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Phytosanitary Applications of Irradiation

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Abstract: Phytosanitary treatments are used to disinfest agricultural commodities of quarantine pests so that the commodities can be shipped out of quarantined areas. Ionizing irradiation is a promising phytosanitary treatment that is increasing in use worldwide. Almost 19000 metric tons of sweet potatoes and several fruits plus a small amount of curry leaf are irradiated each year in 6 countries, including the United States, to control a number of plant quarantine pests. Advantages over other treatments include tolerance by most fresh commodities, ability to treat in the final packaging and in pallet loads, and absence of pesticide residues. Disadvantages include lack of acceptance by the organic food industries and logistical bottlenecks resulting from current limited availability of the technology. A regulatory disadvantage is lack of an independent verification of treatment efficacy because pests may be found alive during commodity inspection, although they will not complete development or reproduce. For phytosanitary treatments besides irradiation, the pests die shortly after the treatment is concluded. This disadvantage does not hamper its use by industry, but rather makes the treatment more difficult to develop and regulate. Challenges to increase the use of phytosanitary irradiation (PI) are cost, because commercial use has not yet reached an optimum economy of scale, lack of facilities, because of their cost and current inability to feasibly locate them in packing facilities, lack of approved treatments for some quarantine pests, and concern about the process by key decision makers, such as packers, shippers, and retailers. Methods for overcoming these challenges are discussed.

Introduction

This review describes the use of irradiation as a phytosanitary measure to overcome quarantine barriers to trade in mostly food but also nonfood items. The history and present use of the technology as well as challenges for further applications are discussed.

The need for phytosanitary measures

Even in sluggish economic times, the amount of transportation in all types of goods traversing sky, sea, and land reaches millions of tons, annually. In 2008, while world economic markets shrunk substantially, the value of all traded agricultural products increased 19% (WTO 2010). With transport often comes invasive species that may cause health, economic, and environmental damage, especially in areas of the world where they do not currently exist. However, plant pests are not only transported in agricultural goods; contaminating pests, such as insects attracted to light in packing facilities and gastropods crawling into loads of ceramic tiles, can conceivably be found in any commodity. Important tree-infesting beetles have been transported in wooden packing materials and pallets (Haack 2006), and an international standard for phytosanitary measures has been established for packaging material made from raw wood (IPPC 2009b).

Phytosanitary measures are regulations to prevent the introduction or spread of quarantine pests and must be followed if interested parties are to ship regulated articles out of quarantine areas. Examples of phytosanitary measures are inspection of crops, management of survey traps, and pesticide treatments during the growing phase. Phytosanitary treatments are measures done to the regulated article itself to lower the risk to levels that are acceptable of the article carrying reproductively viable quarantine pests.

Phytosanitary treatments

A number of techniques have been studied as phytosanitary treatments, and those most frequently used for commercial purposes involve extreme temperatures and fumigants (Heather and Hallman 2008). A subjective comparison of the major commercially used phytosanitary treatments is shown in Table 1. The majority of fresh commodities that require treatment are treated with low temperatures or with methyl bromide fumigation. Almost all of the 300000 metric tons of mangoes exported to the United States each year are immersed in 46.1 °C water for 65 to 110 min. Apart from mangoes exported to the United States, little other use is made of hot water immersion phytosanitary treatment. Heated air treatments are used for a variety of fresh commodities shipped from several countries to Japan and the Republic of Korea and a modest amount of papayas shipped from Hawaii to the mainland United States. Ionizing radiation is a fairly recent treatment, used on a continual basis only since 1995.

Ionizing Radiation as a Phytosanitary Treatment

The nature of ionizing radiation

Ionizing radiation results in the breaking of chemical bonds due to electromagnetic radiance or high-energy particles. The ionizing portion of the electromagnetic spectrum includes visible light

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Table 1–Subjective comparison of major phytosanitary treatments (after Hallman 2007).

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

and shorter wavelengths, although visible light ionizes only certain chemicals, such as chlorophyll that is ionized to initiate photosynthesis. Ultraviolet light (10 to 400 nm with photon energies of 3 to 124 eV) is ionizing and has been researched as a phytosanitary treatment for surface pests (Heather and Hallman 2008). It is not commercially used and will not be covered in this review. Gamma rays from the isotopes cobalt-60 (1.17 and 1.33 MeV) and cesium-137 (0.66 MeV) may be legally used for food irradiation according to the U.S. Food and Drug Administration and the Codex Alimentarius Commission (CAC 2003). Cobalt-60 is bred from standard nonradioactive cobalt (atomic weight 58.9) via neutron irradiation. It has a half-life of 5.27 y and decays to standard nickel. Cesium-137 is a fission product of uranium and plutonium and is recovered when processing spent nuclear fuel. It has a half-life of 30.07 y and decays to barium-137 m. Although cesium-137 could be used in food irradiation, it is not done so on a commercial scale; and because it is soluble in water, its availability has been strictly regulated, and it will probably not be used in food irradiation in the near future.

Machine sources of radiation produce electrons and X-rays. Electrons are high-energy particles that can be used for food irradiation at energy levels up to 10 MeV. An electron beam (e-beam) directed at a heavy metal, such as tantalum or gold, will give off X-rays, and energies up to 7.5 MeV are allowed for food irradiation. At best, about 14% of the energy from an e-beam is converted to X-rays with the rest given off as heat. The energy levels emitted by all of these sources are below those that could lead to radioactivity in food.

Irradiation, whether by isotopes or machine sources (e-beam or X-ray), has the same mode of action: the gamma rays, X-rays, or electrons knock electrons out of their orbits thus creating ions. The free electrons further collide with other electrons creating an electron shower. Radicals are formed and cause further damage to large organic molecules such as DNA therefore stopping further development of irradiated organisms.

Efficacy of phytosanitary irradiation

Phytosanitary irradiation (PI) differs from all other commercial treatments in one important technical consideration: the end point of the treatment is not acute mortality but prevention of further biological development and reproduction (Table 1). Irradiated arthropods will eventually die, but Hallman (2000) has shown that some may live as long as or even longer than nonirradiated ones at the doses required to prevent reproduction.

Inspection of commodities treated for phytosanitation is an independent form of verifying that the treatment is efficacious and has been done correctly. If live quarantine pests are found upon inspection for all other treatments except irradiation, it is concluded that the treatment was not done, done subefficaciously, or the commodity was reinfested after treatment, and the consignment is rejected. Further research may need to be conducted to determine if the treatment protocol must be changed. For example, after live Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), larvae were found in the United States in mandarin oranges from Spain that had supposedly been properly cold-treated in 2001, 3 cold treatment schedules were lengthened by 13% to 17% and 2 were withdrawn altogether in an attempt to prevent future incidents (Heather and Hallman 2008).

The measures of efficacy used for PI are, broadly speaking, prevention of completion of development for those pests not found as pupae or adults on the exported commodity or prevention of reproduction for those pests that can be present as pupae or adults. For example, the measure of efficacy for fruit flies of the family Tephritidae (that only occur as eggs or larvae on fruit) is prevention of the emergence of adults (IPPC 2009a). The measure of efficacy for the plum curculio, *Conotrachelus nenuphar* (Herbst), is prevention of reproduction when adults are irradiated (IPPC 2010).

Because insects do not quickly die after irradiation, there is no independent verification of treatment efficacy for PI. That places a greater burden compared with all other treatments on the research, implementation, and regulation of PI to ensure that the treatment is efficacious. That challenge has been met by researchers and plant protection agencies in various countries as well as the International Plant Protection Convention that issued an International Standard for Phytosanitary Measures on PI in 2003 (IPPC 2003).

History of phytosanitary irradiation

Shortly after ionizing radiation was discovered in the late 19th century, it was noted that biological organisms could be reproductively sterilized with relatively low doses that showed no other obvious gross effects (Hunter 1912). Early attempts to use radiation to prevent arthropod reproduction found little effect because doses used were too low (Hunter 1912; Morgan and Runner 1913). Soon researchers began using doses high enough to stop development and reproduction. Runner (1916) found that *Lasioderma serricorne* (cigarette beetle) egg age was positively related to the dose required to prevent egg hatch and that larvae hatching from irradiated eggs may not develop further. Although irradiated larvae remained alive some time after treatment, they became steadily less active and did not pupate. The larvae remained alive longer than the normal time required for the larval stage. Irradiation of pupae reduced adult emergence and prevented oviposition by the adults that did emerge. Irradiation of adults did not affect activity, mating, oviposition, or length of life, although no eggs laid hatched. Observations that insects would mate normally after irradiation but not reproduce led to the successful use of irradiation in the sterile insect technique, which uses massive numbers of factory-reared insects reproductively sterilized with radiation and released in the field to sexually outcompete and reduce population levels of wild pests, sometimes to extinction (Dyck and others 2005).

Irradiation as a commercial insect control technique was applied for the first time in the early 1910s to tobacco products, although it seems to have been ineffective because of the low doses used (Morgan and Runner 1913). Adequate dosimetry did not exist then (Imai and others 2006). In 1929, a more effective X-ray source with a conveyor was installed to irradiate cigars but the system was eventually replaced by fumigation (Diehl 1995) that was cheaper, more reliable, and easier to use than the X-ray equipment available then.

The first commercial irradiation of food was to disinfect spices in the Federal Republic of Germany in 1957 (Diehl 1995). Although food irradiation was legislatively prohibited in that country a couple of years later until 2000, spice disinfection is the chief use of food irradiation worldwide today with over 185600 tons irradiated each year (Kume and others 2009). The first use of food irradiation for a fresh commodity was on potatoes in Canada in 1965 to inhibit sprouting (Diehl 1995). Cobalt-60 was the source, and the factory could treat 15000 tons per month. However, the facility closed after one season due to financial problems. Today, irradiation is used to prevent sprouting of 88200 tons of potatoes and onions in China, Japan, and India (Kume and others 2009). In the world today, over 400000 tons of food are irradiated every year among spices, meat, and fresh fruits and vegetables.

Until the late 1920s, phytosanitary treatments were based on fumigation or nonsynthetic pesticide applications. The chemicals used then were largely not safe enough to be used on food but were used on nursery stock and other nonfood items that could carry invasive species. In 1929, nonchemical treatments (heated air and cold) were used as phytosanitary treatments against the Mediterranean fruit fly, *Ceratitis capitata*, infesting citrus fruit in Florida. At about the same time, Koidsumi (1930) first mentioned using radiation as a phytosanitary treatment to rid fruit of fruit flies in Taiwan. He suggested that acute mortality was not necessary to provide quarantine security and that prevention of adult emergence was a reasonable objective for fruit flies. This is the end point used for fruit flies today.

Research into PI accelerated in the 1960s. In 1972, Hawaii filed a petition to the U.S. Food and Drug Administration (FDA) to use PI on papayas (Moy and Wong 2002) and 14 years later the FDA (1986) approved the use of irradiation up to 1 kGy to disinfest foods of arthropods at doses up to 1 kGy. The food must be labeled with the radura logo (Figure 1) and the statement "treated with radiation" or "treated by irradiation." That same year the first commercial use of PI occurred when one load of irradiated mangoes was shipped from Puerto Rico to Florida (Heather and Hallman 2008). This shipment was part of a search for alternatives to the fumigant ethylene dibromide used as a phytosanitary treatment for fruit that was then being banned as a health risk. Another alternative treatment, hot water immersion, was used for mangoes, and further irradiation treatments were not done.

A single pilot shipment of Hawaiian papayas irradiated at a small research facility was sent to California in 1987, and in 1989 APHIS approved an irradiation treatment of 150 Gy for papayas from Hawaii (APHIS 1989). However, that treatment was never used by the fruit industry because of perceived problems with consumer acceptance, the large capital investment required, and logistics in moving all quarantine fruit through one facility (Moy and Wong 2002). Funding from the U.S. Department of Energy that was mandated by the U.S. Congress for a food irradiation facility in Hawaii ran out after 2 X-ray sources were funded in Iowa and Florida. Alternative heat treatments were developed for papayas.

In 1992, a cobalt-60 facility was completed in Mulberry, Florida, to irradiate grapefruits as a phytosanitary treatment against Caribbean fruit fly, *Anastrepha suspensa*, to replace ethylene dibromide making it the first irradiation facility in the world built expressly for PI. However, other phytosanitary measures were used and commercial irradiation of grapefruit was not done; the cobalt-60 facility was used for other types of food irradiation. In 1999, the facility began to be used for PI when guavas were irradiated and shipped to Texas and California; a few other fruits (carambola and grape) have been commercially irradiated. In 2000, the facility began irradiating white-fleshed sweet potato for shipment to California (Hallman 2001). This was the first use of PI expressly for a quarantine pest that may occur in the adult stage (sweet potato weevil, *Cylas formicarius elegantulus*) on shipped commodities and represents a major step in acceptance of PI because plant protection organizations are more concerned about having live, albeit reproductively sterile, adults on imported commodities than live immature stages, as is the case with fruit flies.

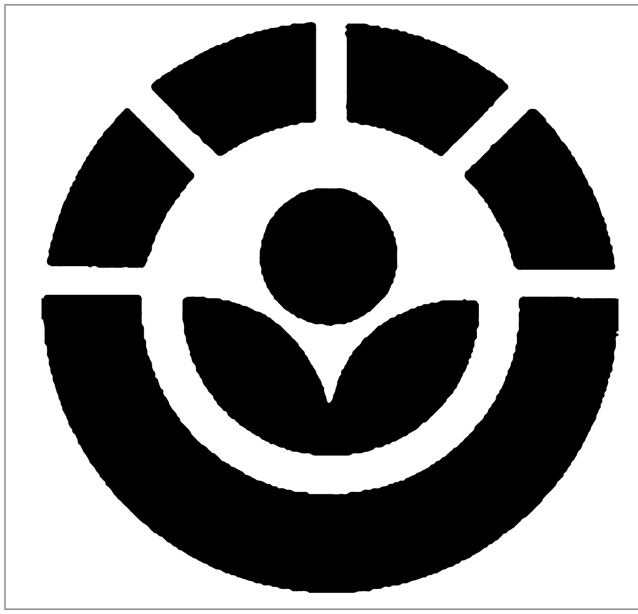

Figure 1–Radura, the international green-colored symbol to indicate that a food has been irradiated. A variation by the U.S. Food and Drug Administration uses empty green outlines of the 2 leaf-like parts (FDA 1986). The plant-like structure represents agricultural products in a closed package (the circle) broken in the upper half by penetrating ionizing rays or particles (Ulmann 1972).

Moy and Wong (2002) discuss the first years of continuing commercial use of PI in Hawaii starting in 1995. Although this was not the first commercial use of PI for tropical fruits in the world (that honor goes to the 1-time shipment of Puerto Rican mangoes 9 y earlier) because the FDA (1986) did not approve the process for fruits until 1986, it is paramount because PI has been used increasingly every year since then. Personnel from the Univ. of Hawaii and Hawaii Dept. of Agriculture decided in 1994 to forge ahead with PI and obtained a limited use permit by APHIS in early 1995 to allow papayas to be air-freighted to a cobalt-60 facility in Morton Grove, Illinois, to be irradiated with 250 Gy. That dose was established after Hallman (1994) noted that research done in Hawaii did not support doses lower than that for the quarantine fruit flies there. The first shipment was on April 5th, and the papayas were distributed to supermarkets in Illinois and Ohio where market and consumer acceptance were "excellent" (Moy and Wong 2002). Over the next 5 y, an increasing amount and variety of irradiated Hawaiian fruits were shipped to more markets (Table 2). Fruits were irradiated at 2 facilities near Chicago and 1

Table 2–Commercial shipments of Hawaiian fruits to the U.S. mainland between 1995 and 2000 for irradiation at 250 Gy (Moy and Wong 2002). Beginning in August 2000, commodities were irradiated in a newly built X-ray facility in Hawaii, and amount shipped (mostly sweetpotato) reached 4000 tons/year.

Fruit	Total quantity shipped (tons)
Papaya	309.2
Rambutan	65.8
Litchi	19.8
Atemoya	7.6
Carambola	1.0
Banana	0.17
Orange	0.09
Melon	0.02
Total	403.8

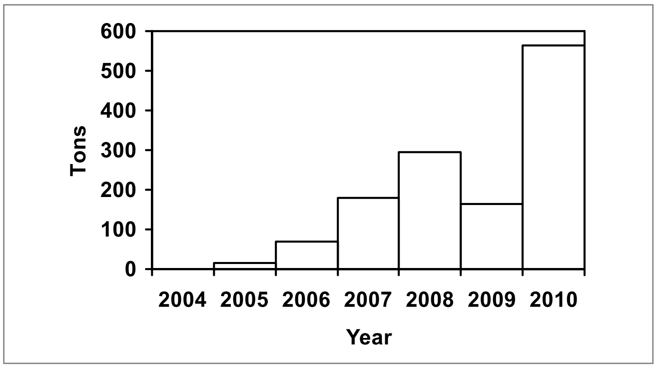

Figure 2–Tons of irradiated mangoes exported from Australia to New Zealand by year ending the season. Amount in 2004 was 0.5 ton.

at Whippany, New Jersey, and distributed to grocery stores in California, Florida, Illinois, Indiana, Iowa, Massachusetts, Minnesota, Michigan, New Jersey, New York, Ohio, Oregon, Pennsylvania, Texas, Washington State, and Washington, DC.

In 1998, a company proposed to install a cobalt-60 facility in Hilo, Hawaii, where most of the commercial papaya production is located. Opposition arose to the presence of radioactive isotopes, but a ballot initiative to ban radioactive materials in a commercial irradiator there was narrowly defeated. The company decided not to proceed anyway and 2 local entrepreneurs entered into a partnership with a company to build an X-ray facility in Keaau using a $6.75 million loan through the USDA Rural Development Business and Industry Guaranteed Loan Program. The facility began operating in August, 2000.

The lessons Moy and Wong (2002) list from this experience are (1) that markets are not adverse to irradiated produce if the quality and price are good; (2) consumers are increasingly accepting irradiated food in the United States; (3) regulatory agencies in the United States are taking the initiative to move the technology forward; and (4) growers and the business community will step forward to support food irradiation.

Current applications of phytosanitary irradiation

Between 500 to 750 tons of guava continue to be irradiated each year in Florida at a dose of 250 to 550 Gy. The minimum required dose is 70 Gy for the pest of concern (Caribbean fruit fly) but that low dose is difficult to measure with the dosimetry system currently used, and the guavas tolerate the treatment well. Sweet potatoes are not currently being irradiated.

The opening of the X-ray facility in Hawaii in 2000 allowed for a greater diversity and quantity of produce to be irradiated at a more economical cost. Capacity of the facility is >13000 tons/year when operated at 0.4 kGy; about a third of that is realized. At first, papayas were about two-thirds of the volume treated with rambutan and lychee making up most of the rest. Today 75% of the volume irradiated is purple-fleshed sweet potato, at 150 Gy for 3 pests, and no papayas are irradiated. After sweet potato, rambutan and longan are the most irradiated, with smaller quantities of apple-banana (*Musa acuminata*), curry leaf, dragon fruit (*Hylocereus* spp.), and mangosteen irradiated at 400 Gy for a variety of pests. All of the products irradiated in Hawaii are sent to the U.S. mainland.

The first international use of PI was in December, 2004, when Australia sent one-half ton of irradiated mangoes to New Zealand. Exports have steadily increased (Figure 2) and now Australia sends irradiated lychee as well. Papaya was irradiated before, but cannot compete in price (cost of irradiation is U.S. $106/ton) with heat-treated papaya, currently.

On March 2, 2006, the U.S. president and the Indian prime minister signed an agreement as part of a broad set of bilateral initiatives that their respective countries would work together to facilitate entry of Indian mangoes to the United States after 17 years of being prohibited for phytosanitary reasons. Irradiation was chosen as a phytosanitary measure that could solve the issues involved. Five wk before this agreement was signed, the United States approved a generic dose of 400 Gy for all insects except pupae and adults of Lepidoptera (APHIS 2006b). This dose would cover all of the insects that are quarantine pests on Indian mangoes bound for the United States. On April 27, 2007, the first irradiated Indian mangoes reached the United States by air freight, and by the end of the season 157 tons had been shipped. In 2008, the total rose to 275 tons. In 2009, 1 14.5-ton shipment was successfully done by boat using low oxygen atmosphere and cold to prolong shelf life. Shipment by boat would reduce costs of the mangoes but it takes 3 wk, which is close to the limit that mangoes tolerate in cold storage. During 2009 and 2010, the amount of irradiated mangoes exported to the United States dropped to 130 and 95 tons, respectively, and no more shipments were made by boat. The lower volume of export during the last 2 y is attributed to mango crop failures in the region in 2009 and problems in air freight due to volcanic ash over Europe in 2010. Irradiated Indian mangoes cost about 4 times the hot water treated Mexican mangoes, but the quality of the cultivars shipped is claimed to be better, and there seems to be a small market for these high-priced but good-quality mangoes in the United States. Some of these mango cultivars do not tolerate hot water immersion well. There have been reports of irradiated mangoes arriving in poor quality, although that may be due more to the shipping conditions than the radiation.

The first irradiated Thai fruit (longan and mango) arrived at the Los Angeles, California, airport on November 1, 2007. Since then, over 70% of the fruit is shipped by boat because of the lower cost compared to air transport, and most of the fruit shipped are longan because they can tolerate the 3-wk boat trip. Mangosteen and rambutan have also been shipped by air. Thailand has permission to irradiate and ship lychee and pineapple to the United States, but has only done test shipments of lychee. Over 4080 tons of Thai fruit have been irradiated and shipped to the United States since late 2007.

In the autumn of 2008, both Vietnam and Mexico started shipping irradiated fruit to the United States. Vietnam has only been given permission by APHIS to ship dragon fruit, although they are hoping to eventually gain permission for other fruits, such as longan, lychee, and rambutan. The dragon fruit goes by boat, and about 500 tons have been shipped to date. Chile will become

Table 3–Mexico is currently the world's largest user of phytosanitary irradiation with the following exports to the United States.

	Tons of irradiated fruit exported per year		
Fruit	2008	2009	2010
Guava	257	3521	9121
Grapefruit	0	67	101
Mango	0	35	239
Sweet lime	0	0	600
Manzano pepper	0	0	257
Total	257	3623	10318

the third country to receive irradiated fruit when Vietnam begins sending irradiated dragon fruit by the end of 2010.

On 21st November, 2008, the first shipments of irradiated Mexican guavas began crossing the border into the United States and by the end of the year 257 tons had been exported (Table 3). The next year exports jumped to 3623 tons of mostly guava, with some grapefruit and mango. In 2010, Mexico exported over 10000 tons of 5 types of irradiated fruits to the United States, making it the world's largest user in volume of PI. The country also has permission to ship irradiated orange and tangerine to the United States, which it may start doing in 2011. Mexico enjoys the advantage of low cost, rapid land transport for its irradiated fruits to the United States.

Effect of phytosanitary irradiation on fruits and vegetables

For a phytosanitary treatment to be commercially viable, the treated commodities must tolerate it. At the doses used for PI (150 to 400 Gy), more fresh fruits and vegetables tolerate radiation than any other commercially available treatment (Heather and Hallman 2008). The most economical form of applying radiation involves treatment in bulk, such as in finished pallet loads, and this will result in a greater dose being absorbed by much of the load to ensure that the minimum required dose is absorbed by the entire load, which means the dose absorbed by the edges of a pallet could be at least twice that received in the center, as in the case of guavas irradiated in Florida. Some commercial arrangements, especially those using X-rays (which travel in more parallel lines instead of diverging outward in the case of gamma rays) combined with loads narrower than the dimensions of a standard pallet can achieve a dose uniformity ratio (the maximum absorbed dose divided by the minimum) as low as about 1.3. Knowing what maximum dose would be absorbed commercially when a minimum is sought gives the maximum dose that a commodity must tolerate if PI is to be used on it.

Because radiation inhibits development, fruit that is not eating-ripe when harvested, such as bananas, papayas, mangoes, and many other tropical fruits, may be more inclined to not ripen normally than fruit that is ready-to-eat when irradiated. The ideal physiological stage of harvest may need to be delayed when using PI; delayed harvest in itself should lead to a better-quality product compared with fruit picked for traditional marketing. The fact that papaya, mango, banana, and guava have been irradiated commercially from different countries for several years while in the hard green stage testifies to the ability of fruit to tolerate PI and still ripen adequately.

Challenges for Future Applications of Phytosanitary Irradiation

The use of irradiation to facilitate trade in quarantined commodities is an active area of food irradiation with yearly increases in the number of countries, commodities, volumes, and quarantine pests treated. For the promising treatment to achieve its optimum potential, several challenges should be overcome.

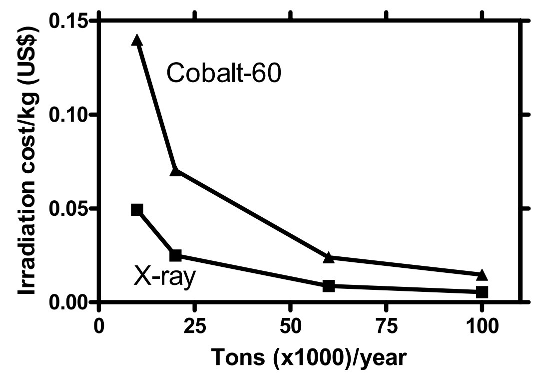

Figure 3–Effect of throughput on cost of PI at 250 Gy (Kunstadt 2001).

Cost of treatment

When alternative treatments are available, PI generally costs more than these alternatives. The higher cost of irradiation is mainly because the initial costs of a treatment facility, which usually does not exist in logistically favorable areas for PI, is several million dollars, much more than the investment for any other phytosanitary treatment. Another reason is that the use of PI is well below optimization at present. As its use increases, therefore the per-unit cost of treatment should fall. Figure 3 shows how the per-unit cost of PI at 250 Gy is expected to decline dramatically as throughput increases. At present, this economy of scale has yet to be reached by any commercial facility doing PI. At the relatively low doses used for PI (150 to 400 Gy), Kunstadt (2001) estimated that X-ray irradiation will cost about 55% of what irradiation with cobalt-60 costs. At higher doses required for medical devices and spices ($\geq$10 kGy) irradiation with cobalt-60 is much cheaper and estimated to cost U.S. \$0.03 to \$0.19/kg while X-ray costs U.S. \$0.22 to \$1.97/kg, depending on throughput.

Regardless of cost, some fruits, such as rambutan and mangosteen, do not tolerate any other phytosanitary treatment and must use PI if they are to be traded across quarantine barriers. Irradiation of Hawaiian rambutans has cost as much as U.S. \$0.60/kg, which was considered economical because the retail price of the fruit was relatively high and no other phytosanitary measure was available. There is also a modest market for irradiated Indian mangoes which may cost 4 to 5 times what Mexican mangoes cost in U.S. retail markets. In this case, special cultivars that command premium prices are shipped. Although hot water immersion and heated air treatments are used for mangoes elsewhere, these cultivars do not tolerate heat well, and heat treatment schedules have not been developed for all of the quarantine pests considered of significant risk in Indian mangoes bound for the United States.

Lack of adequate treatment facilities

Lack of treatment facilities is partially a result of cost. Regulation adds to that cost, and regulation of isotopes and the process itself may preclude its application in individual packing houses as is done with most other phytosanitary treatments. In the 1960s, mobile cobalt-60 commercial irradiation facilities in tractor trailers were developed to irradiate commodities at remote locations (Guerreo 1968), although they were not commercially used because of safety concerns. It is technically possible to design irradiation facilities for incorporation into packing lines that would greatly facilitate the logistics of irradiation (Barrett 1990). It remains to be seen if the development of economical irradiation facilities for packinghouses, including personnel properly trained in safety as well as operation together with a regulatory framework amenable to this size of facility, will result in practical PI capability in packinghouses in the future.

It would be logical to locate big PI facilities near ports used for export of the commodities to avoid increasing transportation and handling costs. These facilities should have cold storage facilities to store products awaiting irradiation and postirradiated product awaiting shipment separately. Facility approval should be done for both nuclear regulatory and phytosanitary issues including nuclear safety, criminal intent, sanitation, accurate dosimetry, protection from reinfestation by quarantine pests, separation of pre- and postirradiated product, adequately trained and screened personnel, record keeping, and traceability of product source, treatment, and destination, as well as procedures in case of accident or other interruption of function (IPPC 2003).

Lack of doses for some quarantine pests

Because PI is applied generically for commodity and is tolerated by a broad variety of fresh commodities, it is available as a phytosanitary solution to many quarantine problems. For imports into the United States, PI is the broadest commercially applicable treatment in existence. Virtually, any fresh commodity can be imported if the quarantine pests for which a treatment is required are any insect, except adults and pupae of the order Lepidoptera (butterflies and moths). No other commercial treatment comes close to being as broadly applicable. For most other countries, however, PI has not been approved for use yet. The generic dose of 0.4 kGy for all insects, except pupae and adults of Lepidoptera, that APHIS accepts was proposed for inclusion in the international standard Phytosanitary Treatments for Quarantine Pests (IPPC 2009a), but was not accepted because it was considered excessive extrapolation for the data that had been accumulated so far (Hallman and others 2010).

Additional treatments are needed. For generic doses for all insects and subgroups of insects to become more widely accepted, more research is needed to establish doses to control key quarantine pests and pest groups. Also, reduction in dose for many insects covered by the generic dose of 0.4 kGy will lead to reduced costs of application and risk of commodity quality damage.

Hallman (1998) provided doses that might provide generic control of pest groups based on the literature at the time. That information has been updated and is provided in Table 4. It would not be necessary to strive for all of the generic doses presented in Table 4 because some may not be of commercial use by themselves. Generic treatments should be developed for groups of pests for which it is feasible that they will be used. For example, the generic dose of 150 Gy for fruit flies is used for mangoes and citrus fruit exported from Mexico to the United States because there are no other organisms of quarantine significance besides fruit flies on those particular Mexican fruits bound for the United States (APHIS 2010b). Mexican guavas shipped to the United States require 400 Gy because of additional pests besides fruit flies, namely whiteflies, weevils, lepidopterous larvae, scale insects, and mealybugs (Table 5). This dose could conceivably be reduced to about 250 Gy with adequate research into these other pest groups. Cost savings and improvements in guava quality would dictate the extent to which it would be worth conducting the research.

Dragon fruit imported into the United States from Vietnam are treated with 400 Gy because of 3 species of mealybugs (Table 5).

Table 4–Possible generic doses that might provide control of various quarantine pest groups.

Pest group[a]	Measure of efficacy	Possible generic dose (Gy)
Aphids	Prevent reproduction of adult	100
Whiteflies	Prevent reproduction of adult	100
Dried seed weevils	Prevent reproduction of adult	100
Fruit fly larvae	Prevent adult emergence	150[b]
Fruit weevils	Prevent reproduction of adult	150
Thrips	Prevent reproduction of adult	250
Lepidoptera larvae	Prevent adult emergence	250
Scale insects	Prevent reproduction of adult	250
Mealybugs	Prevent reproduction of adult	250
All insects except pupae and adults of Lepidoptera[c]	Prevent reproduction of adult or development to adult by eggs, nymphs and larvae	250
Lepidoptera pupae	Prevent reproduction from subsequent adult	350
Mites	Prevent reproduction of adult	350
All arthropods except adults of Lepidoptera	Prevent reproduction of adult	350

[a] Pest group assumes adult is most tolerant stage that may be present in the shipped commodity unless otherwise indicated (fruit flies and lepidopterous borers where adults are not present).
[b] Generic dose of 150 Gy accepted by APHIS (2006b) and IPPC (2009a).
[c] APHIS (2006b) currently accepts 400 Gy, but it might be lowered if additional research continues to support a dose of 250 Gy.

It would be much easier to conduct the research on these insects to lower the dose for that fruit than it would be to accomplish the same with Mexican guavas. This case highlights the potential usefulness of a generic dose for mealybugs.

Pakistani mangoes cleared for export to the United States using irradiation require 400 Gy because of 6 scales (Table 5), an important pest group for which a generic dose would be useful. A generic dose for scales could reduce the required dose for Pakistani mangoes to about 250 Gy (Table 4 and 5).

Indian mangoes for export to the United States are irradiated at 400 Gy because of 5 scales and 2 weevils. Generic doses for weevils and scales could reduce the treatment dose for Indian mangoes to about 250 Gy (Table 4 and 5).

Lepidopterous larvae are important quarantine pests for 3 of 6 Thai fruits (Table 5), while 3 weevils and 1 species of thrips are quarantine pests on 1 fruit each. The generic dose for all insects, except pupae and adults of Lepidoptera, would need to be lowered for Thailand to use a dose <400 Gy on most of their irradiated fruit.

The generic dose of 400 Gy does not cover mites. One mite was identified as a quarantine pest on Thai longans and lychees, and 2 mites were listed for Mexican guavas. The mite on lychee and longan, *Aceria litchii* (Keiffer), is specific to these fruit trees and primarily a pest of foliage and flowers, although it may occur on fruit. To prevent its dissemination via this pathway these 2 fruits from Thailand are prohibited into Florida where both trees are grown in small acreage. Although transshipment to Florida could occur and the fruits are also grown in California (not a prohibited destination state), it was noted that the mite has not been found in shipments of these fruits from Hawaii, China, and India, other areas where the mite is found. In any case, the 400 Gy dose would probably control the mite (Table 4).

The 2 mites found on guavas in Mexico, *Oligonychus biharensis* (Hirst) and O. *psidium* Estébanes & Baker, are more generalist

Table 5–Numbers of species in each quarantine pest group for which the generic dose of 400 Gy is required by APHIS on several fruits from 4 countries (APHIS 2006a, 2007, 2008a, 2008b, 2010a).

	Country and fruit									
	Thailand						Vietnam	Mexico	India	Pakistan
Pest group	Lychee	Longan	Mango	Mangosteen	Pineapple	Rambutan	Dragon fruit	Guava	Mango	Mango
Lepidopterous larva	3	3	0	0	0	1	0	1	0	0
Scale	2	2	4	2	1	1	0	1	5	6
Mealybug	3	4	6	6	2	6	3	6	0	0
Weevil	0	0	3	0	0	0	0	2	2	0
Thrips	0	0	0	0	1	0	0	0	0	0
Whitefly	0	0	0	0	0	0	0	4	0	0

feeders. A phytosanitary certificate must accompany the shipment, certifying that it was inspected and found free of these 2 mites. However, because of the small size of the mites (about 0.3 mm) it is doubtful that some would not escape detection at low population levels when symptoms of infestation (a bronze appearance) may be absent from the fruit. Regardless, the dose of 400 Gy would probably control these two mites (Table 4). Confirmation of a generic dose for mites would be a worthwhile objective.

In 2009, the United Nations Food and Agriculture Organization/International Atomic Energy Agency Division of Nuclear Techniques in Food and Agriculture initiated a 5-y Cooperative Research Project (CRP) with the objective of developing additional generic PI treatments (IAEA 2009). During the next 5 y, researchers from 10 countries propose to develop PI treatments for 29 species of insect and mite pests. Together with research done previously and that which will be done by researchers outside of this CRP, new generic PI treatments will be submitted to the IPPC for future inclusion in Intl. Standard for Phytosanitary Measures 28 (IPPC 2009a).

Hallman and others (2010) discussed the difficulties with research arising out of IPPC vetting of proposed PI treatments. Research shortcomings identified include lack of adequate dosimetry, use of unproven infestation techniques, and inadequate response of control organisms. On some occasions, researchers used artificial infestation without first testing possible effect on efficacy. In other cases, nonirradiated control organisms did not perform as well as expected, indicating existence of factors other than radiation being responsible for some of the supposed effects on the irradiated organisms.

The report on the first meeting of the new CRP on generic treatments includes research guidelines (IAEA 2009). Details on proper dosimetry and precise definition of the treatment endpoint, which should be as precisely defined as is feasible, are included. Testing is divided into preliminary and large-scale (confirmatory) tests. Preliminary tests include those to determine the most radiotolerant stage with which the confirmatory research will be conducted and to estimate the minimum absorbed dose required for control. The guidelines note that radiotolerance increases with increasing development, and Hallman and others (2010) confirmed that with an exhaustive review of the literature. Therefore, research can normally be conducted with the most developed stage that may be present in the exported part of the commodity, saving researchers' time in identifying the most radiotolerant stage. Irradiated and control (nonirradiated) organisms must be kept under conditions favorable for development, and the control must develop or reproduce through the endpoint being measured within normally expected parameters for tests to be valid. Confirmatory testing requires that large numbers (up to 30000 or possibly more) of the most radiotolerant stage be irradiated at a dose that achieves the endpoint without failures, for a treatment to be validated.

Avoidance of food irradiation

Although a number of studies find that the majority of people would buy irradiated food, and that percentage increases with factual education about the process, people do not generally seek out irradiated food, and industry is not anxious to provide it (Eustice and Bruhn 2006). Some people are categorically opposed to food irradiation and may never accept it. Although decision makers in the food marketing chain may not be opposed to food irradiation, they may decline to use the technology for fear of being identified with a process that some consider controversial and believe possessing unknown long-term consequences, although a great many health organizations worldwide have concluded that there is no health concern with consuming irradiated food (Stearns 2006).

Food irradiation has not been accepted by the organic industries (CAC 2007). One widely available international definition of organic agriculture is "*a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved*" (IFOAM 2010a). The principles of organic agriculture are further elaborated by IFOAM (2010b) that scientific knowledge alone is incomplete for ensuring that organic agriculture is healthy, safe, and ecologically sound. "*Practical experience. . . tested by time*," rejection of "*unpredictable technologies*" and "*precaution*" are highlighted as key concerns for organic agriculture. This describes a conservative approach and may mean that if and after PI is widely adopted by mainstream agriculture without major problems, it might become accepted by some organic systems (it is important to note that the organic approach is not monolithic). That may occur because an underlying philosophy of organic agriculture pertaining to phytosanitary treatments is the use of treatments that least change the commodity from its untreated state, and that treatment is arguably PI, because it leaves no residue and is tolerated by more fresh commodities than any other treatment.

Because PI is a useful technology that does not present appreciable risks, its increased commercial use among nonorganic marketers would be beneficial because some commodities have no other viable solution to quarantines, and it often provides for a better product than other treatments (Heather and Hallman 2008). The general public in a number of countries, including important export destinations such as the United States, is not opposed to food irradiation, and the decision not to use it for phytosanitary purposes often rests with key production and marketing personnel who are understandably concerned with negative publicity (Eustice and Bruhn 2006).

Currently in the United States, irradiated produce must carry the words "treated with radiation" or "treated by irradiation."

Codex Alimentarius (CAC 2003) requires that the label include "irradiated" or "treated with ionizing radiation." Some think that this wording is unnecessarily alarming. It is thought that the adoption of wording that does not contain variations of the word "radiation," such as "electronically pasteurized," might be more acceptable to the general public, including those who decide which technology to use (Morehouse and Komolprasert 2004). In 1999, the U.S. FDA sought public comment on changing the labeling of irradiated food but has yet to make any changes.

PI has 2 advantages over most uses of food irradiation that may lead to a higher probability that PI will be commercially used compared with other types of food irradiation: (1) The low doses used for PI (150 to 400 Gy) give the perception of less concern with that process (although it bears repeating that high-dose food irradiation has not been shown to be a problem for human health). (2) Phytosanitary measures are often obligatory if certain commodities are to be imported.

Conclusions

Ionizing irradiation is a promising phytosanitary treatment that is gaining in use worldwide. Currently, a total of almost 19000 metric tons of sweet potatoes and fruit (mangoes, guavas, longans, lychee, rambutan, dragon fruit, citrus, and banana) plus a small amount of curry leaf is irradiated each year in 6 countries to control quarantine pests. Two countries (the United States and New Zealand) import these products and a third (Chile) may soon start. Advantages over other treatments include tolerance by the vast majority of fresh commodities, ability to treat in final packaging in pallet loads, and lack of residues. Disadvantages include lack of acceptance by organic industries and logistical bottlenecks resulting from current unavailability of technology for individual packinghouse facilities. Another disadvantage from the regulatory standpoint is lack of an independent verification of treatment efficacy because pests may be found alive during inspection, although they will not complete development or reproduce. This does not concern the fresh commodity industry, only plant regulators and researchers, unless quarantine pests are found in noticeable numbers on commodities. Challenges to increase the use of PI are cost because commercial use has not yet reached a favorable economy of scale, lack of facilities because of their expense and current inability to feasibly locate them in packing facilities, lack of treatments for some quarantine pests, and concern about the process by key decision makers, such as packing and shipping interests and retailers. Suggestions for dealing with these challenges are offered in this review.

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