Radiation Physics and Chemistry 129 (2016) 39–45

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

# Phytosanitary irradiation – Development and application

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HIGHLIGHTS

- Phytosanitary irradiation is a growing use of food irradiation.
- 25,000 t of fresh produce was irradiated for phytosanitation worldwide in 2015.
- Phytosanitary irradiation has resulted in paradigm shifts applicable to other phytosanitary measures.

ARTICLE INFO

*Article history:*
Received 9 June 2016
Received in revised form
28 July 2016
Accepted 2 August 2016
Available online 3 August 2016

*Keywords:*
Phytosanitation
Quarantine treatment
Phytosanitary treatment
Insects
Pests
Regulation

ABSTRACT

Phytosanitary irradiation, the use of ionizing radiation to disinfest traded agricultural commodities of regulated pests, is a growing use of food irradiation that has great continued potential for increase in commercial application. In 2015 approximately 25,000 t of fresh fruits and vegetables were irradiated globally for phytosanitary purposes. Phytosanitary irradiation has resulted in a paradigm shift in phytosanitation in that the final burden of proof of efficacy of the treatment has shifted from no live pests upon inspection at a port of entry (as for all previous phytosanitary treatments) to total dependence on certification that the treatment for target pests is based on adequate science and is commercially conducted and protected from post-treatment infestation. In this regard phytosanitary irradiation is managed more like a hazard analysis and critical control point (HACCP) approach more consistent with food safety than phytosanitation. Thus, phytosanitary irradiation offers a more complete and rigorous methodology for safeguarding than other phytosanitary measures. The role of different organizations in achieving commercial application of phytosanitary irradiation is discussed as well as future issues and applications, including new generic doses.



## 1. Objective and scope

The commercial use of ionizing radiation to disinfest fresh agricultural commodities exported from areas considered at risk of infestation by quarantine pests has increased significantly in recent years and could have a far reaching impact in facilitating international trade. The objective of this paper is to provide an accurate account of the development and accomplishments of this technology and to propose what remains to be done for it to achieve its maximum potential. There has been considerable written about the technology and its application and we do not wish to repeat it here except for clarification.

## 2. Phytosanitation

The objective of phytosanitation is to prevent the spread of regulated pests from infested to non-infested areas. A phytosanitary treatment is required when a production area is considered infested by a regulated pest and products to be shipped out of that area are considered capable of being infested by that pest. The regulated pest does not have to be an economically controlled pest of the quarantined commodity nor does it even need to attack it. But the pest must pose an unacceptable risk of introduction via the commodity import pathway. For example, snails and slugs are often found in pallet loads of ceramic tiles imported into the USA from Italy and are considered regulated pests if they do not occur in the USA. Therefore, procedures to disinfest the tiles of the molluscs must be done if the tiles are to be imported.

Fresh fruits and vegetables can harbor many pests which without proper control could be introduced and spread widely resulting in economic loss to areas free from such pests. Fruit importing countries may require fruits and vegetables from areas

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http://dx.doi.org/10.1016/j.radphyschem.2016.08.003
0969-806X/

considered to be infested with pests that threaten their agriculture to be treated according to treatment schedules authorized by them. They usually require individual treatment schedules for specific pest/commodity combinations to be applied to any import. Thus, a prospective exporting country of fruits and vegetables may be required to conduct tests to ensure the phytosanitary security of their exports.

The specific phytosanitary requirements of fruit importing countries, such as Australia, Japan, New Zealand, South Korea, and the United States, effectively become technical barriers that are difficult to overcome on a case by case basis. Thus, phytosanitary treatments which have broad spectrum to satisfy phytosanitary requirements of importing countries based on internationally agreed protocols are urgently needed, and ionizing radiation shows promise in becoming that treatment. However, key import markets, such as the European Union, Japan, South Korea, and Taiwan, do not yet accept irradiation.

### 2.1. *Phytosanitary irradiation*

The most commonly used phytosanitary treatments involve exposing commodities to temperatures between −0.6 and 3 °C for a number of days, 43.3–50° C for a few hours, fumigation with various chemicals such as methyl bromide, and ionizing radiation (Heather and Hallman, 2008). Phytosanitary irradiation differs from other phytosanitary treatments in that the measure of efficacy of irradiation is not acute mortality, as it is for all other commercial treatments, but prevention of further development or reproduction. This means that any regulated pests that may have been present at the moment of irradiation could still be alive when they enter the importing area.

This has required a paradigm shift in regulation of phytosanitation in that when live regulated pests are found upon inspection in an importing jurisdiction the lot would normally be rejected as non-compliant. The acceptance of irradiation as a phytosanitary treatment requires that plant protection organizations do not reject shipments containing live regulated pests covered by the treatment. However, that leaves phytosanitary irradiation without an independent verification of efficacy, as any quarantine pests found upon entry inspection should normally be dead for other treatment technologies. The lack of independent verification of efficacy coupled with lack of confidence in a verification system to replace that lack of efficacy was a major obstacle to early commercial implementation of phytosanitary irradiation. That is because all major treatment categories (heat, cold, fumigation) have failed at one time or another (Heather and Hallman, 2008), and this was only discovered because live pests were found upon inspection. Therefore, confidence in the efficacy of phytosanitary irradiation is based entirely on the soundness of the research supporting the regulated minimum treatment dose, the process control in achieving that dose during commercial application, and the phytosanitary safeguarding of the product after irradiation. This is accomplished by making the process control and certification of phytosanitary irradiation akin to a hazard analysis and critical control point (HACCP) approach more consistent with food safety (Hallman, 2016). In that regard phytosanitary irradiation has offered an improved way for safeguarding other phytosanitary measures, including phytosanitary systems, than phytosanitation as it is historically practised for all other measures besides irradiation. Indeed, in recent years phytosanitary systems have evolved in sophistication to resemble HACCP systems.

## 3. Historical development

The history of phytosanitary irradiation has been chronicled in several articles (Moy and Wong, 2002; Hallman, 2001, 2011, 2012; Hallman and Loaharanu, 2002; Follett and Griffin, 2006; Hallman and Blackburn, 2016). Phytosanitary irradiation was first envisioned in 1930, but the first commercial use did not occur until 1986 when one load of mangoes irradiated in Puerto Rico was shipped to Florida for sale to the public as a test of commercial marketing. Further shipments of mangoes were not made because starting in 1987 hot water immersion was approved and used as a replacement for the banned ethylene dibromide fumigation. The following text further details and clarifies the development of phytosanitary irradiation.

The former US Atomic Energy Commission (USAEC) as part of its wide-ranging program on peaceful uses of atomic energy sponsored food irradiation research programs in the 1960s by selecting six food items (papaya, strawberries, shrimp, mushrooms, red meat, and fish) based on their potential technical and economic feasibility and possible market acceptance. Research on phytosanitary irradiation became more intensified during this program. Irradiation of papaya was the sole proposed phytosanitary use among the six items.

The US-Food and Drug Administration (FDA) classified irradiated food as a food additive based on the Food Additives Amendment of 1958. Thus, every irradiated food product must demonstrate its wholesomeness based on defined criteria. Long term animal feeding studies on at least two animal species using diet incorporating irradiated food comprising 35% of the total diet based on dried weight were required for all irradiated foods to demonstrate their wholesomeness. Because this level of papaya consumption in animal feeding studies was impractical, revised diets were established that used only 15% fresh weight of irradiated papaya. Once the animal feeding studies were completed, the USAEC submitted a petition to the FDA to approve papaya phytosanitary irradiation in 1972. By that time the USAEC had come under increasing public opposition to nuclear energy, and in 1975 the USAEC was dissolved and many of its programs discontinued. In 1986 the FDA approved radiation disinfestation of all fresh fruits and vegetables, not only papaya, at a maximum dose of 1.0 kGy. This approval followed the milestone conclusion of the Joint FAO/IAEA/WHO Expert Committee on the Wholesomeness of Irradiated Foods in 1980 that "Food irradiated with an overall average dose of 10 kGy causes no toxicological hazard; thus, testing of food so treated is no longer required" (WHO, 1981).

Hawaii, the early sustained innovator in phytosanitary irradiation, has received a large amount of effort by many organizations over the years to promote and develop phytosanitary irradiation. As stated above, beginning in the 1960s the USAEC chose phytosanitation of papaya as one of the six initial uses of food irradiation, built a research irradiator, and supported phytosanitary irradiation research in the state. Proposed irradiation of Hawaiian papaya was the impetus to request FDA approval of phytosanitary irradiation of fresh agricultural commodities in 1972.

At that time ethylene dibromide (EDB) was the fumigant of choice to satisfy phytosanitary requirements for disinfestation of papaya and other fruits. There was little incentive to develop new technology such as radiation disinfestation especially when food regulatory agencies had not yet approved irradiated fruits for consumption. However, renewed interest in phytosanitary irradiation emerged. When restrictions on the use of EDB were being discussed in the Environmental Protection Agency (EPA) in the USA in the early 1980s and alternative phytosanitary treatments showed questionable results, the USDA and US EPA convened a meeting in Washington D.C. to re-examine the role of phytosanitary irradiation as a phytosanitary treatment in 1982.

A second commercial market test of phytosanitary irradiation, Hawaiian papayas to California, was done in 1987. Moy and Wong (2002) chronicle these early stages of phytosanitary irradiation in Hawaii up to the construction of a commercial facility in Hilo using

**Table 1**
Recommended treatment doses based on an unpublished analysis of the literature by R. J. Corcoran and B. C. Waddell in 2003.

| Pest group | Recommended dose (Gy) | Measure of efficacy |
|---|---|---|
| Tephritidae (fruit flies) | 150 | No adult emergence of eggs and larvae |
| Hemiptera (bugs, scales, mealybugs) | 250 | Reproductive sterility |
| Thysanoptera (thrips) | 250 | Reproductive sterility |
| Lepidoptera (moths, butterflies) | 250 | No adult emergence of eggs and larvae |
| Coleoptera (beetles) | 250 | Reproductive sterility |
| All other insects | 250 | Reproductive sterility |
| Acari (mites) | 350[a] | Reproductive sterility |

[a] Doses for mites have been raised to 400 Gy for Tetranychidae and 500 Gy for all other mites (DABPD, 2014).

a US$6.75 million loan from the United States Department of Agriculture (USDA). The new X-ray phytosanitary irradiation facility became commercially operational on 1 August 2000 and treated mostly papaya at first, comprising 90% of the 2.3 thousand tons of fruit irradiated per year. After a few years the volume of irradiated papayas declined due to drought and maintenance delays, and that volume was gradually replaced by 'Beni-Imo' sweet potatoes which were first irradiated at a generic dose of 400 Gy based on reviews of Hallman (2000, 2001), and later irradiated at 150 Gy based on research with the specific regulated pests (Follett, 2006). Other irradiated produce include lychee, longan, and rambutan.

The phytosanitary irradiation treatments used in Australia and New Zealand are based on an unpublished analysis of the literature by R. J. Corcoran & B. C. Waddell in 2003 who drew on Hallman (1999, 2000, 2001). The recommended doses (Table 1) were adopted by New Zealand in subsequent importations of irradiated Australian produce by the end of 2004 compared with the doses set by the USDA-Animal and Plant Health Inspection Service (APHIS) and the International Plant Protection Convention (IPPC). For example, 250 Gy has been accepted in New Zealand against a broad assortment of insects for which the USDA requires 400 Gy and which has not been accepted even at 400 Gy by the IPPC (Hallman, ,2012).

### 3.1. The role of FAO/IAEA in phytosanitary irradiation

The FAO/IAEA through its former Food Preservation Section and later Food and Environmental Protection Section has supported the development of phytosanitary irradiation for close to a half century. In 1970 it convened an international panel in Hawaii to consider the potential of radiation disinfestation as a method to satisfy phytosanitary requirements of fruits and vegetables. By that time the USAEC had built the Hawaiian Development Irradiator at the University of Hawaii to conduct research on radiation disinfestation of papaya. After examining available entomological, biochemical, physical, and economic data on radiation disinfestation of fruits and vegetables using papaya as a model, the panel concluded that irradiation had a strong potential to be applied as a phytosanitary treatment. It recommended that the FAO/IAEA implement an international research program to include as many types of tropical fruits as possible, using a harmonized scientific protocol.

The FAO/IAEA has sponsored phytosanitary irradiation research in many countries and convened many workshops and meetings to explore the technology and develop research and application guidelines. Four Coordinated Research Projects (CRP) lasting 5 years each, that began in 1986 and ended in 2014 generated a wealth of information on phytosanitary irradiation doses. Most of the resulting data from the first three CRP were published in IAEA technical documents:

1. Use of Irradiation as a Quarantine Treatment of Food and Agricultural Commodities, http://www-pub.iaea.org/books/IAEABooks/3744/Use-of-Irradiation-as-AaQuarantine-Treatment-of-Food-and-Agricultural-Commodities.
2. Irradiation as a Quarantine Treatment of Arthropod Pests, http://www-pub.iaea.org/MTCD/Publications/PDF/te_1082_prn.
3. Irradiation as a Phytosanitary Treatment of Food and Agricultural Commodities, http://www-pub.iaea.org/MTCD/publications/PDF/te_1427_web.pdf.

and some peer-reviewed papers submitted to various journals by individual researchers. Results of the last CRP were published in a dedicated issue of the peer-reviewed journal, Florida Entomologist (Hallman et al., 2016). A recent Manual of Good Practice in Food Irradiation (IAEA, 2015) covers phytosanitary uses of the technology.

### 3.2. The role of the International Consultative Group on Food Irradiation

After the 1980 conclusion by WHO (1981) on the wholesomeness of irradiated food, many governments felt a need for continued international cooperation to ensure widespread regulation and application of food irradiation. The FAO/IAEA was charged with developing a legal instrument for such an international collaboration. A declaration establishing the International Consultative Group on Food Irradiation (ICGFI) was formulated by representatives of several governments in 1983 and was sent under the signatures of the Directors General of FAO, IAEA, and WHO to all of their member governments for acceptance. ICGFI was formally established in May 1984 under the aegis of FAO, IAEA, and WHO after a minimum of 15 governments accepted its terms and conditions. The main role of ICGFI was to advise and inform governments of the role of food irradiation. Initially, 19 governments were members and it later expanded to over 30 governments which agreed to contribute either in cash or in kind to support activities of ICGFI. The FAO/IAEA through its former Food Preservation Section provided Secretariat services to the ICGFI.

With the full participation of WHO, FAO and IAEA, interest in ICGFI activities expanded quickly to cover scientific, regulatory, economic, public information, and consumer aspects. While many significant achievements were made through ICGFI, this paper will limit its scope to phytosanitary irradiation.

ICGFI convened a number of Task Forces of Experts (TFE) to address various issues starting in 1986. The first TFE was on phytosanitary irradiation in February 1986. It was attended by experts in several disciplines including entomology, genetics, plant protection, plant physiology, and fruit irradiation from several countries.

The TFE was requested to consider making definitive recommendations toward the acceptance of irradiation as a phytosanitary treatment by plant protection organizations as well as commercial application. Analysis of the literature indicated that results varied between 75 and 250 Gy among fruit fly species for the minimum dose to prevent adult emergence from irradiated eggs and larvae in fruit. However, the TFE was requested to consider possible generic radiation doses to ensure quarantine security against fruit fly and other insects of quarantine importance and concluded that 150 Gy would suffice to meet phytosanitary requirements by preventing emergence of adults of tephritid fruit fly species capable of flight. Any adult which might emerge at this dose would be reproductively sterile and unable to fly; thus, would not be detected by trapping systems. In certain situations where research data clearly demonstrate that a lower dose would provide phytosanitary security, such as in the case of Queensland fruit fly, *Bactrocera tryoni*, at 75 Gy, a lower minimum dose could be prescribed. With regard to other species of quarantine significance, the TFE agreed that 300 Gy would render them reproductively sterile.

It was recognized that under commercial irradiation treatment the absorbed dose uniformity ratio in a commercial container could vary up to 3 depending on the equipment and configuration. The generic doses mentioned above (150 and 300 Gy) would allow most fruits and vegetables to be treated with phytosanitary irradiation without causing significant injury.

The generic radiation doses for phytosanitation as recommended by the TFE in 1986 represent the first time generic doses were recommended and follow the pattern of food irradiation application by categories, not specific food items. The TFE recommended that the FAO/IAEA initiate a research program to collect additional data on as many types of fruits and vegetables and as many species of insects in as many countries to verify its recommendation. The ICGFI published a series of documents on phytosanitary irradiation that are still available in print and sometimes on line: http://zhangjicai.blog.sohu.com/entry/.

1. Code of good irradiation practice for insect disinfestation of fresh fruits (as a quarantine treatment). ICGFI Document No. 7, Vienna (1991).
2. Irradiation as a quarantine treatment of fresh fruits and vegetables. ICGFI Document No. 13, Vienna (1991).
3. Irradiation as a quarantine treatment of fresh fruits and vegetables. ICGFI Document No. 17, Vienna (1994).

The results of research were evaluated by ICGFI panels in 1991 and 1994. In general, the results reaffirmed the earlier conclusions of the 1986 TFE; i.e., a minimum absorbed dose of 150 Gy was sufficient to control emergence of all species of fruit fly studied. Some variations were observed with regard to a minimum dose to ensure quarantine security against insect pests of other species, especially those of Lepidoptera species. Such results as well as others (Hallman, 2012) were considered by the USDA prior to approving a minimum dose of 400 Gy against all insect pests other than pupae and adults of Lepidoptera (moths and butterflies).

The ICGFI panel in 1994 also considered regulatory procedures to implement phytosanitary irradiation in many countries. Such consideration was made in light of the impending establishment of the World Trade Organization (WTO) following the successful Uruguay Round of Trade Negotiation in 1994. Among the set of international agreements concluded under the Uruguay Round, an Agreement on the Application of Sanitary and Phytosanitary Measures (SPS) was of particular relevance to international trade in food and agricultural commodities. The SPS Agreement recognizes international standards, guidelines, and recommendations of the following organizations to govern trade in such commodities:

1. Codex Alimentarius Commission - for food safety and quality.
2. International Plant Protection Convention - for phytosanitary measures.
3. Organization of International Epizootics (now World Organization for Animal Health) - for animal health and diseases.

Governments which are members of the WTO must abide by all agreements establishing it. Basically, such governments cannot deny entry of commodities produced and processed according to international standards, guidelines, and recommendations of these three standard setting organizations unless it has scientific data to demonstrate to the contrary. There are steps and procedures for governments to challenge/settle disputes to ensure compliance with the agreements of WTO, and results of the dispute settlement process are binding.

### 3.3. Role of the United States Department of Agriculture

As the principle importer of fresh commodities irradiated for phytosanitary purposes, the USA has researched and developed phytosanitary irradiation extensively through some universities and states (especially Hawaii) but mainly through the USDA, APHIS, and Agricultural Research Service (ARS). Three years after the FDA (1986) approved irradiation of fruits and vegetables APHIS approved a treatment of 150 Gy for papaya from Hawaii. That treatment was never used and papayas continued to be disinfested with new heat treatments. However, in 1992 one of the heat treatments was rescinded because it was determined to not be sufficiently efficacious, and concerns with the quality of papayas treated with the heated air treatments led to renewed interest in phytosanitary irradiation as a solution.

In 1994 a phytosanitary irradiation workshop organized by the USDA (1994) aimed to jump start phytosanitary irradiation and see it commercially used. A review of the literature presented at that workshop (Hallman, 1994) pointed out that research done in Hawaii did not support a dose near 150 Gy for the fruit fly species found there. Subsequently doses were set at 210–250 Gy for fruit fly species occurring in Hawaii.

Subsequently APHIS was at the forefront in promoting phytosanitary irradiation and developing the necessary regulations to allow for its commercial application (Follett and Griffin, 2006; Hallman, 2012). In recent years APHIS has increased its research capacity in phytosanitary irradiation (Bailey, 2015) while it has been diminished in ARS. The efforts of USDA and collaborators in developing the regulatory framework for phytosanitary irradiation have largely enabled the USA to be the market destination of approximately 95% of all products irradiated for phytosanitary purposes in the world.

### 3.4. Role of Food Standards Australia New Zealand

The progressive stance for phytosanitary irradiation in Australia and New Zealand is exemplified by the first international use of the technology in 2004 and the liberal establishment of wide-ranging and relatively low generic doses for quarantine pests. These accomplishments are due to the work of Food Standards Australia New Zealand (FSANZ) and allied agencies, such as the Department of Agriculture Biosecurity Plant Division. As a result Australia has shipped irradiated fruit to five countries, more than any other supplier. Current issues under discussion are simplifying labeling requirements and approving the irradiation of fresh fruits and vegetables as a group instead of one by one (Lynch and Nalder, 2015).

### 3.5. Role of International Plant Protection Convention

Following the establishment of WTO and the developments made in this subject, the ICGFI Secretariat made a request to the IPPC at its Session held in Rome in 1998 to consider developing an international standard on radiation disinfestation of food and agricultural commodities to meet quarantine regulations. The IPPC agreed to include this topic in a future session and started elaborating its procedures in 2000. In 2003, the IPPC adopted the International Standard for Phytosanitary Measures (ISPM) No. 18 titled; Guidelines for the use of irradiation as a phytosanitary measure (IPPC, 2003). An explanatory document provides additional details of that standard (Hallman, 2006). That standard is

**Table 2**
Phytosanitary treatments (PT) based on ionizing radiation approved by the International Plant Protection Convention.

| PT No. | Pests covered | Dose (Gy) |
|---|---|---|
| 1 | *Anastrepha ludens* (Mexican fruit fly) | 70 |
| 2 | *Anastrepha obliqua* (West Indian fruit fly) | 70 |
| 3 | *Anastrepha serpentine* (serpentine fruit fly) | 100 |
| 4 | *Bactrocera jarvisi* (Jarvis' fruit fly) | 75 |
| 5 | *Bactrocera tryoni* (Queensland fruit fly) | 75 |
| 6 | *Cydia pomonella* (codling moth) | 200 |
| 7 | Tephritidae (fruit flies) | 150 |
| 8 | *Rhagoletis pomonella* (apple maggot) | 50 |
| 9 | *Conotrachelus nenuphar* (plum curculio) | 92 |
| 10 | *Grapholita molesta* (oriental fruit moth)[a] | 232 |
| 11 | *Grapholita molesta* (oriental fruit moth)[a] | 232 |
| 12 | *Cylas formicarius elegantulus* (sweet potato weevil) | 165 |
| 13 | *Euscepes postfasciatus* (West Indian sweet potato weevil) | 150 |
| 14 | *Ceratitis capitata* (Mediterranean fruit fly) | 100 |
| 19 | *Dysmicoccus neobrevipes, Planococcus lilacinus* and *P. minor* (mealybugs) | 231 |
| 20 | *Ostrinia nubilalis* (European corn borer) | 289, 343[b] |

[a] The two *Grapholita molesta* treatments have different end points and are for irradiation in ambient and low oxygen atmospheres.
[b] The two doses for *Ostrinia nubilalis* have different end points.

currently being revised.

In 2004 the IPPC issued a call for treatment proposals and a number of irradiation ones were proposed along with some other treatments. Only the irradiation ones became approved phytosanitary treatments at that time, testifying to the organization of efforts into phytosanitary irradiation (Hallman et al., 2010). Currently 16 of a total of 21 treatments approved by the IPPC are phytosanitary irradiation treatments (Table 2).

## 4. Recent and future uses of phytosanitary irradiation

Phytosanitary irradiation seems currently in an exponential growth reminiscent of the "early adopters" phase of the classic technology adoption curve (Fig. 1). After growing modestly for a dozen years after continuous commercial use began in 1995, volume irradiated has been growing at a markedly steeper rate of $>2500$ t/yr since 2007. When measured as the number of countries exporting or importing or the number of different commodities treated, marked growth in recent years is also obvious. Countries that have imported fresh commodities disinfested via irradiation are Australia, Indonesia, Malaysia, Mexico, New Zealand, the United States, and Viet Nam. Events indicate that the rate may increase even greater in coming years. China has completed a large electron beam facility along the southern border in Pinxiang designed for phytosanitary import purposes that is capable of irradiating 100,000 t of fruit per year, which is four times the

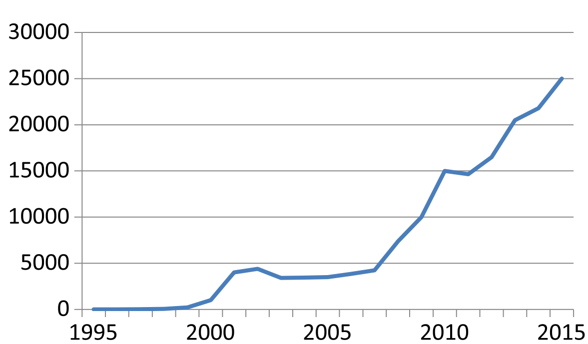


**Fig. 1.** Tons of produce (left margin) irradiated per year for phytosanitation worldwide since continuous commercial use began in 1995.

current total world output using irradiation. Recent reviews (Hallman and Blackburn, 2016; Hallman et al., 2016) discuss the current status of phytosanitary irradiation in the world and we do not repeat that information here.

There are a number of commodities for which irradiation is the sole phytosanitary treatment available. For example, it is the only treatment approved to export mangoes from Australia, India, Pakistan, the Philippines (except Guaimaras Island can use vapor heat), and Thailand to the USA. Sixteen commodities in Hawaii can only be shipped to the mainland USA via irradiation. The commodity that comprises over half of all commodities irradiated for phytosanitary purposes, guava from Mexico, can only be exported to the USA with irradiation. Several commodities shipped from Australia to New Zealand are only possible with irradiation. The fact that many commodities can only be exported via irradiation is due to two reasons: 1) More fresh commodities (especially fruits) tolerate irradiation better than other commercial alternative treatments (heat, cold, fumigation). 2) Phytosanitary irradiation has been approved in a largely generic, broadly applicable manner making it more readily available to overcome quarantines than other treatments which are applied in a much more limited manner.

### 4.1. Phytosanitary irradiation developments by country

Australia is broadening its export markets of irradiated fruits and has recently begun exporting to Indonesia, Malaysia, the USA, and Viet Nam as well as expanding markets in New Zealand.

Mexico is the largest exporter of irradiated produce, all of it going to the USA. Currently there are two commercial facilities in Mexico, and two facilities in the USA have also been used to irradiate on arrival. Two new facilities are being planned in Mexico; one may be an excessed fruit fly sterile insect technique irradiation facility with robust capacity that may be redirected to phytosanitary irradiation within a year or so. A total of 270,000 t of mangoes are exported to the USA every year using a 46 °C water treatment and only 700 t are irradiated although irradiation provides a better quality mango than those treated by immersion in heated water. The transfer of mangoes from heated water immersion to irradiation alone would increase by an order of magnitude commercial use of phytosanitary irradiation. There is not currently the capacity to do this in the exporting and importing countries combined, but it can be developed if the markets seem assured.

A second phytosanitary irradiation facility has been established in Hawaii in 2013 and greatly increased output of the state to the rest of the USA to approximately 7.3 thousand tons (Eustice, 2016).

Although India was the first country to export irradiated fruit to the USA in 2007 it has only treated relatively small amounts of mangoes since then (265 t in 2014). However, it is currently working to get two more irradiation facilities certified for export to the USA.

### 4.2. Phytosanitary irradiation and the "organic" industry

Hallman (2011) argues that although the "organic" food industry (which is growing by approximately the same percentage as phytosanitary irradiation) generally does not accept irradiation it could over time as the process is demonstrated to them to be safe in providing high quality, unaltered products. That is because although much of the organic industry values good science, it might only implement it after personal experience confirms that it is not a technology that could have unintended negative consequences. The organic industry represents a conservative philosophy. For example, a review of fresh produce irradiation by the Organic Center concludes that irradiation could be a useful tool for managing some pathogens in fresh produce but that more research on safety and food quality is needed (Groth, 2007). Given the amount of research that has been done demonstrating the efficacy and safety of food irradiation, more research is probably not needed. What are needed are more commercial scale trials where retailers and the public can experience the benefits and become familiar with the process.

### 4.3. Potential new phytosanitary irradiation treatments

Hallman and Blackburn (2016) list seven generic irradiation treatments that are adequately supported by research. These are 300 Gy for all insects except pupal and adult Lepidoptera, 400 Gy for pupal Lepidoptera, 250 Gy for mealybugs, 150 Gy for weevils, 70 Gy for the fruit fly genus *Anastrepha*, 250 Gy for all eggs and larvae of Lepidoptera, and 250 Gy for the Lepidoptera family Tortricidae, if that dose for the entire Order Lepidoptera is not adopted. These are all key groups of regulated pests and their adoption would help to advance the use of phytosanitary irradiation.

Besides these groups possible generic irradiation doses are supported with less data for several other groups: whiteflies 100 Gy; agromyzid leafminers 200 Gy; scale insects 250 Gy; thrips 250 Gy; spider mites 400 Gy, and other mites 500 Gy (Hallman et al., 2016). Once sufficient research with regulated insects and mites is done final broad generic doses could end up being 150 Gy for several groups including fruit flies, aphids, whiteflies, and psyllids, 250 Gy for all insects except pupal and adult Lepidoptera, and 350–400 Gy for essentially all arthropods. That would be a culminating achievement for phytosanitary irradiation and permit widespread application of the technology.

## 5. Factors possibly affecting efficacy of phytosanitary irradiation

Phytosanitary irradiation was first applied assuming that dose was the only factor that needed to be controlled. But Hallman (2000) reviewed the irradiation literature and noted that several factors are reported to affect efficacy and these should be further studied keeping in mind that, unlike all other commercial phytosanitary treatments, irradiation has no independent measure of efficacy; i.e., if the treatment was not efficacious because of one of these factors that fact would probably not become known.

The factor most likely to be problematic is low oxygen conditions upon irradiation, which could be purposely done in controlled atmosphere storage, such as is done with apples, or by placement of commodities in bags restrictive of gas flow when the commodities are still warm enough to be respiring. Plant protection organizations have put restrictions on irradiation when products are in low oxygen atmospheres. Some research has been done on the effect of low oxygen on efficacy and it is expected that modifications in the policy of irradiating commodities in low oxygen atmospheres will result (López-Martínez et al., 2016).

## 6. Conclusions

Supported by good research practices, international collaboration, and regulatory advances over the past few decades, irradiation has emerged as a very viable phytosanitary treatment. However, while the volume of fruits treated by irradiation has increased significantly in recent years, it remains a small fraction of those treated by other phytosanitary measures. Continued efforts by national and international organizations to inform the fruit and vegetable industry of the comparative advantages of irradiation, often unique in meeting trade regulations in a number of fruits and vegetables, are warranted to enable it to reach its full potential. Further effort toward using irradiation for non-food commodities such as cut flowers and wood could lead to still broader application.

Based on $>20$ years of continuous experience with the commercial application of irradiation and the accumulation of further research on doses required for phytosanitary security against a broad array of regulated pests, broadening of the generic concept coupled with reduction in doses to more reasonable levels similar to those that have been applied in Australia and New Zealand for $>10$ yr is warranted. The apparent exemptions to these doses can be adequately explained by other circumstances (Hallman et al., 2010). The ICGFI recommendations of 30 years ago on a generic dose of 300 Gy for all insects are well justified with the prudent exemption of pupae and adult Lepidoptera and mites, which may require closer to 400 Gy (Hallman et al., 2013). As already accepted by New Zealand, it may be possible to reduce this dose even further to 250 Gy. Doses for mites lack large-scale confirmatory testing, but should also be similar to what New Zealand currently uses: 400 Gy for Tetranychidae and 500 Gy for all other mites (DABPD, 2014).

Although the restrictions on use of irradiation for commodities under low oxygen conditions should be held for most insects until further research clarifies the issue, it does not seem that they are a problem for tephritid fruit flies (Hallman, 2004). Commercial implementation of irradiation could be aided by removal of the 1 kGy absorbed dose limit set by the US FDA in 1986 as abundant studies have shown no need for this limit (WHO, 1981, 1999), and the limit should depend on tolerance of each commodity to radiation, not an arbitrary limit.

## Acknowledgments

Robert Griffin, USDA-APHIS, Raleigh, NC, USA, who was instrumental in development of the regulatory framework for phytosanitary irradiation, is thanked for a detailed review of an earlier draft. Lyle Wong, formerly of the Hawaii Department of Agriculture and currently with Pa'ina Hawaii, and who was primarily responsible for the first sustained commercial development of phytosanitary irradiation, which was in Hawaii, is also thanked for a helpful review of an earlier draft. Russell Stein of Gray*Star, Inc., Mt. Arlington, New Jersey USA, is thanked for providing information on commodities that may only be treated by irradiation for export.

## References

Bailey, W.B., 2015. Phytosanitary Irradiation Research Needs. 〈https://www.iaea.org/technicalcooperation/documents/Presentations/RLA5066/Woodward_BAILEY.pdf〉.

DABPD [Department of Agriculture Biosecurity Plant Division], 2014. Australia-New Zealand Bilateral Quarantine Arrangement. Canberra.

Eustice, R.F., 2016. Irradiation: The Pathway for PA'ina Hawaii to Open Markets for Hawaiian produce. 〈http://foodirradiation.org/PDF/Painahawaii.pdf〉.

Follett, P.A., 2006. 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., Griffin, R.L., 2006. Irradiation as a phytosanitary treatment for fresh horticultural commodities: research and regulation. In: Sommers, C.H., Fan, X. (Eds.), Food Irradiation Research and Technology. Blackwell Publishing, Ames, Iowa, pp. 143–168.

Groth III, E.G., 2007. Food Irradiation for Fresh Produce. Critical Issue Report, The Organic Center. 〈https://organic-center.org/reportfiles/IrradiationReport.pdf〉.

Hallman, G.J., 1994. Effective irradiation doses for quarantine of fruit flies and other arthropods. In: Proceedings of USDA, Workshop on Irradiation as a Quarantine Treatment for Fruits and Vegetables. February 1–3, 1994, pp. 68–84.

Hallman, G.J., 1999. Ionizing radiation quarantine treatments against tephritid fruit

flies. Postharvest Biol. Technol. 16, 93–106.
Hallman, G.J., 2000. Expanding radiation quarantine treatments beyond fruit flies. Agric. For. Entomol. 2, 85–95.
Hallman, G.J., 2001. Irradiation as a quarantine treatment. In: Molins, R.A. (Ed.), Food Irradiation Principles and Applications. John Wiley & Sons, New York, pp. 113–130.
Hallman, G.J., 2004. Irradiation disinfestation of apple maggot (Diptera: Tephritidae) in hypoxic and low-temperature storage. J. Econ. Entomol. 97, 1245–1248.
Hallman, G.J., 2006. Explanatory Document on International Standard for Phytosanitary Measures No. 18 (Guidelines for the use of irradiation as a phytosanitary treatment). 〈https://www.ippc.int/static/media/files/publications/en/2013/06/04/1143537627526_ispm18_in_format_201304232112en.pdf〉.
Hallman, G.J., 2011. Phytosanitary applications of irradiation. Compr. Rev. Food Sci. Food Saf. 10, 143–151.
Hallman, G.J., 2012. Generic phytosanitary irradiation treatments. Radiat. Phys. Chem. 81, 861–866.
Hallman, G.J., 2016. Process control in phytosanitary irradiation of fresh fruits and vegetables as a model for other phytosanitary treatment processes. Food Control (in press).
Hallman, G.J., Blackburn, C.M., 2016. Phytosanitary irradiation. Foods 5, 8.
Hallman, G.J., Hénon, Y.M., Parker, A.G., Blackburn, C.M., 2016. Phytosanitary irradiation. Fla. Entomol. 99 (in press).
Hallman, G.J., Levang-Brilz, N.M., Zettler, J.L., Winborne, I.C., 2010. Factors affecting ionizing radiation phytosanitary treatments, and implications for research and generic treatments. J. Econ. Entomol. 103, 1950–1963.
Hallman, G.J., Parker, A.G., Blackburn, C.M., 2013b. The case for a generic phytosanitary irradiation dose of 400 Gy for Lepidoptera that infest shipped commodities as pupae. J. Econ. Entomol. 106, 525–532.
Heather, N.W., Hallman, G.J., 2008. Pest Management and Phytosanitary Trade Barriers. CABI Press, Wallingford, Oxfordshire, England.
IAEA (International Atomic Energy Agency), 2015. Tech. Rep. Ser. No. 481, Manual of Good Practice in Food Irradiation. 〈http://www-pub.iaea.org/MTCD/Publications/PDF/trs481web-98290059.pdf〉.
IPPC (International Plant Protection Convention). 2003. ISPM No. 18, Guidelines for the use of irradiation as a phytosanitary measure. 〈https://www.ippc.int/en/publications/604/〉.
López-Martínez, G., Meagher, R.L., Jeffers, L.A., Bailey, W.D., Hahn, D.A., 2016. Low oxygen atmosphere enhances post-irradiation survival of *Trichoplusia ni* (Lepidoptera: Noctuidae). Fla. Entomol. 99 (in press).
Lynch, M., Nalder, K., 2015. Australia export programmes for irradiated fresh produce to New Zealand. Stewart Postharvest Rev. 3, 8.
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. Radiat. Phys. Chem. 63, 397–401.
USDA (United States Department of Agriculture), 1994. Proceedings of Workshop on Irradiation as a Quarantine Treatment for Fruits and vegetables. February 1–3, 1994.
WHO (World Health Organization),1981. Wholesomeness of Irradiated Food. Geneva, Technical Report Series No. 659.
WHO (World Health Organization), 1999. High-dose Irradiation: Wholesomeness of Food Irradiated with Doses Above 10 kGy. Geneva, Technical Report Series No. 890.