AM19002 Building Capacity in Irradiation

Existing international standards for accepted phytosanitary irradiation dose by Australian insect pests: an overview

South Australian Research and Development Institute (SARDI)

January 2022

Author(s):

Dr Humayra Akter, Senior Research Officer (Fruit fly Entomologist), South Australian Research and Development Institute (SARDI), PIRSA, South Australia

Nancy Cunningham, Senior Research officer, South Australian Research and Development Institute (SARDI), PIRSA, South Australia

Dr Polychronis Rempoulakis, Leader Plant Biosecurity Entomology, NSW Department of Primary Industries, NSW

Martin Bluml, Portfolio Manager - Research and Innovation, Agriculture Victoria Research, Department of Jobs, Precincts and Regions, Victoria

Project RDC Number: AM19002 Building capacity in irradiation

Contents

EXECUTIVE SUMMARY

Phytosanitary irradiation is used to prevent the introduction or spread of unwanted plant pests and diseases found in horticulture commodities, both in a domestic and international trade setting. The technology is considered safe and environmentally friendly, being chemical free, ozone positive, carbon neutral and zero waste.

For domestic and international trade purposes, protocols must be agreed between governments on how plant pests of quarantine concern will be treated. A framework of rules for trade in irradiated fresh produce was not available until 2003, with the adoption of the International Standard for Phytosanitary Measure (ISPM) 18 by the International Plant Protection Commission (IPPC). In following years, ISPM 28 and its annexes specified minimum absorbed dose for many pests of quarantine concern. Australia has its own domestic internal certification process (ICA-55) for irradiated products and closely follows operational protocols outlined in ISPM 18, FSANZ Standard 1.5.3, PSW2-02 guidelines and the Plant Biosecurity Act of 2010.

Australia started exporting irradiated horticulture commodities to New Zealand in 2004. Since then, exports of irradiated products have continued to grow as phytosanitary irradiation becomes more widely accepted for the treatment of plant pests by our international trading partners. Domestically, Food Standards Australia New Zealand (FSANZ) now allow irradiation of all fresh fruits and vegetables using an irradiation dose of 150 to 1000 Gy for all insect pests (ICA-55, 2020).

To facilitate further domestic and international trade in Australian irradiated horticulture products, a literature review has been conducted to:

- Identify information gaps for Australian pests of quarantine concern
- Identify where differences may exist between the minimum absorbed dose accepted by Australia and our international trading partners.

In Australia, a minimum absorbed dose of 400 Gy can be used to treat all insect pests of quarantine concern. A lower minimum absorbed dose of 150 Gy is used for many fruit fly species that are important for domestic and international trade. For most insect groups, sufficient research has been undertaken to confirm a minimum dose whereby the insect dies, does not continue to develop or becomes sterile. However, for a limited number of priority pests highlighted by the horticulture sector, there were gaps found in the literature. Steritech, an Australian company operating two commercial irradiation facilities, also identified the same pests of concern. These pests include vineyard snails, Serpentine leaf miners and Fuller's rose weevil. Studies to establish the minimum absorbed dose and efficacy data for vineyard snails, Serpentine leaf miners and Fuller's rose weevil are therefore recommended. There is scope within project AM19002 to begin such a study for one of the above pests.

Vineyard snail or common white snail (*Cernuella virgata*)(Da Costa) is an invasive species and an agricultural pest in many parts of Southern Australia. Missed timing for treatment sprays increases the probability that snail populations will be detected at threshold levels in high-value commodities such as table grapes. Snails and slugs are cold resistant, thus relatively hard to treat with cold storage. However, irradiation has the potential to treat all snail and slug pests.

Serpentine leaf miner species (*Liriomyza huidobrensis* and *Liriomyza trifolii*) were intercepted in Western Australia and New South Wales in 2021. These interceptions raised biosecurity concerns for Australia's vegetable industry. The current contingency plan for interception and possible eradication is via a destruction strategy (primarily foliar sprays). Phytosanitary irradiation will however provide additional security for market access where eradication is not possible and market access is threatened.

Fuller's rose weevil (*Synonychus cervinus*) (FRW) is an insect pest that has had considerable impact on market access for the Australian citrus industry. The pest is notoriously hard to control both in field and during the postharvest phase of fruit treatment. Limited overseas research has been undertaken for FRW, so further research is needed to establish the minimum dose and efficacy data needed for irradiation to become a widely accepted phytosanitary treatment.

In addition to the gaps identified for the pests above, there may be merit in research to refine the minimum dose for other priority pests and commodities. This can reduce the cost of treatment and potential impacts on quality, such is the case for lychee and acari mites.

INTRODUCTION

For domestic and international trade purposes, protocols must be agreed between governments on how pests of quarantine concern will be treated. There are a range of phytosanitary treatment options that can be employed to prevent the introduction or spread of unwanted pests. They protect horticultural produce and help the horticultural sector manage plant biosecurity risks, safeguarding both overseas and domestic trade, and ensuring imports are pest free.

Traditional phytosanitary measures include heat treatments (with hot air or hot water at 43–48°C), cold disinfestation (0–3°C), chemical dip treatment (dimethoate) and chemical fumigation (with ethylene dibromide and methyl bromide). Phytosanitary measures need to be carried out in a consistent and effective manner and reach the required efficacy for every application. This ensures Australian treatment standards align with the principals and obligations of sanitary and phytosanitary (SPS) agreement governed by the World Trade Organisation (WTO). The Commonwealth Department of Agriculture, Water and Environment (DAWE) plays an important role in maintaining and improving technical market access, working closely with international and other national jurisdictions to resolve SPS issues and meet Australia's obligations under the WTO SPS agreement.

Concern for health and environmental issues is on the increase worldwide. How farmers grow food and treat the land on which they grow is of increasing importance to consumers. Several of Australia's trade partners have called into question the use of certain phytosanitary measures and the use of agrichemicals to control pests and diseases of quarantine significance. For example, methyl bromide is known to deplete ozone once released into the atmosphere and is toxic to humans and fauna if not used correctly. In response to this, several of Australia's export markets have established strict guidelines on what phytosanitary treatments can be imposed and accepted level of chemical residue. This has led Australia's many horticultural industries to re-examine the role and use of irradiation as a means of effective quarantine pest control.

Regulatory restrictions and specific pest and commodity requirements imposed by importing countries can inhibit trade, therefore traditional phytosanitary postharvest treatments need to take this into consideration. For instance, New Zealand does not accept heat treatments and fumigation as a disinfestation method for Australian pests. For Australia to meet New Zealand quarantine requirements, alternative phytosanitary treatments are needed. Movement of fresh produce between Australian states is also strongly regulated, and like New Zealand, heat treatments and fumigation are not approved for all horticultural products.

Heat treatment adversely affects stone fruits, pome fruits and avocados. Cold treatments can also affect fruit quality and commonly require a defined period at set temperatures (1-2°C). For some invasive species of fruit fly, the required period of cold storage may be as long as 22 days (Hallman, 2011). In practice, cold treatment for some horticultural commodities (e.g., apple, pear, citrus etc.) is cost effective and achievable for both domestic and export markets, but for more perishable commodities (e.g., apricots, peaches, nectarines, leafy vegetables), extending the period between harvest and retail will usually result in reduced quality, shelf life and price.

Phytosanitary irradiation offers a viable alternative for eliminating these concerns. It is fast and residue free, with the added advantage that it can be applied to pre-packaged fresh produce (Corcoran, 2001). It is effective for a wide range of arthropod pests (Loaharanu & Mainuddin, 1991), is particularly effective on internal pests such as fruit flies, and insects have not developed resistance to its application (Jarrett, 1982). Consuming irradiated food, including fresh fruit and vegetables, has shown to be safe for human health and the environment (WHO, 1981, 1999). Irradiation is increasingly being seen as an important strategy for improving food hygiene (Loaharanu & Mainuddin, 1991).

Irradiation as a horticultural market access treatment can ensure that no viable insect pest is transported to importing countries (Golding and Singh 2020). Phytosanitary irradiation is considered acceptable if the following conditions are met:

- The pest dies (DAWE, 2021, Hallman, 1999, Follett et al., 2007)
- The pest is prevented from successful development (no adult emergence) (DAWE, 2021, Hallman, 2006)
- The pest cannot reproduce (sterility), or the treatment inactivates the pest completely (DAWE, 2021, Golding & Singh, 2020).

Phytosanitary measures are subject to internationally recognized protocols (FAO IPPC, 2003) to which Australia is a signatory. A framework of rules for the conduct of trade in irradiated fresh produce was not available until 2003, with the adoption of International Standards for Phytosanitary Measures (ISPM) 18 by the International Plant Protection Commission (IPPC). In following years, ISPM 28 and its annexes specified minimum absorbed dose for many pests of quarantine concern. Domestically, Food Standards Australia New Zealand (FSANZ) now allow irradiation for all fresh fruits and vegetables at doses of 150 to 1000Gy for all insect pests with domestic certification of irradiated product administered through ICA-55 protocols.

Irradiation as a phytosanitary treatment, like fumigation with methyl bromide, has a unique advantage in that it works as a broad-spectrum treatment for almost all important regulated arthropod pests (Follett & Neven, 2006). Phytosanitary irradiation protocols are designed to prevent the reproduction of harmful pests through death, prevention of adult emergence, and adult or F1 generation sterility (Follett, 2009). It also aims to avoid adverse effects on the sensory qualities of most fresh produce (Follett & Neven, 2020). Phytosanitary irradiation measures for imported product as well as domestic and exported products align with Australian treatment application standards (DAWR, 2018).

Australia started exporting irradiated horticulture commodities to New Zealand in 2004. Since then, exports of irradiated products have continued to grow as phytosanitary irradiation becomes more widely accepted for the treatment of pests of quarantine concern by international trading partners. There is significant opportunity to expand the use of phytosanitary irradiation to treat specific pests for priority markets and commodities (Appendix A, Table 1).

This literature review was conducted as part of project AM19002 - Building Capacity in Irradiation, the objectives of this project are to:

- Build a body of knowledge concerning phytosanitary irradiation for the Australian horticulture sector, government, and our international trading partners
- Fill gaps in our knowledge regarding the effective use of phytosanitary irradiation
- Identify future research and development activities that will increase the use and acceptance of phytosanitary irradiation domestically and internationally.

METHOD

To prepare this review, minimum and recommended dose for Australian pests of quarantine significance were collected for Australia and key international trading partners. The steps that were followed are given below:

- Topic identification and exchange of knowledge: meeting with project collaborators, meeting with stakeholders from industry, government, and research. Discussions with international experts.
- Outlining review structure: Based on the discussion outlines of the review were identified that covers the topic of this project component.
- Searching for relevant information: Published peer reviewed literatures were searched by key words in Google Scholars, PubMed, journals website. In addition, databases like the International Database on Insect Disinfestation and Sterilization (IDIDAS) that includes data on dose required for the phytosanitary irradiation (disinfestation) and dose required to induce sterility (sterilisation) in target pests were searched. Grey literature such as industry reports, government reports/ websites, different international standards published by IPPC-FAO were also consulted. Apart from the printed and online documents, personal communication with expert from USDA and Steritech also supported to acquire information on current phytosanitary irradiation status here in Australia and abroad.
- Assessing and synthesizing information: All information gathered from above mentioned sources were studied for getting knowledge and ideas about the international and national status of previous and current phytosanitary irradiation dose application. Collected information were also shared and assessed by discussion with project collaborators to include the most relevant information that align with the review outline.

INTERNATIONAL STANDARDS FOR ACCEPTANCE OF IRRADIATION DOSE FOR PHYTOSANITATION

The Codex Alimentarius Commission (the Codex General Standard for Irradiated Foods, CXS 106- 1983, Rev.1-2003) and the International Plant Protection Convention (IPPC) international standards for the use of irradiation as a phytosanitary measure (IPPC, 2003) provide an international framework and guidelines for plant protection. These standards are recognized by Food and Agriculture Organization (FAO), World Health Organisation (WHO), the International Consultative Group on Food Irradiation (ICGFI), and World Trade Organisation (WTO). These standards were prepared and endorsed to achieve international harmonization of phytosanitary measures, with the aim to facilitate global trade and avoid the use of unjustifiable phytosanitary measures as barriers to trade. The IPPC sets internationally recognized protocols and standards for food irradiation including the International Standard for Phytosanitary Measures 18 (ISPM 18, 2003) – Guidelines for the use of irradiation as a phytosanitary measure (IPPC, 2003) and ISPM 28 (2007) – Phytosanitary treatments for regulated pests, with Part 7 being specific to fruit flies.

In conjunction with the international standards, building and safety requirements are regulated in Australia by the Australian Radiation Protection and Nuclear Safety Authority (ARPANSA), and Food Standards Australia and New Zealand (FSANZ) approves the use of irradiation on food. In developing food regulatory measures, FSANZ plays a vital role to promote consistency between domestic and international food standards in Australia and New Zealand.

A maximum absorbed dose of 1000 Gy to irradiate food was considered as safe by FAO/IAEA/WHO expert committee in 1980 if it fulfils proper technological requirements and was approved in 1983 (Barkai-Golan & Follett, 2017). A maximum absorbed dose of 1000 Gy has also been approved by the FDA (FDA, 1986) and FSANZ (FSANZ, 2021). Thus, keeping irradiation dose within this limit is a prerequisite to facilitate international trade of irradiated horticultural products.

A minimum absorbed dose of 400 Gy is sufficient to satisfy quarantine regulations without adversely affecting the physicochemical and nutritional value of most fruits and vegetables (IAEA, 1986). In 2006, the USDA-APHIS recommended that a minimum absorbed dose of 400 Gy be used to control broad taxonomic groups of insect pests without affecting the quality of a wide range of commodities (Follett & Armstrong, 2004, Follett & Neven, 2006, IAEA, 2004), however this is yet to be endorsed through an ISPM at international level. Nevertheless, a minimum dose of 150 Gy is internationally recognized as an effective treatment for all tephritid fruit flies (USDA-APHIS, 2006, Follett et al., 2007,) and 400 Gy as a treatment for all pest insects in host fruits and vegetables (USDA-APHIS, 2006). A notable exception is adult lepidoptera that pupate internally (USDA-APHIS 2006, Follett et al 2007).

DOMESTIC STANDARDS FOR ACCEPTANCE OF PHYTOSANITARY IRRADIATION

On May 2021, FSANZ announced a new domestic food regulatory measure that permits the use of irradiation as a phytosanitary treatment for all fresh fruit and vegetables. Although all types of fruits and vegetables are currently approved for irradiation in Australia, only 0.3-8% of total fruit and vegetables consumed in Australia and New Zealand (NZ) are irradiated (FSANZ, 2021). Nevertheless, demand for irradiation services is increasing in Australia as more trading partners accept irradiation as a phytosanitary treatment. Regarded as simple and highly reliable, phytosanitary irradiation is opening doors for Australian exporters in Asia. Both Vietnam and Thailand recognize irradiation as a phytosanitary treatment for Australian horticulture products.

According to FSANZ, irradiation must not be used as a substitute for good hygiene, manufacturing and agricultural practices and must be within 150 Gy to 1000 Gy (FSANZ, 2021). At present, Australia uses irradiation as a phytosanitary treatment for fresh commodities including mangoes, cherries, grapes, citrus, lychee, melons, and tomatoes with proven technical and commercial benefits. Commodities like berries, summer fruit, apples, pears, pomegranate, asparagus, and kiwi fruit are also irradiated before export, but in limited numbers due to higher perishability and/or temperature sensitivity. A list of exportable fresh commodities is attached in Appendix A.

The minimum absorbed dose is accepted for Australian domestic trade for the following insect pests/groups; 150 Gy for tephritid fruit flies; 300 Gy for mango seed weevil; and 400 Gy for all other insect pests excluding Lepidopterans that pupate internally (Benjamin Reilly, Steritech, personal communication).

However, 250 Gy has been applied successfully for control of arthropods on mango and papaya (Follette, 2009), and 350 Gy for all arthropods on lychee (Hallman, 2012) when exported from Australia to New Zealand.

PHYTOSANITARY IRRADIATION DOSE AND EFFICACY DATA FOR PESTS OF QUARANTINE CONCERN

To ensure the minimum absorbed dose is reached in a commercial irradiation facility, the actual absorbed dose is always higher than the minimum absorbed dose due to the relatively high dose uniformity ratio (2.5 or 3.1) (Follett & Weinert, 2012, Wall, 2015). A dose of 600 Gy to 1000 Gy is absorbed to ensure a minimum absorbed dose of 400 Gy is achieved (Wall, 2015, Follett & Weinert, 2012), while 300 Gy could be absorbed to ensure the minimum absorbed dose of 150 Gy is achieved (Hallman, 1999).

Although 400 Gy has been recommended to treat broad pest insect groups, many insects from the orders Diptera, Coleoptera, some Lepidopterans, as well as insects from sub-order Homoptera (aphids) do become sterile and stop further development at a lower dose (Hallman, 1998). In general, most insect, mite, and tick families require a sterilizing dose of <200 Gy which could serve as phytosanitary treatment (Bakri et al., 2005). USDA APHIS have already approved a reduction in the minimum absorbed dose accepted for specific pests such Queensland fruit fly 100 Gy, codling moth 200 Gy, oriental fruit moth 200 Gy, mango seed weevil 300 Gy (USDA-APHIS, 2008) (Appendix B).

The following case studies from Hawaii are provided as examples where research has led to a reduction in the minimum absorbed dose accepted by the USDA APHIS:

1. A dose of 400 Gy was accepted for white peach scale control in some papayas; but a dose of 600- 650 Gy was absorbed to ensure 400 Gy. Therefore, a large-scale study was conducted to test if a lower dose could give quarantine security. Results showed that 150 Gy would be effective for quarantine control of white peach scale (resulting in commercial doses up to 250 -300 Gy) was adequate for phytosanitary disinfestation (Follett, 2006b).
2. A dose of 400 Gy was accepted for Hawaii sweet potato (USDA-APHIS, 2004) until research later demonstrated that 150 Gy was also sufficient to give quarantine security against vine borer and sweet weevil (Follett, 2006a). Hawaii has been using 150 Gy for sweet potato exports to the continental U.S since this research was published.

These case studies indicate that the accepted minimum absorbed dose for a pest insect/group may be higher than is required for effective treatment. Further large-scale confirmatory tests (as outlined in ISPM 18) could be conducted to support the use of a lower minimum absorbed dose (Hallman, 1999). A review of the minimum absorbed dose used within Australia for priority insect pests/groups may be warranted where a reduction in treatment costs will benefit the Australian horticulture sector. Appendix B provides a comparison of the minimum absorbed dose identified through research and the dose accepted within the USA and Australia.

Tephritids-fruit flies

A dose 150 Gy is accepted for all Tephritid flies (USDA-APHIS, 2006, Follett et al., 2007), although at lower doses sterilisation of some species can ensure effective treatment. For instance, at 75 Gy no adult *B. tryoni* emerged from a total of 24700 third instars in orange and avocado (Rigney & Wills, 1985) and over one-half million third instar *B. tryoni* in apple, orange, avocado, mango, tomato, and cherry were irradiated with 75 Gy and none survived to the adult stage (Jessup et al., 1992), 138635 larvae were treated in mango from which no adult Qfly emerged at 74 to 101 Gy (Heather & Corcoran, 1992). Therefore, for Qfly 100 Gy is sufficient to inhibit development. Bustos et al. (1992) treated 100000 third instars of each of three species of *Anastrepha ludens*, *Anastrepha obliqua*, and *Anastrepha serpentina*, in mangoes with 100 Gy without any adults developing. Thus 100 Gy is considered effective as a phytosanitary treatment for these species.

Lepidopterans-moths and borers

After fruit flies, Lepidopterans, especially tortricid moths, are the most significant pests of economic and quarantine concern, especially species that significantly impact mangoes and summerfruit (Bloem et al., 1999, 2003). Lepidopterans are sterilised at a lower dose than 400 Gy. Tortricid moths can be controlled at doses between 120 and 200 Gy (IDIDAS, 2007). A dose of 200 Gy was shown to be sufficient to control codling moth, *Cydia pomonella* (L.) (Mansour, 2003); Citrus fruit borer *Ecdytolopha aurantiana* (Lima) (Arthur, 2004); oriental fruit moth, *Grapholita molesta* (Busck) (Hallman, 2004); and light brown apple moth, *Epiphyas postvittana* (Walker) (Dentener et al., 1990). Irradiation tests with litchi borer/moth *Cryptophlebia illepida* (Butler) indicated that 250 Gy prevented adult emergence from irradiated fourth and fifth instars, but 125 Gy was sufficient to cause sterility (Follett & Lower, 2000). Information on several other tortricid species is available from studies undertaken for sterile insect release programs (Bloem et al., 1999, 2003, IDIDAS, 2007, Suckling et al., 2007). These studies concur that 200 Gy is sufficient to sterilise females. Thus, a dose of 200 Gy could be effective as a minimum absorbed dose for tortricids. Nevertheless, large scale validation tests on several additional species in the same family is desirable before making a full recommendation (Follett, 2008).

Identifying a dose for tortricid moths below 400 Gy could reduce treatment time, thereby reducing cost of treatment and increasing the volume of product that can be treated at an irradiation facility (Follett & Neven, 2006). For a limited number of fresh products, a lower dose will help minimize or avoid the impact of irradiation treatment on product quality (Follett & Griffin, 2006).

Mites

Australia and New Zealand accept a minimum absorbed dose of 400 Gy for all mites including Tetranychidae (Acari mite family) (DABPD 2014). The minimum absorbed dose of 400 Gy is also required by Japan for Acari mite (Dohino et al., 1994). More specifically, the lychee erinose mite, *Aceria litchii* (Keifer) (Trombidiformes: Eriophyidae) is reported to require a dose of 400 Gy to treat (Arthur and Machi 2016).

Although the 400 Gy dose is not yet supported by large-scale confirmatory testing, it is high enough to be considered safe (Hallman et al., 2016). Hallman (2012) also suggested that a recommended dose for acari mites might be as low as 350 Gy. Other studies have shown that a sterilising dose for Tetranychidae is 300 Gy (Osouli et al., 2013, Nicholas et al., 2018, Arthur & Mineiro, 2009). Additional large-scale species specific confirmatory testing will likely be required to demonstrate that a lower dose is effective for mites.

Thrips

Thrips often result in a remedial fumigation in NZ, but studies in Japan showed that a generic treatment dose of 400 Gy (Dohino et al., 1996) could control the pests. Four species of thrips (*Frankliniella occidentalis*, *Frankliniella schultzei*, *Thrips tabaci* and *Thrips imaginis*) exposed to gamma irradiation at doses 200 Gy became sterile. This would be sufficient to control these species of thrips in fresh produce (Nicholas et al., 2018). A minimum absorbed dose of 250 Gy is recommended as a safety margin until large-scale confirmatory trials are conducted (Nicholas et al., 2018). However, the FAO continues to recommend 150-350 Gy for sterilising thrips (FAO, 2003).

GAPS IN DOSE AND EFFICACY DATA FOR AUSTRALIAN PESTS OF QUARANTINE CONCERN

In Australia, a minimum absorbed dose of 400 Gy can be used to treat all insect pests of quarantine concern. However, a lower dose of 150 Gy is used to treat fruit fly species (Appendix B) that are of quarantine concern for domestic and international trade. Nevertheless, there are a limited number of pests impacting horticulture commodities where no minimum absorbed dose information has been found in the literature. These pests of concern include Fuller's rose weevil, Serpentine leaf miner and vineyard snail.

Fuller's rose weevil

Fuller's rose weevil (FRW), *Asynonychus cervinus* has proven to be a major pest of quarantine significance for the citrus industry. FRW lays eggs under the calyx of citrus fruit and is the most common stage of FRW reported on export citrus. The South Australian Research and Development Institute (SARDI) has run several projects to control this pest, focusing on monitoring techniques, egg removal from fruit, biological control, and chemical control (Crisp et al., 2016). Although removal of eggs from under the calyx has had partial success with various treatments (Jameison et al., 2016), mortality and removal has not reached an acceptable level and cannot be considered a satisfactory phytosanitary treatment.

Management practices are limited to a systems approach including orchard control through tree skirting, weed control and six weekly applications of chemical spray (Baker & Crisp, 2012), followed by inline postharvest treatments to reduce FRW incidence from under the calyx.

Golding & Palou (2018) and McDonald et al. (2013) examined the effect of low dose irradiation on fruit quality in citrus, but less research has been undertaken to determine an effective minimum absorbed dose, and no work has been done on phytosanitary irradiation for FRW in Australia. Studies in the USA, (Johnson et al., 1990, Coats & Ismail, 1990) found that FRW eggs failed to hatch at irradiation treatment levels of ≥50 Gy. Johnson's study showed that eggs laid under the calyx of lemons were susceptible to irradiation levels as low as 100 Gy with no eggs hatching at levels above 175 Gy. This irradiation dose was comparable to other species of coleopteran reported in the literature. Detailed study is therefore recommended to identify an effective minimum absorbed dose for FRW in an Australian context.

Serpentine leaf miner

Another insect pest of concern is Serpentine leaf miner *Liriomyza huidobrensis* (Blanchard) detected on vegetable crops in the Sydney Basin in October 2020 (Hassan, 2021) and American serpentine leaf miner *Liriomyza trifolii* (Burgess) reported in Western Australia by DPIRD in July 2021 (Jelinek & Eccles, 2020), both of which are from family Agromyzidae. Both are polyphagous, feed on most vegetable and legume crops as well as ornamental plants and pose a serious threat to Australian agriculture and horticultural industries. To manage serpentine leaf miner, integrated pest management (IPM) techniques are being used that involve a combination of biological control, modification of cultural practices, monitoring of pests and insect friendly insecticides.

The previous over reliance on insecticide use has led to a rise in resistance among some of the most damaging insect pest species. This leads to increased levels of plant damage under heavy pest pressure in many countries (Jelinek & Eccles, 2020). Hence, development of phytosanitary irradiation dose could be an alternative control technique to manage and provide quarantine security. Some studies on phytosanitary irradiation dose development have been already done on agromyzid leafminers. For instance, phytosanitary irradiation treatment against 3 species of agromyzid leafminers (Diptera: Agromyzidae), *Liriomyza sativa* (Blanchard), *L. trifolii* (Burgess) and *L. huidobrensis* (Blanchard) showed that irradiation of late-stage pupae at 150Gy and 180Gy prevented formation of leaf mines by F1 offspring. Confirmatory testing on all 3 species using > 30,000 late-stage pupae suggest that 150Gy is sufficient to prevent the formation of leaf mines completely and thus can be used as phytosanitary dose (Ozyardimci et al., 2016). Hallman et al. (2011) suggested that a generic dose for agromyzids and other insects found on cut flowers could be 250Gy.

Vineyard snail

Vineyard snail, or common white snail *Cernuella virgata* (Da Costa) is an invasive species and an agricultural pest in many parts of southern Australia. Missed timing for treatment sprays increases the probability that snail populations will be detected at threshold levels in high-value commodities such as table grapes. Snails and slugs are cold resistant, thus relatively hard to treat with standard phytosanitary cold treatment. Currently, there is no minimum absorbed dose and efficacy data for this pest. However, irradiation has the potential to treat snails and slug pests.

Little research exists on the radiosensitivity of terrestrial herbivorous gastropods, although several studies have been carried out on the medically important aquatic snail *Biomphalaria glabrata* (Say) (Planorbinae) (Hallman, 2016). Studies with the orchid snail *Zonitoides arboreus* (Say) (Stylommatophora: Gastrodontidae) showed reproduction could be prevented by irradiation the pest at 70 Gy (Hollingsworth et al. 2003). Another terrestrial species citrus tree defoliator, the brown garden snail, *Cornu aspersum* (Müller) became sterile after irradiation with ≥ 75 Gy (Hallman, 2016). A dose of > 150 Gy prevented the establishment of viable populations of semi-slug *Parmarion martensi* Simroth (Stylommatophora: Ariophantidae), a pest of sweet potato and other fruits and vegetables in Hawaii (Follett et al., 2021). These studies suggest prevention and control on snail reproduction is possible with relatively low doses. Follett et al. (2021) suggested a minimum absorbed dose of 150 Gy may be effective against many slug and snail pests.

DIFFERENCES IN AUSTRALIAN AND INTERNATIONALLY ACCEPTED IRRADIATION DOSE FOR PESTS OF QUARANTINE CONCERN

In Australia, the minimum absorbed dose of 150 Gy is accepted for all tephritid fruit fly, 300 Gy for mango seed weevil and 400 Gy for all other insect pests. Nevertheless, differences exist in the minimum absorbed dose required for insect pests between the scientific literature, domestic and international phytosanitary protocols (Appendix B). National plant protection organizations (NPPO) are responsible for specifying the minimum absorbed dose within a phytosanitary protocol and require large scale confirmatory experiments to provide certainty about dose efficacy. Even then, the minimum absorbed dose specified by the research may not be accepted and a higher rate employed to provide an added safety margin.

Using fruit fly as an example, most tephritid fruit flies do not require 150 Gy for disinfestation and lower doses of 70 Gy have already been accepted by the USAD APHIS for certain species. Native fruit flies (e.g., Queensland fruit fly and Jarvis fly) are a major concern for Australia exports and large-scale confirmatory tests were performed on Queensland fruit fly and Jarvis fly. Data showed that 150 Gy is not required to achieve efficacy, lower doses of 75 Gy for Queensland fruit fly (Rigney & Wills, 1985, Jessup et al., 1992) and 100 Gy for Jarvis fly (Heather et al., 1991) are sufficient for treatment (Appendix B). Nevertheless, Australia accepts a minimum absorbed dose of 150 Gy. For Australia, the reasons for accepting 150 Gy might include the following (but not limited to):

- To follow FSANZ (2021) requirements in section 1.5.3-3 where it is specified that 'fresh fruit and fresh vegetables may be irradiated for the purpose of pest disinfestation for a phytosanitary objective if the absorbed dose is: (a) no lower than 150 Gy; and (b) no higher than 1 kGy'.
- To avoid risk of uncertainty of disinfestation from other tephritid fruit flies like island flies for which no phytosanitary irradiation efficacy data are recorded (although island fly is mostly found in citrus fruits).
- To meet the phytosanitary protocols agreed with international trading partners se of 150 Gy for specified commodities, such as the case for New Zealand for tephritid fruit fly.

Similar considerations will be at the forefront of all NPPO's when negotiating and agreeing protocols for phytosanitary irradiation.

CONCLUSION

Most major insect groups of quarantine concern for Australia have irradiation dose and efficacy data available to facilitate effective trade using phytosanitary irradiation. Nevertheless, some gaps exist in minimum absorbed dose and efficacy data for plant pests that impact market access and growth of Australian horticulture exports. Filling the gap for insect pests including Fuller's rose weevil, Serpentine leaf miners and vineyard snail would be of particular benefit to the Australian citrus, vegetable, and table grape industries.

The minimum absorbed dose accepted for phytosanitary treatment insect pests may also differ between Australia and its international trading partners. Although the minimum effective dose can be reduced for some species/insect groups based on large scale confirmatory research, phytosanitary protocols agreed with our international trading partners often result in higher dosage rates being specified in phytosanitary protocols. However, it is generally accepted that 150 Gy is effective as a treatment for all tephritid fruit flies and 400 Gy is effective for all insect pests in host fruits and vegetables.

The generic 400 Gy treatment suggested by the USDA APHIS in 2006, could be beneficial from an international trade perspective if endorsed as an ISPM. It provides for a single effective dose, can be used on multiple commodities, is cost effective, simplifies quarantine inspection and certification, and reduces the need for remedial treatment scenarios. Steritech Australia supports the establishment of a generic dose with most important quarantine pests treated at either 150 Gy and 400 Gy for domestic and export purposes.

Likewise, identifying the minimum effective dose for an insect pest can also be important for specific commodities and markets. A reduction in treatment time can deliver cost savings and limit damage to horticultural products that are sensitive to irradiation, for example treating lychee for acari mite.

For project AM19002, further opportunity exists to conduct a study for one of the priority pests identified from the literature review. Testing of different irradiation doses, including sterilising doses (below the generic dose 400 Gy) for vineyard snails is recommended given the potential for orchard infestation and risk to carton contamination in table grape exports.

RECOMMENDATIONS

In order to protect and grow export markets for Australian horticulture commodities, research should be conducted for specific pests where no minimum absorbed dose and efficacy data is available.

Based on this literature review the following recommendations for research are made:

1. Develop phytosanitary irradiation minimum absorbed dose and efficacy data for vineyard snails
2. Develop phytosanitary irradiation minimum absorbed dose and efficacy data for leaf miners (particularly Serpentine leaf miners).
3. Develop phytosanitary dose and efficacy data for Fuller's rose weevil.

Additional trade benefits may also be achieved from research that will support international efforts to establish 400Gy as a generic treatment for insect pests at international level, and to lower the accepted minimum absorbed dose with our trading partners to reduce the cost of treatment for priority pests and commodities.

ACKNOWLEDGEMENT

Authors are indebted to Dr Peter A Follett, Research Entomologist USDA-ARS, Daniel K. Inouye U.S. Pacific Basin Agricultural Research Center, for his generous support by providing literature and expert suggestions regarding phytosanitary irradiation technique and current research status in the world. Benjamin Reilly, Fresh Produce Business Manager, Steritech, Victoria also helped by providing information about t priority crop list that are important for phytosanitary irradiation in Australia and comments on review for which authors are grateful.

REFERENCES

Agriculture Victoria (2020). ICA-55: Irradiation Treatment. Victorian Government Department f Jobs, Precincts and Regions, Victoria, Australia. https://www.vgls.vic.gov.au/client/en_AU/search/asset/1301146/0

Australian Horticultural Exporters and Importers Association (AHEIA). (2018). Providing leadership to support and strengthen Australia's trade in horticultural produce. https://www.horticulturetrade.com.au

Arthur, V. (2004). Use of gamma irradiation to control three lepidopteran pests in Brazil. In Irradiation as a phytosanitary treatment of food and agricultural commodities, IAEA-TEC-DOC 1427, 45-50. International Atomic Energy Agency, Vienna, Austria.

Arthur, V., & Mineiro, J. L. C. (2009). Irradiation as a phytosanitary treatment for mites of the species *Tyrophagus putrescentiae* (acari: acaridae). International Nuclear Atlantic Conference - INAC 2009. Rio de Janeiro, RJ, Brazil, September 27 to October 2, 2009.

Arthur, V., & Machi, A. R. (2016). Development of phytosanitary irradiation against *Aceria litchii* (Trombidiformes: Eriophyidae) on lychee. *Florida Entomologist*, 99 (2).

Baker, G., & Crisp, P. (2012). Market access solutions for Fuller's rose weevil and Island fly. CT11002.

Bakri, A., Heather, N., Hendrichs, J., & Ferris, I. (2005). Fifty Years of Radiation Biology in Entomology: Lessons Learned from IDIDAS. *Annals of the Entomological Society of America*, 98(1), 1-12.

Barkai-Golan, R., & Follett, P. A. (2017). Irradiation for Quality Improvement, Microbial Safety, and Phytosanitation of Fresh Produce. Academic Press, 125 London Wall, London EC2Y 5AS, United Kingdom.

Bloem, S., Bloem, K. A., Carpenter, J. E., & Calkins, C. O. (1999). Inherited sterility in coding moth (Lepidoptera: Tortricidae) effect of sub sterilizing doses of radiation on insect fecundity, fertility and control. *Annals of the Entomological Society of America*, 92, 1-8.

Bloem, S., Carpenter, J. E., & Hofmeyr, J. H. (2003). Radiation biology and inherited sterility in false codling moth (Lepidoptera: Tortricidae). *Journal of Economic Entomology*, 96, 1724- 1731.

Bustos, M.E., Enkerlin, W., Toledo, J., Reyes, J., & Casimiro, A. (1992). Irradiation of mangoes as a quarantine treatment. In: Use of Irradiation as a Quarantine Treatment of Food and Agricultural Commodities. International Atomic Energy Agency, Vienna, 77–90.

Castro, D., Espinosa, J., & Vargas, M. (2004). Ionising radiation as a quarantine treatment for controlling *Brevipalpus chilensis* (Acarina: Tenuipalpidae) in Thompson seedless grapes. In: Irradiation as a phytosanitary treatment of food and agricultural commodities. IAEA-TECDOC-1427. International Atomic Energy Agency, Vienna,143-153.

Coats, S. A., & Ismail, M. A. (1990). Ovicidal Effects of Gamma Radiation on Eggs of the Fuller Rose Beetle, *Pantomorus cervinus* Coleoptera: Curculionidae). The Florida Entomologist, 73(2), 237–242. https://doi.org/10.2307/3494806

Chakroun, S., Rempoulakis, P., Lebdi-Grissa, K., & Vreysen, M. J.B. (2017). Gamma irradiation of the carob or date moth *Ectomyelois ceratoniae*: dose–response effects on egg hatch, fecundity, and survival. *Entomologia Experimentalis et Applicata*, 164, 257–268.

Codex. (2003). General standard for irradiated food: CODEX STAN 106-1983, Rev. 1-2003. FAO, Roma, Italy.

Concoran, R. J. (2001). New and emerging disinfestation technologies-an Australian experience. Australian disinfestation workshop 24-25 July 2001, Gosford, NSW, 44-48.

Crisp, P., Taverner, P., & Cunningham, N. (2016). Fuller's Rose Weevil in citrus. Factsheet, South Australian Research and Development Institute, PIRSA. https://www.pir.sa.gov.au/__data/assets/pdf_file/0009/285534/Fullers_Rose_Weevil_in_Citrus_Fact_Sheet.pdf

Department of Agriculture Biosecurity Plant Division (DABPD). (2014). Australia New Zealand Bilateral Quarantine Arrangement. Canberra.

Department of Agriculture and water resources (DAWR). (2018). Australian phytosanitary treatment application standard for irradiation treatment, version 1.0. Canberra, September. CC BY 4.0. http://agriculture.gov.au/export/controlled-goods/plants-plant-products/plantexportsmanual

Department of Agriculture, water and the environment (DAWE). (2021). Use of phytosanitary treatments for plant exports. Version no.: 1, 1-8. https://www.awe.gov.au/sites/default/files/documents/ref-use-of-phytosanitary-treatments-for-plant-exports.pdf

Dentener, P. R., Wadell, B. C., & Batchelor, T. A. (1990). Disinfestation of light brown apple moth: a discussion of three disinfestations methods. *Proceedings of the Australian Conference Postharvest Horticulture: managing postharvest horticulture in Australasia*, Australian Institute of Agricultural Science Occasional Publication, Australia, 46, 166-177.

Dohino, T., Masaki, S., Takano, T., & Hayashi, T. (1996). Effects of electron beam irradiation on Thrips *Palmi Karny* and *Thrips Tabaci* Lindeman (Thysanoptera: Thripidae) Research Bulletin of the Plant Protection Service Japan, 32, 23-29.

Dohino, T., Tanabe, K., & Hayashi, T. (1994). Comparison of lethal effects of electron beams and gamma rays on eggs of two spotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae). Research Bulletin of the Plant Protection Service Japan, 30, 69 -73.

European Food Safety Authority. (2011). EFSA panel on food contact materials, enzymes, flavourings and processing aids (CEF); Scientific opinion on the chemical safety of food irradiation. *EFSA Journal*, 9(4), 1930.

Food and Agriculture Organization (FAO). (2003). Guidelines for the use of irradiation as a phytosanitary measure. International Plant Protection Convention, ISPM No. 18, Rome, Italy.

Food and Drug Administration-FDA. (1986). Irradiation in the production, processing, and handling of food. Rules and regulations. *Federal Register*, 51 (75), 13376. April 18, 1986.

Federal Register. (2006). Treatments for fruits and vegetables. Rules and regulations, 71, 4451-4464.

Federal Register. (2013). Rules and regulations, 78(184).

Food Standards Australia New Zealand (FSANZ). (2002). Final assessment report. Application a443. Irradiation of tropical fruits - breadfruit, carambola, custard apple, litchi, longan, mango, mangosteen, papaya and rambutan. www.Foodstandards.Gov.Au

Food Standards Australia New Zealand (FSANZ). (2021). Irradiation as a phytosanitary measure for all fresh fruit and Vegetables. Approval report – Application A1193.

Follett, P. A. (2004). Irradiation quarantine treatments for mango seed weevil and Crytpophlebia spp. In: Irradiation as a Phytosanitary Treatment of Food and Agricultural Commodities. IAEA-TECDOC-1427. International Atomic Energy Agency, Vienna, 9-18.

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

Follett, P. A. (2006b). Irradiation as a Phytosanitary Treatment for White Peach Scale (Homoptera: Diaspididae). *Journal of Economic Entomology*, 99(6), 1974-1978.

Follett, P. A. (2006c). Irradiation as a phytosanitary treatment for *Aspidiotus destructor* (Homoptera: Diaspididae). *Journal of Economic Entomology*, 99(4), 1138-1142.Follett, P.A. (2009). Generic radiation quarantine treatments: the next steps. Journal of Economic Entomology, 102, 1399–1406.

Follett, P. A., & Neven L. G. (2020). Phytosanitary irradiation: Does modified atmosphere packaging or controlled atmosphere storage creating a low oxygen environment threaten treatment efficacy? *Radiation Physics and Chemistry*, 173, 108874.

Follett, P. A., & Lower, R. A. (2000). Irradiation to ensure quarantine security for Cryptophlebia spp. (Lepidoptera: Tortricidae) in sapindaceous fruits from Hawaii. *Journal of Economic Entomology*, 93, 1848-1854.

Follett, P.A., & Wall, M. M. (2013). Phytosanitary irradiation for export of fresh produce: commercial adoption in Hawaii and current issues. *Journal of Radioanalytical and Nuclear Chemistry*, 296, 517-522.

Follett, P. A., Yang, M. M., Lu, K. H., & Chen, T. W. (2007). Irradiation for Postharvest Control of Quarantine Insects. *Formosan Entomology*, 27, 1-15.

Follett, P. A., & Griffin, R. (2006). Irradiation as a phytosanitary treatment for fresh horticultural commodities: research and regulations. In C. H. Sommers, & X. Fan (Eds.), *Food irradiation research and technology* (pp. 143-168). Blackwell Professional, Ames, IA.

Follett, P. A., & Neven, L. G. (2006). Current trends in quarantine entomology. *Annual Review of Entomology*, 51, 359-385.

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 tephritids. *Journal of Economic Entomology,* 97, 1263-1268.

Follett, P.A., Hamilton, L., Tagami, Y., Kaluna, L., & Jarvi, S. 2021. Phytosanitary Irradiation Using X-rays Prevents Reproduction in the Semi-slug *Parmarion martensi* (Stylommatophora: Ariophantidae), a Host of the Human Pathogenic Nematode *Angiostrongylus cantonensis* (Rhabditida: Angiostrongylidae). *Pest Management Science* (submitted October 15, 2021).

Friends of the Earth Australia. (2020). Food and technology news. TAKE ACTION: Why is Queensland fast tracking a blanket approval for irradiation of all fruit and vegetables? https://www.foe.org.au/queensland_irradiation).

Golding, J., & Singh, S.P. (2020). Advances in the use of irradiation for the market access of fresh horticultural produce. In C. Watkins (Ed.), *Advances in postharvest management of horticultural produce*, Burleigh Dodds Science Publishing, Cambridhe, UK.

Golding, J.B., & Palou, L. (2018). Exploring the potential of low dose irradiation phytosanitary treatments for the Australian citrus industry. Report for Hort Innovation Citrus Fund Project Australian Citrus Postharvest Science Program (CT15010). 24 pages https://www.horticulture.com.au/globalassets/hort-innovation/resource-assets/ct15010-exploring-the-potential-of-low-dose-irradiation-phytosanitary-treatments.pdf

Hallman, G. J. (1998). Ionizing radiation quarantine treatments. *Anais da Sociedade Entomológica do Brasil*, 27(3), 313-323.

Hallman, G. J. (1990). Ionizing radiation quarantine treatments against tephritid fruit flies. *Postharvest Biology and Technology*, 16, 93–106.

Hallman, G. J. (2003). Ionizing Irradiation Quarantine Treatment Against Plum Curculio (Coleoptera: Curculionidae). *Journal of Economic Entomology*, 96,1399-1404.

Hallman, G. J. (2004). Ionizing irradiation quarantine treatment against oriental fruit moth (Lepidoptera: Tortricidae) in ambient and hypoxic atmospheres. *Journal of Economic Entomology*, 97, 824-827.

Hallman, G. J. (2006). Explanatory document on international standard for phytosanitary measures No. 18 (guidelines for the use of irradiation as a phytosanitary treatment). ISPM No. 18 / Explanatory document, IPPC.

Hallman G.J., Guo K., & Liu T. X. (2011). Phytosanitary irradiation of *Liriomyza trifolii* (Diptera: Agromyzidae). *Journal of Economical* Entomology, 104, 1851-1855.

Hallman, G.J. (2012). Generic phytosanitary irradiation treatments. *Radiation Physics and Chemistry*, 81, 861–866.

Hallman, G. J. (2013). Rationale for a Generic Phytosanitary Irradiation Dose of 70 Gy for the Genus Anastrepha (Diptera: Tephritidae). *Florida Entomologist*, 96(3), 989–990. doi:10.1653/024.096.0336

Hallman, G. J. (2016). Phytosanitary irradiation of the invasive herbivorous terrestrial snail *Cornu aspersum* (Stylommatophora: Helicidae). *Florida Entomologist*, 99 (2), 156-158.

Hallman, G. J., Zhang, D., & Arthur, V. (2016). Generic phytosanitary irradiation dose for phytophagous mites (Sarcoptiformes: Acaridae; Trombidiformes: Eriophyidae, Tarsonemidae, Tenuipalpidae, Tetranychidae). *Florida Entomologist*, 99, 2.

Hassan, Z. (2021). Knowledge is Key: Serpentine Leaf Miner. A high risk pest for vegetables and potatoes Situation Update. Webinar, Ausveg. file:///C:/Users/akterh20/Desktop/Irradiation%20pathways/Serpentine%20leaf%20miner_Zarmeen-Hassan-AUSVEG.pdf

Heather, N.W., Corcoran, R.J., & Banos, C. (1991). Disinfestation of mangoes with Gamma Irradiation against two Australian fruit flies (Diptera: Tephritidae). Journal of Economic Entomology, 84(4),1304 – 1307.

Heather, N. W., & Corcoran, R. J. (1992). Effects of ionizing energy on fruit flies and seed weevil in Australian mangoes. *Proceedings of the final research co-ordination meeting on use of irradiation as a quarantine treatment of food and agricultural commodities*, FAO/IAEA, Vienna, 43-52.

Hollingsworth, R. G, Follett, P. A., & Armstrong, J. A. (2003). Effects of irradiation on the reproductive ability of *Zonitoides arboreus*, a snail pest of orchids. *Annals of Applied Biology*, 143, 395-399.

International Atomic Energy Agency (IAEA). (1986). Report of a Task Force Meeting on Irradiation as a Quarantine Treatment, Chiang Mai, Thailand, 17-28 February 1986.

International Plant Protection Convention (IPPC). (2003). Guidelines for the Use of Irradiation as a Phytosanitary Measure, ISPM 18. IPPC/Food and Agriculture Organization of the United Nations, Rome.

International Plant Protection Convention (IPPC). (2016). ISPM 28 Annex 9 (2010). PT 9 (2010) Irradiation treatment for Conotrachelus nenuphar. Rome, IPPC, FAO

International Atomic Energy Agency (IAEA). 2004. Irradiation as a phytosanitary treatment of food and agricultural commodities. Proceedings of a final research coordination meeting organized by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture 2002, IAEA-TECDOC-1427, Vienna, Austria: 181.

International Database on Insect Disinfestation and Sterilization (IDIDAS). (2007). International Database on Insect Disinfestation and Sterilization. International Atomic Energy Agency, Vienna, Austria. (http://www-ididas.iaea.org/ididas/).

ISPM 2003. International Standards for Phytosanitary Measures. Guidelines for the use of irradiation as a phytosanitary measure. FAO, Rome, Italy.

ISPM 28. (2007). International Standards for Phytosanitary Measures 28, Phytosanitary treatments for regulated pests. International plant protection convention. IPPC, FAO, Rome, Italy. https://www.ippc.int/core-activities/standards-setting/ispms

Jarrett, R.D. (1982). Isotope radiation sources. In E.S., Josephson, & M.S. Peterson (Eds.), *Preservation of Food by Ionizing Radiation*, CRC Press, Boca rato´, 137-163.

Jelinek, S., & Eccles, J. (2020). Management of Serpentine Leafminer, December 2020, Primefact PUB20/933, First edition. www.dpi.nsw.gov.au

Jessup, A.J., Rigney, C.J., Millar, A., Sloggett, R.F., & Quinn, N.M. (1992). Gamma irradiation as a commodity treatment against the Queensland fruit fly in fresh fruit. Proceedings of the final research co-ordination meeting on use of irradiation as a quarantine treatment of food and agricultural commodities, FAO/IAEA, Vienna, 13–42.

Johnson, J. A., Soderstrom, E. L., Brandl, D. G., Houck, L. G., & Wofford, P. L. (1990). Gamma radiation as a quarantine treatment for Fuller rose beetle eggs (Coleoptera: Curculionidae) on citrus fruit. Journal of economic entomology, 83(3), 905-909.

Loaharanu, P., & Mainuddin A. (1991). Advantages and disadvantages of the use of irradiation for food preservation. *Journal of Agricultural and Environmental Ethics*, 4(1), 14-30.

Mansour, M. (2003). Gamma irradiation as a quarantine treatment for apples infested by codling moth (Lep., Tortricidae). *Journal of Applied Entomology*, 127, 137-141.

McDonald, H., Arpaia, M. L., Caporaso, F., Obenland, D., Were,L. M., Rakovski, C. S., & Prakash, A. (2013). Effect of gamma irradiation treatment at phytosanitary dose levels on the quality of 'Lane Late' navel oranges. Postharvest Biology and Technology, 86, 91-99.

Nicholas, A., Lidbetter, F., Eagleton, N., Spohr, L., Harris, A., & Barchia, I. (2018). Phytosanitary irradiation of three species of spider mites (Trombidiformes: Tetranychidae). Austral entomology.

Nicholas, A., Lidbetter, F., Eagleton, N., Spohr, L., Harris, A., & Barchia, I. (2018). Effects of gamma radiation on the survival of four species of thrips (Thysanoptera: Thripidae). *Austral entomology.* 10.1111/aen.12348

Osouli, Sh., Ziaie, F., Nejad, K. H. I., & Moghaddam, M. (2013). Application of gamma irradiation on eggs, active and quiescence stages of *Tetranychus urticae* Koch as a quarantine treatment of cut flowers. *Radiation Physics and Chemistry*, 90, 111-119.

Ozyardimci, B., Aylangan, A., Ic, E., & Aydin, T. (2016). Phytosanitary irradiation against leafminers (Diptera: Agromyzidae) and radiotolerance of shelled peas, *Pisum sativum* (Fabales: Fabaceae). *Florida Entomologist*, 99(2), 171-177.

Plant Health Australia. (2021). National Plant Biosecurity Status Report (2020), Canberra, ACT. https://www.planthealthaustralia.com.au/industries/

Rigney, C. J., & Wills, P. A. (1985). Efficacy of gamma irradiation as a quarantine treatment against Queensland fruit fly. In J.H. Moy, (Ed.), *Radiation Disinfestation of Food and Agricultural Products*, University of Hawaii at Manoa, Honolulu, 116–120.

Suckling, D. M., & Barrington, A. M., Chhagan, A., Stephens, A.E.A., Burnip, G. M., Charles, J. G., & Wee, S. L. (2007). Eradication of the Australian painted apple moth *Teia anartoides* in New Zealand: trapping, inherited sterility, and male competitiveness. In M.J.B. Vreysen, A. S. Robinson, & J. Hendrichs (Eds.), *Area-wide control of insect pests*, Springer, Dordrecht, The Netherlands, 603-615.

Tiryaki, O. (1990). Inhibition of *Penicilllium expansum*, *Botrytis cinerea*, *Rhizopus stolonifer*, and *Alternaria tenuissima*, which were isolated from Ankara pears, by gamma irradiation. *The Journal of Turkish Phytopathology*, 19(3), 133-140.

U.S. Department of Agriculture–Animal and Plant Health Inspection Service (USDA–APHIS). (2008). Treatments for fruits and vegetables. Rules and Regulations. Federal Register 73 (88), 24851-24856.

U.S. Department of Agriculture–Animal and Plant Health Inspection Service (USDA–APHIS). (2006). Treatments for fruits and vegetables. Rules and Regulations. Federal Register 71(18), 4451-4464.

World health organization (WHO). (1999). High-dose irradiation: wholesomeness of food irradiated with doses above 10kGy. Report of a joint FAO/IAEA/WHO Study Group 890.

World health organization (WHO). (1981). Wholesomeness of irradiated food. Report of a joint FAO/IAEA WHO Expert Committee, Technical Report Series No. 659.

World Trade organization (WTO). Sanitary and phytosanitary measures: text of the agreement. The WTO Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement). https://www.wto.org/english/tratop_e/sps_e/spsagr_e.htm

APPENDICES

Appendix A:

Table 1: Priority commodities that have high demand in international market and associated pests of quarantine concern for Australian horticultural industry

Priority commodities	Export value (year)	Prospective international market	Associated important pests
Table grapes	$555M (2018-19) $623M (2019-20)	Vietnam, New Zealand, China, Indonesia, Japan, Hongkong, the Philippines	Grape leaf rust mite, false red mite, yellow peach moth, false codling moth, Vineyard snails, fruit flies, Beetle, Western flower thrips, spider
Cherry	$79.5 M (2018-19)	Vietnam, Indonesia, China, Korea	Spider mite, oriental fruit moth, green fruit worm, leaf roller, fruit flies, black cherry aphid, black peach aphid, Thrips
Lychee	$7.4 M (2018-19)	United States, Hong Kong, USA, New Zealand and Canada	Mites, moth, fruit flies, beetles
Stone/summer fruit (apricots, nectarines, peaches and plums)	$89M (2018-19)	China, Hong Kong, United Arab Emirates, Saudi Arabia, Singapore and Malaysia	Mites, plum fruit moth, fruit flies, Aphid, beetle, Western flower thrips In 2020, Summer fruit Australia was involved in several responses to pest incursions affecting the industry, including detections of brown marmorated stink bug, Varroa mite and exotic fruit fly.
Blackberry and raspberry	1.87M (2018-19)	Hong Kong, Singapore, India, Indonesia, Pacific Island countries, the United Arab Emirates, Canada and Europe	Mites, moth, borer, fruit flies, vinegar flies, thrips
Strawberry	$24.4M (2018-19)	United Arab Emirates, New Zealand, Singapore, Thailand and Hong Kong	Mites, moth, borer, fruit flies, vinegar flies, thrips
Citrus: oranges, mandarins, lemons, limes and grapefruit	$457M (2018-19)	China, Japan, Hong Kong, Malaysia, Indonesia, United Arab Emirates, Singapore, the United States and Thailand. citrus industry is Australia's largest fresh fruit exporting industry by volume	citrus rust mite, citrus mite, false red mite, false codling moth, citrus fruit borer, fruit flies, Scale, Fuller rose weevil, citrus thrips
Papaya	Export value not availble	New Zealand	Moth, fruit flies
Tomato	Export value not availble	New Zealand, Indonesia	Tomato worm, borer, fruit flies, serpentine leaf miner
Capsicum	Export value not availble	New Zealand	Moth, serpentine leaf miner, fruit flies

Melons	Export value not availble	Indonesia	Fruit flies
Persimmon	Export value not availble	Thailand	Fruit flies

Source: 1. Plant Health Australia, 2021. https://www.planthealthaustralia.com.au/industries/),
2. Australian Horticultural Exporters and Importers Association (AHEIA), 2018. https://www.horticulturetrade.com.au
3. Benjamin Reilly, Steritech, Melbourne

Appendix B:

Table 2: Minimum absorbed dose approved for insects/insect groups within Australia and the United States

Insect pest		Minimum absorbed dose (Gy) (study reference)	Minimum absorbed dose (Gy) approved by USDA APHIS[1]	Minimum absorbed dose (Gy) approved in Australia[2]
Scientific name	Common name			
Anastrepha ludens **(Loew)**	Mexican fruit fly	70 (Hallman, 2013)	70	150
Anastrepha obliqua **(Macquart)**	West Indian fruit fly	70 (Hallman, 2013)	70	150
Anastrepha serpentina **(Wiedemann)**	Sapote fruit fly	100 (Bustos et al., 1992)	100	150
Anastrepha suspensa **(Loew)**	Caribbean fruit fly	70 (Hallman, 2013)	70	150
Bactrocera jarvisi **(Tryon)**	Jarvis fly	100 (Heather et al., 1991)	100	150
Bactrocera tryoni **(Froggatt)**	Queensland fruit fly	75 (Rigney & Wills, 1985, Jessup et al., 1992)	100	150
Fruit flies in the family Tephritidae not listed above		150 (Follett et al., 2007)	150	150
Brevipalpus chilensis **(Baker)**	False grape mite/ false red spider mite (acari mite)	300 (Castro et al., 2004)	300	400
Cryptophlebia ombrodelta **(Lower)**	Litchi fruit moth	250 (Follett, 2004)	250	400
Cydia pomonella **(L.)**	Codling moth	200 (Mansour, 2003)	200	400
Grapholita molesta **(Busck)**	Oriental fruit moth	200 (Hallman, 2004)	200	400
Omphisa anastomosalis **(Guenee)**	Sweet potato vine borer	150 (Follett, 2006a)	150	400
Pseudaulacaspis pentagona **(Targioni Tozzetti)**	White peach scale	150 (Follett, 2006b)	150	400

***Aspidiotus destructor* (Signoret)**	Coconut scale	150 (Follett, 2006c)	150	400
***Sternochetus mangiferae* (F.)**	Mango seed weevil	300 (Follett, 2004, Heather & Corcoran, 1992)	300	300
Cylas formicarius elegantulus **(Summers)**	Sweet potato weevil	150 (Follett, 2006a)	150	400
***Euscepes postfasciatus* (Fairemaire)**	West Indian sweetpotato weevil	150 (Follett, 2006a)	150	400
***Conotrachelus nenuphar* (Herbst)**	Plum curculio	92 (Hallman 2003, IPPC, 2016)	92	400
Asynonychus cervinus	Fuller's rose weevil	174.1 (Johnson, 1990)	No information	Not selected yet
***Cernuella virgata* (Da Costa)**	Vineyard snails	No information	No information	Not selected yet
***Liriomyza huidobrensis* (Blanchard)**	Serpentine leaf miner	No information	No information	Not selected yet
***Liriomyza trifolii* (Burgess)**	American serpentine leaf miner	No information	No information	Not selected yet

Source: [1]USDA-APHIS, 2006,2008, Follett, 2009

[2]Steritech personal communication, FSANZ 2021

Appendix C:

Table 3: Country specific dose requirement for phytosanitary irradiation of fresh commodities

Country	Commodities	Doses (Gy)
USA	Fresh fruit and vegetables	1000
New Zealand	Fresh fruit and vegetables	150 to 1000
Philippines	Mangoes for disinfestation	1000
Vietnam	Fresh fruit and vegetables	200 to 2500
Indonesia	Fresh fruit and vegetables	1000 to 2500
India	Fresh fruits and vegetables	200 to 2500
Malaysia	Fresh fruits and vegetables	150 to 2500
China	Fresh fruits and vegetables	≤1500

Source: Food Standards Australia New Zealand (FSANZ), 2021