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Phytosanitary irradiation of fresh tropical commodities in Hawaii: Generic treatments, commercial adoption, and current issues

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ABSTRACT

Hawaii is a pioneer in the use of phytosanitary irradiation. The commercial X-ray irradiation facility, Hawaii Pride LLC, has been shipping papaya and other tropical fruits and vegetables to the United States mainland using irradiation for 11 years. Irradiation is an approved treatment to control quarantine pests in 17 fruits and 7 vegetables for export from Hawaii to the US mainland. Hawaiian purple sweet potato is the highest volume product with annual exports of more than 12 million lbs (5500 t). The advent of generic radiation treatments for tephritid fruit flies (150 Gy) and other insects (400 Gy) will accelerate commodity export approvals and facilitate worldwide adoption. Lowering doses for specific pests and commodities can lower treatment costs and increase capacity owing to shorter treatment times, and will minimize any quality problems. Current impediments to wider adoption include the 1 kGy limit for fresh horticultural products, the labeling requirement, and non-acceptance of phytosanitary irradiation in Japan, the European Union, and elsewhere. Irradiation has potential as a treatment for unregulated imports to prevent new pest incursions.

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1. Introduction

World trade in agricultural commodities continues to grow. As agricultural trade expands, the risk of introducing exotic insects into new areas where they may become plant pests increases. The establishment of new pests can be costly due to increased crop damage, control programs, and quarantine restrictions on trade. Quarantine or phytosanitary treatments such as irradiation disinfest host commodities of insect pests before they are exported to areas where the pests do not occur, and are often the simplest approach to overcome regulatory trade barriers and gain market access.

2. Low-dose radiation treatments

The United States Food and Drug Administration has approved radiation doses up to 1000 Gy (1 kGy) for preservation and disinfestation of fresh fruits and vegetables (FDA, 1986). Ionizing radiation breaks chemical bonds within DNA and other biomolecules, thereby disrupting normal cellular function in the infesting insect Radiotolerance can vary among the life stages of an insect (Follett and Lower, 2000), and between taxonomic groups of insects. Unlike other disinfestation techniques, irradiation does not need to kill the pest immediately to provide quarantine security, and therefore live (but sterile or not viable) insects may occur with the exported commodity (Follett and Griffin, 2006). The goal of a quarantine treatment is to prevent reproduction, and therefore the required response for a radiation treatment may be prevention of adult emergence (Follett and Armstrong, 2004) induction of adult sterility (Follett, 2006a,b,c), or F_1 sterility (Follett, 2006b,c).

3. Phytosanitary irradiation in Hawaii

Hawaii was the first place in the world to use irradiation as a quarantine treatment of tropical fruits for export. In the early 1970s, commercial quantities of papayas were shipped from Hawaii to California and Florida to learn how handling and shipping might affect fruit quality (Moy and Wong, 2002). Following the approval of irradiation by the US Food and Drug Administration for control of insects in produce in 1986, a permit was issued for a one-time shipment of papayas from Hawaii to California to test for the first time consumer in-store response to irradiated food (Bruhn and Noell, 1987). During the period from 1968 to 1986, numerous studies were conducted in Hawaii on the efficacy of radiation treatment against fruit flies and the effects of irradiation on the quality of tropical fruit crops (Moy and Wong, 2002). At the Hawaii Tropical Fruit Growers' 1995 annual international fruit conference, Dr. Lyle Wong, Director of Plant Industry at the Hawaii Department

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of Agriculture, introduced the Hawaii exotic fruit growers to irradiation technology for insect disinfestation. The industry was in its infancy in Hawaii and commercial quantities of exotic fruit crops like rambutan, lychee, and longan were just starting to be harvested. The industry was looking at treatment options to export these crops to the US mainland. Tephritid fruit flies were the primary pests of concern to US agriculture. Subsequent to that meeting, a delegation flew to Washington and Beltsville to arrange for USDA approval of direct non-stop trial shipments of Hawaii fruit and treatment in Chicago at an irradiation facility located near the airport (Moy and Wong, 2002).

The treatment proved successful for insect disinfestation while maintaining excellent fruit quality. Commercial shipments of Hawaiian fruit began soon after the initial trial shipment. During 1995–2000 more than 300,000 kg (300 t) of papayas and 100,000 kg (100 t) of other fruits were shipped from Hawaii to the continental US for distribution in 16 states (Moy and Wong, 2002). The extra transportation expenses of shipping to Chicago and then back to markets in California, as well as losses caused by flight delays, necessitated building a facility in Hawaii. The key to the economic success of an irradiation facility is sufficient volume to amortize the substantial initial capital costs. Papaya was chosen as that volume fruit because the industry was mature, there were sufficient quantities, and the fruit was available year round.

Several years of extreme controversy within the community followed the public announcement of interest to construct a facility on the Big Island of Hawaii. Opposition to the idea of bringing in radioactive isotopes to an island with a pristine environment was widespread. In fact, concerned citizens organized a petition drive to have the issue decided by popular vote through referendum. In November 1998 the measure to "prohibit the use of radioactive isotopes for commercial purposes in the County of Hawaii" was defeated by 492 votes, less than one percent of total votes cast in the election. Because of this deep division within the community, Eric Weinert (founding partner in the LLC) sought a non-radioactive source irradiation technology to provide insect disinfestation.

4. Hawaii Pride commercial X-ray facility

Isomedix Corporation was the entity treating Hawaiian fruit in Chicago and it was assumed that they would construct a Hawaiian facility. They insisted cobalt was the only technology that would work both economically and physically. After the referendum vote of 1998 they chose not to build a Hawaiian facility citing the risk of an "unproven" market for Hawaiian fruit. Eric Weinert then contacted the Titan Corporation in San Diego who was willing to cooperate in the design and construction of an all electric X-ray-type irradiator. A test shipment of Hawaiian fruit was flown to Iowa State University in March of 1999, and after X-ray treatment the fruit was brought back to Hawaii to prove the high quality of fruit to the Hawaiian farmers. Eric Weinert and John Clark formed Hawaii Pride, LLC, obtained a loan for $6.5 million and started construction. Hawaii Pride opened for production in August of 2000.

There were assurances by some retailers that they would sell the irradiated Hawaiian fruit. However, that was not the case. Retailers are conservative by nature and did not want to expose their company's reputation to risk. Despite understanding the benefits of the irradiation technology and the safety of the product and the process, communicating these issues to their customers is difficult. They viewed the risk to their company's good name far outweighing any benefit from selling a few more pounds of tropical fruit. Hawaii Pride's owners spent the next two years meeting with retailers across the country in an attempt to get them to change their minds and carry irradiated products. Because Hawaii Pride used all electric X-ray technology and not radioactive isotope source material, they were able to schedule appointments and get in the door. This difference (in source) was hugely important to retailers.

Table 1
Change in volumes of irradiated agricultural products at Hawaii Pride, LLC between 2005 and 2010.

Product	2005		2010	
	Pounds	Tonnes	Pounds	Tonnes
Papaya	2,300,000	1040	26000	12
Tropical exotics[a]	643,000	290	571,000	260
Sweet potatoes	3,940,000	1780	11,842,000	5370
Other[b]	38,000	17	203,000	92
Total	6,921,000	3127	12,642,000	5734

[a] Longan, dragon fruit, rambutan, mango, mangosteen.
[b] Sweet basil, curry leaf, banana.

Rainbow Foods, a small retailer in Minneapolis, was the first brave company to feature Hawaii's irradiated papaya. Scott Schaeppi, vice president of produce at Rainbow Foods was featured on the cover of the trade publication "Produce Merchandising" standing in front of a huge display of Hawaiian papaya. Following his success, other retailers began to take the risk. The discussion was about the delicious flavor of Hawaiian fruit, not about irradiation technology. Soon, Albertson's, Safeway and Kroger's all had successful marketing trials of irradiated Hawaiian papaya.

In 2008, Calavo Growers, Inc. purchased Hawaii Pride, LLC and Tropical Hawaiian Products (THP) (a papaya vapor heat treatment facility and packinghouse), making them the largest packer and exporter of papaya from Hawaii to the US mainland. To streamline their Hawaii papaya packing operations Calavo chose to use vapor heat technology and to discontinue irradiating papaya because some of their customers would still not accept irradiated product. Calavo Growers sells over 7 million pounds of Hawaiian papaya but does not irradiate a single pound.

The Hawaiian purple sweet potato is now the largest volume product for Hawaii Pride (Table 1). It is mostly sold to Asian markets and is not sold in major national retail markets. This is also true for Hawaii's tropical exotic fruits like rambutan and longan. Because Calavo is not irradiating papaya, many of the large national retailers who once carried "irradiated" papaya have not carried any products treated with irradiation for several years. Wal-Mart is now the largest national produce retailer and does not carry irradiated products. Their management has indicated that Wal-Mart will carry irradiated produce once labeling is no longer required. Labels are viewed by the American public as a "warning" that something is harmful rather than information transfer. The logic is if there isn't anything harmful, why require labeling.

One approach to changing retailer's policies regarding irradiated product is to understand the issue from their perspective. Education is not enough as retailer management already understands the safety and benefits of irradiation. The irradiation industry needs to listen and ask the retailers what they need to accept irradiated products. They are the gatekeepers. Until we address their concerns we won't get our products on their shelves.

5. Research partnership leading to sweet potato exports

Several years after opening, Hawaii Pride was in a critical financial situation as papaya production and exports were at a low point due to a prolonged drought. Hawaii Pride identified sweet potato as an opportunity to diversify their product line and generate new income. Hawaii's vegetable growers produce several unique varieties of sweet potatoes, including a purple-fleshed type. Methyl bromide was previously the only accepted quarantine treatment for sweet potatoes destined for export from Hawaii to the US mainland. Methyl bromide can cause damage to the sweet potato and had become increasingly costly, and therefore no sweet potatoes were being exported. Hawaii Pride petitioned APHIS to approve irradiation as a substitute treatment for methyl bromide, and ARS began irradiation research with the key quarantine pests (Follett, 2006a). An irradiation treatment of 400 Gy for sweet potatoes was published as an interim rule in 2003 (USDA-APHIS, 2003) and a final rule in 2004 (USDA-APHIS, 2004) based on preliminary data on radio-tolerance of three quarantine pests—sweet potato weevil, West Indian sweet potato weevil, and sweet potato vine borer—and an ARS recommendation for a high-dose. This was the first time USDA-APHIS considered the high-dose approach for controlling a pest complex until research is completed to confirm a lower dose. This 400 Gy treatment protocol was the precursor to a generic treatment for all insects (see discussion below). Sweet potato production doubled soon after the rule was published, and currently approximately 12 million lbs (5500 t) of sweet potatoes are exported using irradiation treatment (Table 1). Eventually, research lowered the radiation dose from 400 Gy to 150 Gy to control the sweet potato pests resulting in a 60% cost savings to the commercial X-ray radiation facility (Follett, 2006a).

6. Generic radiation doses

In 2006, USDA-APHIS published a pioneering rule providing generic low-dose radiation quarantine treatments to control insects. A generic treatment is a single treatment that controls a broad group of pests without adversely affecting the quality of a wide range of commodities. The rule approved radiation doses of 150 Gy for any tephritid fruit fly and 400 Gy for all other insects except the pupa and adult stages of Lepidoptera (moths and butterflies) (USDA-APHIS, 2006). The generic radiation treatments apply to all fresh horticultural commodities. Therefore, if a pest risk assessment demonstrates that no pupae or adult Lepidoptera are associated with a commodity, export approval can be forthcoming with no further research. The logic behind generic doses is that information on radio tolerance for a subset of species in a group can be extrapolated to related species to arrive at an effective generic dose. Traditionally, quarantine treatments are developed for one pest and commodity at a time, and research could take years to complete, so this first-ever approval of a generic treatment was a huge leap forward.

Generic treatments are the culmination of decades of research but not an end point (Follett, 2009). Future research will focus on development of specific doses for quarantine Lepidoptera not covered by the generic treatments (e.g. Hollingsworth and Follett, 2007); reduction of dose levels for specific pests and commodities to shorten treatment time (Follett, 2006a); development of generic doses below 400 Gy for important groups of quarantine arthropods other than fruit flies (Follett, 2009); and development of information on commodity tolerance and novel methods to reduce injury and extend shelf-life (Morris and Jessup, 1994; Wall, 2008; Follett and Weinert, 2009).

7. Research to lower doses

Most fresh commodities traded between countries will initially make use of the 400 Gy generic dose due to the diversity of insect pests and the absence of information on radiotolerance for each specific pest. If lowering the dose for a quarantine pest or group of pests allows lowering of the dose for the commodity of interest, the cost of treatment will be reduced, any quality problems will be minimized, and the capacity of the treatment facility may be increased owing to shorter treatment time (Follett, 2009).

Development of generic doses for groups of common plant pests other than fruit flies (e.g. mealybugs, mites) would be beneficial. A generic radiation dose is recommended after information has accumulated on effective quarantine radiation doses for a wide range of insects within the group or for the important economic species within the group (Follett and Neven, 2006).

The approved generic radiation treatment of 400 Gy excludes the pupa and adult stages of Lepidoptera (USDA-APHIS, 2006). Typically, exported fresh commodities that may contain pupae or adults of actionable lepidopteran pests must be inspected and found free of the pest before export is permitted, and their presence could result in rejection. Development of a radiation dose to control the lepidopteran pest would reduce inspections and prevent potential rejections of host commodities.

The radiation dose for a pest may also be lowered using a combination treatment. For example, Mediterranean fruit fly is controlled in clementine mandarins with a radiation dose of 30 Gy and subsequent exposure to 1 °C for 2 days (Palou et al., 2007), and oriental fruit fly and melon fly are controlled with 30 Gy and 6–9 days at 2 °C (Follett, unpublished data). These are significant reductions from both the approved generic radiation dose for fruit flies of 150 Gy and the standard cold quarantine treatments of 1.1–2.2 °C for 14–18 days. Cold is a convenient combination treatment with irradiation for commodities that are shipped with refrigeration.

8. Trade facilitation

Generic treatments will facilitate safe trade between countries that have approved the use of irradiation as a phytosanitary treatment. Irradiation is an approved treatment to control quarantine pests in 17 fruits and 7 vegetables for export from Hawaii to the U.S. mainland (Table 2) (Follett, 2004; Follett and Griffin, 2006). During the past few years, India, Mexico, Pakistan, South Africa, Thailand, and Vietnam and have received approvals to export fruits to the U.S. using generic radiation treatments. In 2009, the International Plant Protection Commission approved the generic radiation dose of 150 Gy for tephritid fruit flies, which will facilitate worldwide adoption (IPPC, 2009). The availability of

Table 2
Commodity quarantine treatments or systems approved for export of Hawaii's fruits and vegetables to the United States mainland.

Abiu	I	Jackfruit	I
Atemoya	I	Longan	I, H
Avocado	C	Lychee	I, H
Banana	I, N	Mango	I
Breadfruit	I	Mangosteen	I
Capsicum spp.	I	Moringa	I
Carambola	I, C	Papaya	I, H
Citrus	I, H	Pineapple	I, N, H
Cucurbita spp.	I	Rambutan	I, H
Dragon fruit	I	Sapodilla	I
Durian	N	Sweet potato	I, F, H
Eggplant	I	Tomato	I
Guava	I	Cowpea	I

I=irradiation, C=cold, N=non-host status, H=heat (hot water immersion or vapor heat), F=fumigation. Updated from Follett, 2004.

generic dose treatments makes irradiation an attractive option compared with other quarantine treatments.

9. Current issues

There are several issues that present barriers to the wider use of phytosanitary irradiation. The 1 kGy limit established by the FDA has no scientific basis and serves no practical purpose. In reality, many fresh horticultural products show radiation injury at doses above 1 kGy, but commodities that can withstand doses above 1 kGy without injury should not have to meet the requirements of an arbitrary ceiling. The 1 kGy limit for phytosanitary uses should be raised to 3–5 kGy or eliminated. This may be particularly useful when using existing irradiation facilities designed for another purpose (e.g. medical device sterilization) to treat fresh commodities at low doses. Due to a relatively high dose uniformity ratio (2.5 or 3:1) at such facilities, insect disinfestation at a minimum radiation dose of 400 Gy may result in a maximum dose above 1 kGy. Practically, the maximum dose that can be applied will be determined by commodity tolerance. For tolerant commodities, raising or eliminating the 1 kGy limit will allow for a wider variety of product configurations and help guarantee economic feasibility. The formation of furan, a carcinogen, at low levels in certain fruits after radiation treatment at 4–5 kGy may complicate this issue (Fan and Sokorai, 2008).

Irradiation is not a universally accepted phytosanitary treatment. Japan and Taiwan irradiate potatoes for sprouting control but do not permit the import of irradiated produce or other food products. The European Commission allows irradiation of spices, herbs and vegetable seasonings, but prohibits the use of irradiation as a phytosanitary measure by members of the European Union. The U.S. and other nations should seek approvals for phytosanitary uses of irradiation in these lucrative export markets.

Labeling is an impediment to the marketing of irradiated fresh produce. In the U.S. irradiated whole foods or fresh horticultural products must be labeled with the radura symbol and as ''treated by irradiation'' either on individual fruits or at the point of sale (Morehouse, 2002). No other insect disinfestation process requires labeling. Phytosanitary treatments are applied to meet regulatory requirements that protect agriculture and the environment, but the treated product has no added value to the retailer or consumer. Retailers are reluctant to carry irradiated fruits and vegetables because the label implies a warning. In contrast, sanitary uses of irradiation result in a value-added product because food borne illness and spoilage organisms may be eliminated, and shelf life may have been extended. This food is safer to eat and therefore retailers would like to advertize the difference through labeling. A proposed rule by the FDA would allow the labeling of irradiated foods as ''pasteurized,'' and if an irradiated product exhibited no material change due treatment, labeling may not be required at all.

To date, irradiation is not being used to treat unregulated imported fresh produce. Hawaii imports 2/3 of its fruits and vegetables, and these imports are an important source of new invasive plant pests. USDA-APHIS inspects passengers and cargo leaving Hawaii destined for the U.S. mainland but does not inspect products from the mainland destined for Hawaii. A potential use of irradiation is to disinfest unregulated imported food and prevent pest incursions. Radiation treatment of high risk commodities at 100–200 Gy would disinfest them of most insect pests while minimizing quality problems. The cost of radiation treatment of imports could be offset by a reduced need for inspection or by charging inspection fees.

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References

Bruhn, C.M., Noell, J.W., 1987. Consumer in-store response to irradiated papayas. Food Technol., 83–85. Sept. 1987.

Fan, X., Sokorai, K.J., 2008. Effect of ionizing radiation on furan formation in fresh-cut fruits and vegetables. J. Food Sci 73 (2), C79–C83.

Follett, P.A., 2004. Irradiation to control insects in fruits and vegetables for export from Hawaii. Rad. Phys. Chem. 71, 161–164.

Follett, P.A., 2006a. Irradiation as a methyl bromide alternative for postharvest control of *Omphisa anastomosalis* (Lepidoptera: Pyralidae) and *Euscepes postfasciatus* and *Cylas formicarius elegantulus* (Coleoptera: Curculionidae) in sweet potatoes. J. Econ. Entomol. 99, 32–37.

Follett, P.A., 2006b. Irradiation as a phytosanitary treatment for *Aspidiotus destructor* (Homoptera: Diaspididae). J. Econ. Entomol. 99 (6), 1138–1142.

Follett, P.A., 2006c. Irradiation as a phytosanitary treatment for white peach scale (Homoptera: Diaspididae). J. Econ. Entomol. 99 (6), 1974–1978.

Follett, P.A., 2009. Generic radiation quarantine treatments: the next steps. J. Econ. Entomol. 102, 1399–1406.

Follett, P.A., Lower, R., 2000. Irradiation to ensure quarantine security for *Cryptophlebia* spp. (Lepidoptera: Tortricidae) in sapindaceous fruits from Hawaii. J. Econ. Entomol. 93, 1848–1854.

Follett, P.A., Armstrong, J.W., 2004. Revised irradiation doses to control melon fly, Mediterranean fruit fly and oriental fruit fly (Diptera: Tephritidae) and a generic dose for tephritid fruit flies. J. Econ. Entomol 97, 1254–1262.

Follett, P.A., Neven, L.G., 2006. Current trends in quarantine entomology. Annu Rev. Entomol. 51, 359–385.

Follett, P.A., Griffin, R., 2006. In: Sommers, C.H., Fan, X. (Eds.), Irradiation as a Phytosanitary Treatment for Fresh Horticultural Commodities: Research and Regulations. Food Irradiation Research and Technology. Blackwell, pp. 143–168.

Follett, P.A., Weinert, E.D., 2009. Comparative radiation dose mapping of single fruit type and mixed-fruit boxes for export from Hawaii. J. Food Process. Preserv. 33, 231–244.

Food and Drug Administration (FDA), 1986. Irradiation in the production, processing, and handling of food. Fed. Regist. 51 (75), 13376. April 18, 1986. Rules and Regulations.

Hollingsworth, R.G., Follett, P.A., 2007. Ionizing radiation for quarantine control of *Opogona sacchari* (Bojer) (Lepidoptera: Tineidae). J. Econ. Entomol. 100, 1519–1524.

International Plant Protection Convention (IPPC), 2009. International Standards for Phytosanitary Measures (ISPM) No. 28, Phytosanitary treatments for regulated pests FAO, Rome. (Originally published in 2007; irradiation treatments annexed in 2009).

Morehouse, K.M., 2002. Food irradiation—US regulatory considerations. Rad. Phys. Chem 63, 281–284.

Moy, J.H., Wong, L., 2002. The efficacy and progress in using radiation as a quarantine treatment of tropical fruits—a case study in Hawaii. Rad. Phys. Chem 63, 397–401.

Palou, L., Del Rio, M.A., Marcilla, A., Alonso, M., Jacas, J.A., 2007. Combined postharvest X-ray and cold quarantine treatments against the Mediterranean fruit fly in 'Clemenules' mandarins. Span. J. Agric. Res. 5, 569–578.

USDA-APHIS, 2003. Irradiation of sweetpotatoes from Hawaii. Fed. Regist. 68 (123), 37931–37936. June 26, 2003. Rules and Regulations.

USDA-APHIS, 2004. Irradiation of sweetpotatoes from Hawaii. Fed. Regist. 69 (32), 7541–7547. February 18, 2004. Rules and Regulations.

USDA-APHIS, 2006. Treatments for fruits and vegetables. Fed. Regist. 71 (18), 4451–4464. June 27, 2006. Rules and Regulations.

Wall, M.M., 2008. Quality of postharvest horticultural crops after irradiation treatment. Stewart Postharvest Rev. 4 (2), 1. online at 〈www.stewartpostharvest.com〉.