ripening and Senescence.** Ripening of bananas is inhibited at irradiation doses of 0.25–0.35 kGy, and the irradiated fruits later can be ripened to good quality by treatment with ethylene. Similar results have been reported for mango, papaya, guava, and several other subtropical and tropical fruits (Akamine and Moy, 1983; Thomas, 1986). Since all these fruits are susceptible to chilling injury and cannot be held below about 10–15°C (depending on commodity, cultivar, and maturity stage), supplemental treatments to retard their ripening might be very useful. The potential usefulness of ionizing radiation for retardation of ripening will depend on its cost/benefit evaluation relative to other treatments that elicit the same response, such as modified atmospheres and ethylene-removal methods.

Some temperate-zone fruits, such as apple, pear, and apricot, require much higher doses (>1 kGy) for effective inhibition of ripening. Serious detrimental effects of such treatments have been observed, including uneven ripening and excessive softening, which makes the fruits more susceptible to physical damage during postharvest handling and may result in mushy fruit reaching the consumer. Irradiation stimulates respiration rates of both climacteric (e.g., pear, peach) and nonclimacteric (e.g., cherry, strawberry) fruits. It also stimulates (<4 kGy) or inhibits ($\geqslant 4$ kGy) ethylene production by the fruits. The higher doses reduce the sensitivity of most fruits to the ripening action of ethylene (Maxie and Abdel-Kader, 1966).

Ionizing radiation at doses above 1 kGy can induce various types of physiological disorders in fresh fruits and vegetables (Bramlage and Couey, 1965; Bramlage and Lipton, 1965; Lipton et al., 1967; Maxie et al., 1971). Examples include increased surface blemishes and swelling of oil glands, followed by peel pitting in oranges and grapefruits; internal cavities in lemons and limes; skin damage in bananas; internal browning of avocados; skin discoloration and stem darkening of grapes; external and internal discoloration of olives; surface browning of 'Kadota' figs; accelerated yellowing of cucumbers, summer squash, and peppers; stem pitting of artichokes; reddish-brown sunken spotting on leaf midribs of lettuce and endive; and increased denting of sweet-corn kernels (associated with aging). Also, irradiated commodities are more sensitive to other stresses, such as chilling injury.

Ionizing energy at doses that fresh fruits and vegetables can tolerate does not reduce their caloric value or nutritional quality significantly. Only negligible losses in niacin, thiamin, riboflavin, and beta-carotene (provitamin A) have been attributed to irradiation. Ascorbic acid (vitamin C) is more radiosensitive, and its losses range from 0 to 95%, depending on commodity, cultivar, irradiation dose, and duration and temperature of storage (Maxie and Abdel-Kader, 1966). Reported changes in pigments, sugars, fats, proteins, and enzymes in fresh fruits and vegetables subjected to irradiation doses below 3 kGy are slight in most cases. Other observed compositional changes, which may be desirable, include decrease in acidity of some commodities, loss of astringency in persimmons, increased juice yield of grapes, and inhibition of chlorophyll and solanine formation in potatoes exposed to light.

The solubilization of pectins, cellulose, hemicellulose, and starch in response to >0.6 kGy is important because it results in softening of fresh fruits and vegetables, which is undesirable for postharvest handling. In general, changes in flavor and nutritional quality are not limiting at doses the commodity's structural components can tolerate. The undesirable effects of ionizing radiation on firmness can be reduced by irradiating at low temperature and/or under nitrogen (anoxia). However, such conditions also reduce the effectiveness of ionizing radiation against pathogens and insects.

- **Control of Postharvest Disease.** The potential use of ionizing radiation to control postharvest diseases depends on the radiation sensitivity of the fungus or bacterium relative to the ability of the host to withstand the required radiation level with little or no acute injury or other detrimental effects. The effectiveness of irradiation as a fungicidal and/or fungistatic treatment depends on the pathogen, its stage of growth, and the number of viable fungal cells on or within the tissue. Generally, a minimum dose of 1.75 kGy is required for effective inhibition of postharvest fungi. However, 2.25 kGy is near the maximum dose that most fresh commodities can tolerate without serious loss of firmness, ripening abnormalities, altered flavor, and increased susceptibility to mechanical injury (Sommer and Fortlage, 1966).

Combination treatments, such as heat + irradiation, may be synergistic. Thus, by using both heat and irradiation, levels of irradiation can be used that are less detrimental to quality attributes of the commodity. Such combination has been shown to be effective for control of brown rot on stone fruits and anthracnose on papaya and mango fruits.

Postharvest disease control methods that are currently used include fungicides, modified atmospheres (elevated carbon dioxide or 5–10% carbon monoxide in less than 5% oxygen), and hot-water treatment. For ionizing radiation to become a viable alternative for some commodities, it must be shown to provide better control and/or cost less than existing treatments. The use of ionizing radiation would be favored if some postharvest fungicides were withdrawn by government agencies from approved lists of chemicals and no substitutes were found.

Potential Limitations

In addition to the technical considerations, the extent of future commercial application of ionizing radiation on fresh fruits and vegetables will also depend on cost (Morrison and Roberts, 1985), consumer acceptance (Bruhn et al., 1986), and solution of logistical problems related to handling and treating the large but seasonable quantities of the various commodities.

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