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AM19002

Building Capacity in Irradiation

Review of phytosanitary irradiation pathways and product quality tolerance

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Author(s):

Dr. John Golding. NSW Department of Primary Industries, Australia

Glenn Hale. Agriculture Victoria, Australia

Jung Cho. Plant and Food Research, New Zealand

Dr Allan Woolf. Plant and Food Research, New Zealand

Collaborators:

Dr. Anuradha Prakash. Chapman University, United States

Dr. Penta Pristijono. University of Newcastle, Ourimbah, Australia

Dr. Hongxia Qu. Chinese Academy of Sciences, Guangzhou, China

Dr. Apiradee Uthairatanakij. King Mongkut's University of Technology Thonburi, Thailand

Dr. Baogang Wang. Beijing Academy of Agriculture and Forestry Sciences, China

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EXECUTIVE SUMMARY

The ongoing development of irradiation as a successful and commercial phytosanitary treatment is critical to both market access security and the development of Australian horticultural exports. It is well established and accepted that phytosanitary irradiation is an international market access treatment, but it is critical that this treatment does not affect fruit quality out-turns, shelf life and eating quality.

While there are a number of excellent technical reviews on the effects of irradiation on fruit and vegetable quality, this report highlights the current status of irradiation on product quality, with a focus on treatment timing, dose, transit timing and shelf-life marketability. This report reviewed the published scientific literature and unpublished reports of phytosanitary irradiation to give clear information on the effects of irradiation on product quality following treatment and export. It should be noted that a lot of older scientific literature has been conducted using doses that are above the current phytosanitary limits (i.e. above 1,000 Gy) and these higher doses are not suitable for phytosanitary treatment. This review focused on the effects of low-dose irradiation treatment (< 1,000 Gy).

The results of this review across all major fruit and vegetables showed that in general, phytosanitary irradiation treatment maintained final product quality during the supply chain with few negative impacts on fruit and vegetable quality. However these negative attributes can impact market and consumer acceptability. For example, a known quality attribute affected by irradiation is softening in some fruit. However more research needs to be conducted in order to fully understand and manage fruit softening to ensure it does not become a barrier to consumer acceptance and export. It is also interesting to note that while the effects of irradiation on fruit quality has been widely studied in many major horticultural crops, there have been relatively few studies on other major crops (e.g. melons and many vegetables) with export potential. More work is required on these horticultural crops, especially on newer cultivars.

Most of the research conducted on fruit and vegetable tolerance to irradiation has been very descriptive and generally only treats a single batch of fruit at one time. While this research is valuable to compare irradiation treatments and untreated control fruit, the inferences which can be drawn from these descriptive trials are limited, i.e. the results just reflect that of one batch for a given treatment time. Indeed most of this fruit tolerance research has limited information on sensory or consumer acceptance of the produce following treatment and simulated supply chain storage. In the future, more sensory and consumer research is required to validate the objective R&D storage trials.

The limited research scope of current product tolerance R&D is limiting our understanding, management and commercial application of phytosanitary irradiation. There have been very few studies which have attempted to understand some of the pre- and postharvest factors affecting the effects of irradiation on product quality, or indeed the underlying mechanisms of the effects of irradiation on produce quality. It will be important to apply practical R&D to identify, manage and apply best practice guidelines to the consumer to consistently deliver high quality produce with good eating quality. The interaction of pre-harvest practices (such as harvest maturity), handling and storage conditions and irradiation treatment have not always been identified. To fully exploit the potential of irradiation as a phytosanitary treatment, these management factors need to be identified and managed to optimise fruit quality.

The review of published and unpublished literature identified some short- and longer-term recommendations to improve the commercial outcomes of phytosanitary irradiation treatment. These recommendations include:

1. Demonstrate the efficacy of phytosanitary irradiation treatment to maintain the quality for Australian horticulture through domestic and export supply chains.

2. Understand the basis for the action of irradiation and maintenance of fruit quality following irradiation.

3. Identify and understand the pre- and postharvest factors which effect product tolerance to phytosanitary treatment.

4. Develop management strategies to improve the quality outcomes of Australian exports which use phytosanitary irradiation.

5. Comparison of different commercial market access treatments on produce quality and eating quality.

6. Develop and implement crop specific best practice guidelines for the commercial use of irradiation as a phytosanitary market access treatment.

Within the scope of this current Project (Section 1.3b), it is recommended to explore *Recommendation 1* to give industry confidence in the use of phytosanitary treatment.

INTRODUCTION

Irradiation is a technologically proven, viable and scientifically sound disinfestation treatment (Follet, 2009). Irradiation has recently been approved as a market access treatment for all fruit and vegetables in Australia and New Zealand (FSANZ, 2021). Irradiation has been approved for use in Australia and New Zealand in some commodities for 20 years and internationally since the 1950s. Irradiation breaks chemical bonds in DNA and other molecules, thereby sterilizing the pest or preventing it from achieving sexual maturity. Phytosanitary irradiation treatment is increasingly becoming an approved and agreed treatment in world trade of food and horticultural products. Indeed irradiation as a market access treatment has been endorsed by two internationally recognised standards-setting agencies for human and plant health; Codex Alimentarius (Codex) and the International Plant Protection Convention (IPPC). Irradiation as a market access treatment has been approved in several export markets such as Indonesia and Vietnam.

Generic irradiation treatments have been approved by U.S. Department of Agriculture - Animal and Plant Health Inspection Service (USDA-APHIS) at doses of 150 Gy (Gray) for Tephritid fruit flies and 400 Gy for all insects except pupal and adult Lepidoptera (USDA-APHIS, 2006). Further APHIS rulings and new rulings by the International Plant Protection Convention (IPPC) have approved new minimum doses for 6 fruit fly pests and 14 other plant insect pests regardless of the host product, at doses between 60 and 300 Gy (USDA-APHIS, 2008). An excellent review of irradiation quarantine treatments was published by Follet (2009).

Food Standards Australia New Zealand (FSANZ) have granted food safety approval for irradiation (at 150 – 1,000 Gy) as a technique for phytosanitary purposes (FSANZ, 2021) with mandatory labelling requirements for irradiated fruit and vegetables. As part of the risk and technical assessment for this approval, FSANZ undertook a comprehensive review of all available evidence and showed that :

- irradiation is an appropriate and effective treatment for regulated pests, including fruit fly,
- irradiation as a treatment for pest disinfestation is technologically justified and effective,
- there are no public health and safety concerns associated with the consumption of fresh fruit and vegetables that have been irradiated at doses of up to 1,000 Gy.

FSANZ conducted a thorough toxicological assessment and concluded there are no safety concerns with the consumption of fresh fruit and vegetables that have been irradiated at doses of up to 1,000 Gy (FSANZ, 2021). They also showed that radiolytic compounds generated through food irradiation are at levels generally comparable to those naturally present in cooked food and are not likely to result in harm to humans (FSANZ, 2021). Further, there is no evidence that phytosanitary irradiation of fruit and vegetables at the proposed doses would increase the toxicity of any mycotoxin contamination, or increase the allergenicity of the produce, or result in additional dietary exposure to furan (FSANZ, 2021). The nutrition risk assessment by FSANZ showed that the effect of irradiation on the micro-nutrient intake across the Australian and New Zealand populations from fruit and vegetables was minimal.

This review examines the published literature on the effect of low dose irradiation (<1,000 Gy) as a market access treatment on fruit and vegetable quality and will assist industry, exporters and importers to commercialise the use of irradiation as phytosanitary treatment.

The review was conducted by John Golding (NSW Department of Primary Industries) and Glenn Hale (Agriculture Victoria) with contributions from Jung Cho and Allan Woolf (Plant and Food Research, New Zealand). In addition, the review also had contributions from the Project collaborators: Dr. Anuradha Prakash, Chapman University, United States, Dr. Penta Pristijono, University of Newcastle, Ourimbah, Australia, Dr. Hongxia Qu, Chinese Academy of Sciences, Guangzhou, China, Dr. Apiradee Uthairatanakij, King Mongkut's University of Technology Thonburi, Thailand, and Dr. Baogang Wang, Beijing Academy of Agriculture and Forestry Sciences, China.

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.

Summary of current products and markets of irradiated produce

This section summarises the use of irradiated produce within Australia and internationally:

1. World trade using irradiation as a market access treatment.
2. Use of irradiation as market access treatment in Australia.
3. Import of irradiated fruit and vegetables into Australia.
4. Domestic trade of irradiated fruit and vegetables within Australia.

1. World trade using irradiation as a market access treatment

While irradiation as a market access treatment is effective, technologically proven and safe, its world wide application has been limited with relatively few countries accepting irradiation. Table 1 outlines the countries which permit food irradiation and those countries which use irradiation as a phytosanitary treatment (Kingham and Roberts, 2022). The remaining countries are in a group that do not have regulations permitting food irradiation (or the situation is unknown).

Table 1. Counties which permit phytosanitary irradiation and those that permit food irradiation, but not its use for phytosanitary purposes (from Kingham and Roberts, 2022).

	Countries allow phytosanitary irradiation for fresh produce	**Permit food irradiation but not for phytosanitary purposes**
Asia and the Pacific	Australia, Bangladesh, China, India, Indonesia, Malaysia, New Zealand, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Vietnam	Japan, Republic of Korea;
North America	United States	Canada
Central, South America and Caribbean	Argentina, Bolivia, Brazil, Chile, Cuba, Ecuador, Peru	
Africa	Algeria, South Africa	Ghana, Egypt
Europe	Russia, United Kingdom	European Union, Ukraine

Table 2 shows the world trade (excluding Australia) of some fruit and vegetables. Note that this table is incomplete as international approvals regularly change, but this illustrates the range of produce treated and traded around the world which can use irradiation as a phytosanitary treatment.

Table 2. Selected world export trade (excluding Australia) of irradiated fresh fruit and vegetables (from Golding and Singh, 2020).

Exporting country	**Fruit / vegetable**	**Importing country**	**Dose (Gy)**
Hawaii	dragon fruit, guava, longan, lychee, mango, mangosteen, moringa, papaya, sweet potato	US mainland	150 or 400
India	mango	Australia, United States	400
Indonesia	mango	Australia	400
Mexico	carambola, chili, dragon fruit, fig, guava, manzano, mango, sweet lime, pitaya, pomegranate	United States	150 or 400
Pakistan	mango	United States	400*
		Australia	400
Peru	blueberry, fig	United States	
South Africa	lychee, persimmon	United States	400*
Thailand	longan, mango, mangosteen	United States	400

	mango	Australia	
United States (mainland)	peach	Mexico	250
Vietnam	dragon fruit, longan, lychee, rambutan	United States	400
	mango, litchi	Australia	

** treated on arrival in the United States*

Developing on-going commercial trade is a long process even after treated fruit had been granted approval for import. The commercial adoption of irradiation as a phytosanitary treatment relies on many technical, commercial and regulatory factors including the evolution of treatment infrastructure and biosecurity needs. Table 3 show the extensive range of irradiated produce and countries of origin that have been granted approval to be imported into the USA (QDAF, 2019) but only a proportion of these commodities have substantial trade into the USA.

Table 3. Irradiated produce allowed to be imported into the USA (from QDAF, 2019)

Exporting country	**Fruit / vegetable**
Australia	litchi, mango
Ghana	eggplant, okra, pepper
Hawaii	abiu, atemoya, banana, breadfruit, capsium spp (peppers), cucurbita spp. (squash, pumpkins), cowpea, pitaya (dragon fruit), eggplant, jackfruit, litchi, longan, mango, mangosteen, melon, moringa pods, papaya, pineapple, rambutan, sapodilla, sweet potato, tomato, starfruit, curry leaf
India	mango
Malaysia	rambutan
Mexico	carambola, clementine, grapefruit, guava, mango, manzano, sweet lime, sweet orange, tangelo
Pakastan	mango
South Africa	grapes, stonefruit, pear, persimmon
Thailand	litchi, longan, mango, mangosteen, pineapple, pomello, rambutan, dragon fruit
Vietnam	dragon fruit, rambutan

Source: QDAF (2019)

2. Use of irradiation as market access treatment in Australia

The growth in domestic trade and exports volumes using irradiation as a market access treatment in Australia has increased significantly over the last 15 years (Figure 1) (Kingham and Roberts, 2022). In the 2019-2020 season, Australia exported 5,837 pallet loads of 10 different types of irradiated fresh produce to five countries (Kingham and Roberts, 2022). Freight issues related to Covid-19, storm damage to seedless grapes and a 30% reduction in the national mango crop led to a reduction in export volumes in 2020/21 but indications for the first few months of 2021/22 are that the year-to-date volumes are up 135% driven by multiple new protocols for irradiated fruit into New Zealand (Kingham and Roberts, 2022).

The major commodities treated with irradiation are mangoes and tablegrapes. However the FSANZ approval of all commodities (FSANZ, 2021), there are increased opportunities for other industries to explore irradiation. The Queensland Department of Agriculture and Fisheries has provided conservative estimates that between 0.3 – 8% of total fruit and vegetables consumed in Australia and New Zealand might be irradiated (FSANZ, 2021).

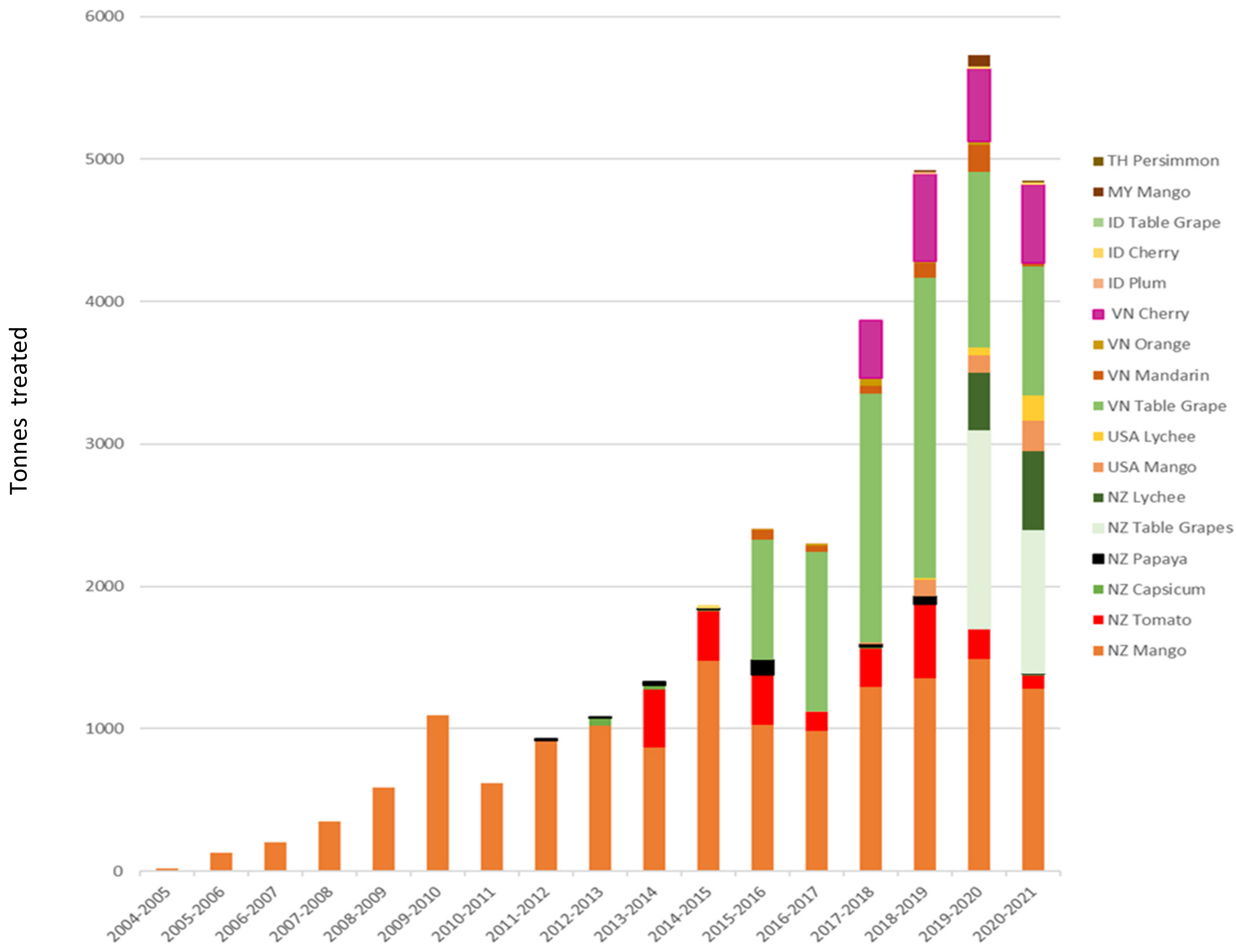


Figure 1. Growth of Australian phytosanitary irradiation treatment (export and domestic volumes). (from Kingham and Roberts, 2022; Data supplied by Steritech, Australia)

QDAF (2019) classified Australian horticulture products as either high, medium and low for their expected commercial significance of irradiation to sustain commercially viable trade (Table 4). Table 5 similarly provides a simple classification (year round, seasonality and rarely) indicating the significance of the treatment to balance season supply and demand (QDAF, 2019).

The Tables are indicative only and take a medium (10 year) fruit of potential trade. The classifications made by QDAF were based on experience (existing irradiated exports), expected commodity tolerance relative to other phytosanitary treatments and informal market assessments.

A ‘high / medium’, or ‘year-round / seasonal’ classification does not mean that large volumes of that crop will be irradiated. For example, it is possible that the bulk of the supply may be sourced from a pest free region or via a high volume cold disinfestation treatment, while irradiation is used for a niche opportunities (for example for the air freight of premium products).

Table 4. Commercial significance of irradiation to meet quarantine requirements and / or industry needs (e.g. quality, seasonal availability) (from QDAF, 2019).

High	Medium	Low
asparagus, berry, cherry, garlic, ginger, lemon, lime, lychee, longan, mango, papaya, peach, persimmon, plum, pomegranate, nectarine, tablegrape, tomato	dragon fruit, melon, pear, capsicum	apple, avocado, broccoli, carrot, corn cucumber, cauliflower, mandarin, onion, orange, potato, pumpkin, salad leaf, zucchini

Table 5. Supply and demand influences on the use of irradiation (from QDAF, 2019).

Year round / regularity	Medium	Rarely used / Emergency trade need
garlic	berry, cherry, dragon fruit, ginger, lemon, lime, mango, nectarine, papaya, peach, pear, plum, pomegranate, lychee, longan, tablegrape, tomato	apple, asparagus, avocado, broccoli, capsicum, carrot, corn, cucumber, cauliflower, mandarin, melon, onion, orange, potato, onion, pumpkin, salad leaf, zucchini

3. Import of irradiated fruit and vegetables into Australia

Australia allows the import of irradiated fresh fruit and vegetables from overseas countries following comprehensive import risk analyses and issues import permits detailing the specific conditions and requirements for importation of each product, including the requisite phytosanitary treatments. Import conditions are published on the Department's Biosecurity Import Conditions Database (https://bicon.agriculture.gov.au/) . Examples of approvals by DAWE for the import of fresh fruit and vegetables irradiated for quarantine purposes are outlined in Table 6. Please note that this list is not comprehensive and is only a guide to some current approvals.

Table 6. Examples of DAWE approvals for the import of irradiated fruit and vegetables from other countries (from FSANZ, 2021).

Commodity	Exporting country	Report date	Purpose	Dose (Gy)
longan	Vietnam	May 2019	control of fruit fly and litchi fruit borer.	minimum dose of 400 Gy
mango	India	April 2011	control of fruit fly, mango weevil, mealybug, and red-banded mango caterpillar.	minimum dose of 400 Gy
mango	Thailand	November 2015	control of mango weevil, fruit fly, mealybug, and red-banded mango caterpillar.	minimum dose of 150 Gy (fruit fly) minimum dose of 300 Gy (weevil) minimum dose of 400 Gy (red-banded mango caterpillar)
lychee	Vietnam	April 2013	control of fruit fly, litchi fruit borer and mealybug.	minimum dose of 400 Gy

4. *Domestic trade of irradiated fruit and vegetables within Australia*

The use of irradiation as a market access treatment is approved with the Interstate Certification Assurance (ICA) Scheme under Operational Procedure Number 55 (ICA-55) (ICA, 2011), which is accepted by the other states and territories. Kingham and Roberts (2022) showed in their review that phytosanitary irradiation is permitted for the treatment of Mediterranean fruit fly (MFF) and Queensland fruit fly (QFF) at 150 Gy generic dose for fruit flies, and that the treatment is mostly applied on mixed consignments of QFF host produce destined for South Australia, Tasmania and Western Australia (see Table 7).

While the volumes of treated irradiated Australian produce had traditionally been low, following the FSANZ approval for all fruit and vegetables in 2021 (FSANZ, 2021), the use of irradiation as a market access treatment has been growing into new markets and crops. Indeed, Kingham and Roberts (2022) report that by volume, the domestic trade of 112 tonnes of irradiated fresh produce in 2020/21 was the eighth largest destination for irradiated fresh produce from Steritech (pers. comm., Ben Reilly, Steritech, 2021).

Table 7. Summary of approved fresh produce, domestic market regulated pests, and minimum absorbed dose in Australian domestic regulations (from Kingham and Roberts, 2022)

State	Approved fresh produce	Pest and additional requirements	Minimum absorbed dose (Gy)
NSW	FSANZ approved	Mediterranean fruit fly	150 Gy
South Australia	FSANZ approved	Fruit fly Insecta except pupae and adults of Lepidoptera	150 Gy 400 Gy
Tasmania	FSANZ approved	Queensland fruit fly, Mediterranean fruit fly	150 Gy
Western Australia	On a commodity basis	Queensland fruit fly Arthropods including Serpentine Life Miner and Melon Thrips, but excluding Lepidopteron that pupate internally	150 Gy 400 Gy
Victoria	FSANZ approved	Mediterranean fruit fly. The quarantine manual only lists 19 FSANZ approved fruit and vegetables	150 Gy
Queensland	FSANZ approved	Mediterranean fruit fly. The quarantine manual only lists 26 FSANZ approved fruit and vegetables	150 Gy
Northern Territory	All host produce	*Bactrocera musae,* Mediterranean fruit fly	150 Gy

General effects of irradiation on nutritional content

Numerous reviews have been published on the effects of irradiation on the nutritional quality of food, including fresh fruit and vegetables (World Health Organization, 1981, 1994, 999; Scientific Committee on Food, 2003; Arvanitoyannis, 2010; European Food Safety Authority, 2011). These reviews have examined the efficacy, safety and nutritional effects of irradiation on a wide range of foods. Irradiation can induce changes in nutrient content, depending on a variety of factors including the irradiation dose, composition of the food, packaging material, ambient temperature and atmospheric oxygen concentration (Diehl et al., 1991; Kilcast, 1994; World Health Organization, 1994). A relatively small proportion of nutrients are sensitive to irradiation, with higher doses of irradiation associated with greater nutritional losses (World Health Organization, 1999), however these doses are more than the maximum 800 Gy used for disinfestation of fresh fruit and vegetables.

Vitamins have been shown to be susceptible to oxidation and breakdown with high levels of irradiation treatment. There is a general hierarchy of vitamin sensitivity to irradiation, with vitamins A, C, E and thiamin being most sensitive (Figure 2) (Kilcast, 1994; Diehl, 1995). As fruits and vegetables are the predominant dietary sources of vitamin A (as carotene) and vitamin C, the majority of studies examining the effects of irradiation on fruit or vegetable quality have focused on these nutrients.

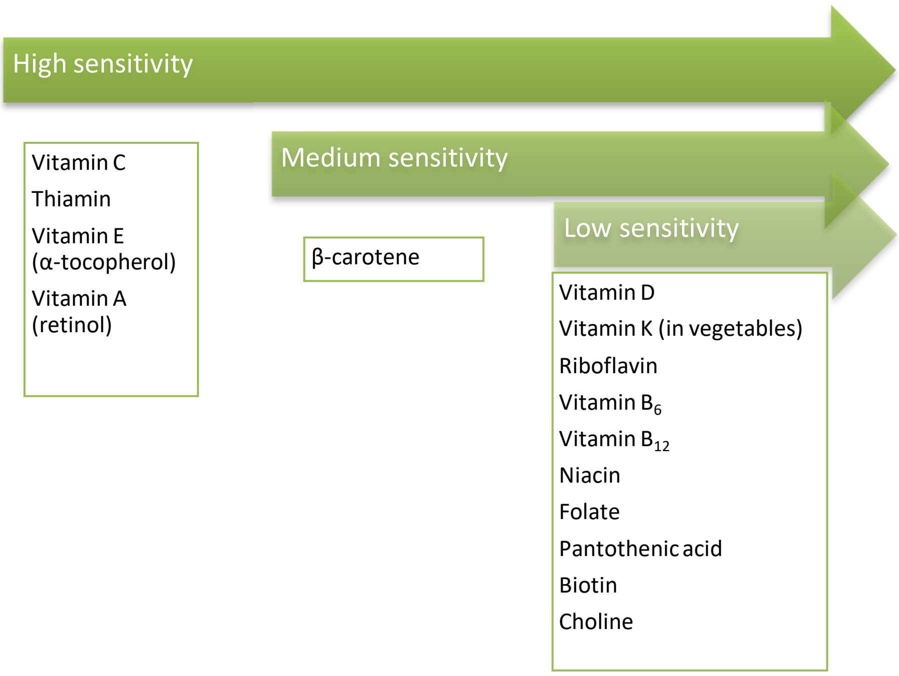


Figure 2. General sensitivity of vitamins in fresh fruit and vegetables to irradiation.
(modified from FSANZ, 2014 and Kilcast, 1994)

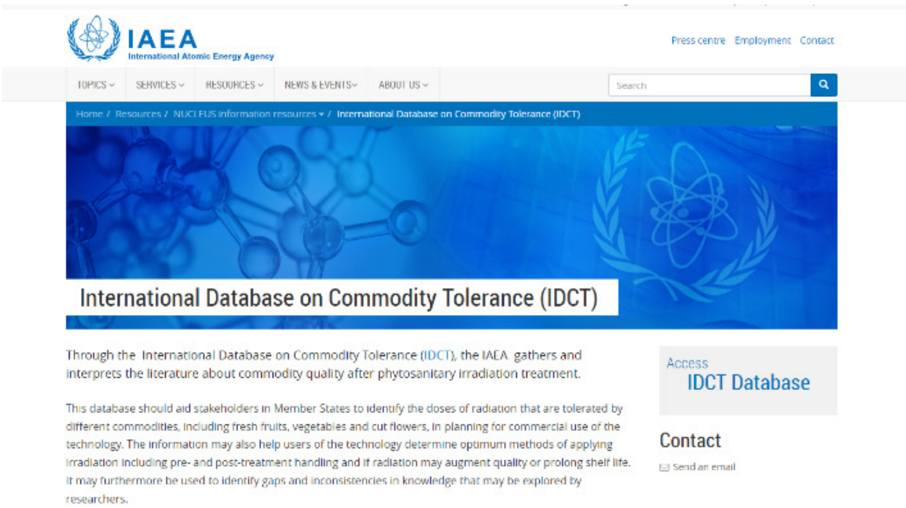
In a recent comprehensive review of the nutritional impact of phytosanitary irradiation on a range of fruit and vegetables, FSANZ (2020) reiterated its conclusions that phytosanitary irradiation does not affect the macronutrient or mineral content of fruit and vegetables. FSANZ (2020) state that five vitamins (or pro-vitamins) are potentially sensitive to irradiation, of which vitamin C, β-carotene and vitamin E are most relevant for fruit and vegetables. Phytosanitary irradiation was shown to have little effect on the vitamin C content of most fruit and vegetables with only small depletion ranging from 1 to 3 mg per 100 g observed in a small number of vegetables; however, it did find larger losses in two leafy vegetables – spinach and rocket (FSANZ, 2020). In general, β-carotene levels are stable in irradiated fruit, some inconsistency was observed across studies, but the losses were always small (FSANZ, 2020). Very limited data were available on the effect of irradiation on the vitamin E content, with one study reporting a negligible effect (<5%) on vitamin E content in spinach. Therefore, losses of vitamin E in other commodities due to phytosanitary irradiation cannot be discounted (FSANZ, 2020). In addition, there has been no demonstrated effect of irradiation up to 1,000 Gy on the amount and nutritional quality of carbohydrates, proteins or fats and no evidence to suggest that irradiation reduces the mineral content of food (Diehl et al., 1991; World Health Organization, 1994). Therefore, macronutrients and minerals have not been given further consideration in this review.

METHODS

A review of the published literature was conducted using a range of established search engines (Google Scholar, Web of Science, Scopus etc.). In addition the results of unpublished fruit quality and product tolerance storage trials from the authors and collaborators are also presented and integrated into the review.

A key source of information was the International Database on Commodity Tolerance (IDCT) which is part of the International Atomic Energy Agency (IAEA) NUCLEUS information resources. Through the IDCT, the IAEA gathers and interprets the literature about commodity quality after phytosanitary irradiation treatment.

International Database on Commodity Tolerance (IDCT) - https://www.iaea.org/resources/databases/idct



RESULTS

Summary of individual product tolerances / quality

A significant issue with the older scientific literature in the irradiation of fresh horticultural produce is that many studies examined the effects of relatively 'higher' doses (i.e. greater than 1,000 Gy) on product quality. While it is valid to report these effects, these higher irradiation doses are not commercially used and are not applicable for comparing to current commercial treatments. This section will generally only source studies with commercial market access treatments of doses less than 1,000 Gy.

It is not possible to summarise the effect of irradiation on all fresh fruit and vegetables in this review. There have been extensive reviews on the effects of irradiation on product tolerance and quality after treatment and storage (Morris and Jessup, 1994; Wall, 2015; Barkai-Golan and Follett, 2017; Golding and Singh, 2020). This review will examine the effects of irradiation on a range of important commodities which have been identified as current and potential candidates for increased trade using irradiation. The commodities of interest were broadly divided into four different groups; sub/tropical fruit, temperate fruit, berries and vegetables.

Tropical and subtropical fruit

Tropical fruit are often grown in areas with high pressures of 'exotic' quarantine pests such as fruit flies, which restricts the marketing of fruit from these areas into other areas which are free of these pests. Therefore, the development and application of market access phytosanitary treatments have traditionally been greater for important of tropical fruit such as mangoes.

The most common market access treatment for temperate fruit is cold treatment which involves treating the fruit with cold (for example <3 °C for 18 days). For many temperate fruit such as tablegrapes and cherries this is also the ideal storage temperature, and this cold treatment can be easily integrated into long supply chains. But many tropical fruit are susceptible to cold treatment and develop chilling injury at treatment temperatures, less than 7 °C (Wills and Golding, 2017). Chilling injury is a physiological disorder which prevents normal ripening and generally results in browning / bronzing symptoms on the skin which are commercially unacceptable. Therefore many tropical fruit cannot use cold treatment as a market access treatment. Other common phytosanitary market access treatments include fumigation, hot water treatments, vapour heat treatment and irradiation. This discussion will review the effects of irradiation on fruit quality and will periodically compare the use of irradiation to other common market access treatments such as hot water treatment.

Mango

Mahto and Das (2013) treated two local Indian mango cultivars (Dushehri and Fazli) with irradiation (300, 500, 700 and 1,000 Gy) and showed all irradiated fruit showed greener peel and lighter pulp throughout the storage. Loss of fruit due to postharvest decay was less in the irradiated fruit in both cultivars. All the treated fruit registered a slower rate of increase of sugars with storage compared to the respective controls and those treated with the lower doses of 500 and 700 Gy attained peak sugar concentration later. This study showed the ideal treatment dose of 300 – 700 Gy for Dushehri and 500 - 700 Gy for Fazli mango as a useful delay in ripening and extension of shelf-life by a minimum of 3 and 4 days, respectively (Mahto and Das, 2013).

Using other cultivars, Yadav et al. (2014) found that Alphonso mango fruit exposed to 400 Gy irradiation and stored at 9 °C resulted in significant reduction in physiological loss in weight, reduced ripening, increased marketability, whereas, maximum scores on skin and pulp colour, texture, taste and overall acceptability were observed in 400 Gy irradiated fruits stored at 12 °C. Yadev et al. (2013) also showed that when Kesar mango fruit exposed to 400 Gy and stored at 12 °C showed the highest total soluble solids, total and reducing sugars and ascorbic acid contend and minimum acidity compared to non-irradiated fruit stored at ambient condition at ripening stage.

Malik et al. (2013) demonstrated that no significant effect was found on firmness, lenticel disorders, weight loss, biochemical and organoleptic properties in three commercial mango cultivars from India; Sindhri, Samar Bahisht Chaunsa and Sufaid Chaunsa irradiated up to 1,000 Gy. However Cancino-Vázquez et al. (2020) showed that Ataulfo mangoes treated with 0, 150, 300 and 450 Gy had significant differences for sweetness, sourness, astringency, juiciness, firmness, mango odour and honey odour in at least one treatment. They showed treatment at 450 Gy were affected by irradiation, and concluded that 150 Gy could be used as phytosanitary treatment without substantially affecting the sensory properties of Ataulfo mango (Cancino-Vázquez et al., 2020).

Moreover, mangoes cv. Tommy Atkins treated at doses of 400 Gy and 1,000 Gy showed no significant differences in the total sugar content (Cruz et al., 2012). However, Uthairatanakij and Jitareerat (2018) report that irradiation induced fruit softening in Chok Anan mango fruit, but not in Nam Dok Mai mango. These results illustrate the cultivar variability in response to irradiation.

In a local study, Hofman et al. (2015) showed significant differences in the response to irradiation of different local mango cultivars at commercial maturity. They showed that in general irradiation treatment retarded softening in the early stages of ripening, but usually had little effect after 7 to 9 days storage. Irradiation also retarded the loss of green colour in most instances, resulting in eating soft fruit with less yellow skin colour. They showed that Honey Gold mangoes were the least affected by irradiation, with Kensington Pride mangoes generally having the least yellow colour at eating soft (Hofman et al., 2015). Irradiation did not affect total soluble solids at eating soft, but 500 Gy increased titratable acidity in all cultivars except B74 (Calypso™) mango, and increased titratable acidity in Kensington Pride fruit by more than 100%. They also showed that irradiation was shown to reduce the production of volatiles in Kensington Pride (Hofman et al., 2015). There were few effects at 500 Gy, but at 1,000 Gy the concentrations of all of the measured volatiles were significantly reduced compared to no irradiation. These results indicate that irradiation at typical disinfestation doses significantly reduces the external appearance of B74, Kensington Pride, Honey Gold and R2E2 mangoes by reducing the yellow colour and increasing lenticel disorder at eating soft. Honey Gold was generally the least affected by irradiation. It is likely that irradiation may also affect the flavour of Kensington Pride by increasing titratable acidity and reducing volatile concentrations during fruit ripening (Hofman et al., 2015).

There have been many studies comparing the relative effects of hot water treatment and irradiation on the quality of mango fruit following treatment and storage (Potchanachai et al., 2010; Hernández et al., 2018; Gómez-Simuta et al., 2017). For example, Hernández et al. (2018) showed there were no significant differences in the external and internal colour, total sugar content, firmness, pH, or weight of mango fruit cv. Ataulfo niño treated with 150 Gy irradiation and hot water treatment (46.3 - 47°C for 51 min). Gómez-Simuta et al. (2017) also reported the effect of different irradiation doses on the sensorial quality and the physiochemical properties of mango cv. Ataulfo compared with the traditional hot water treatment. They found that radiation at doses of 150 Gy and 300 Gy can be applied successfully as well as the hot water treatment. They also showed there were no significant differences between irradiation treatments in terms of weight loss, external and internal colour, pH, soluble solids, titratable acidity and firmness, and consumer acceptance (Gómez-Simuta et al., 2017).

Many of the responses to irradiation are cultivar specific, growing time, harvest maturity etc. However these interactions are often not observed in single factor storage trials (e.g. just comparing irradiation doses in one batch of fruit) and are only observed when in well designed and conducted research trials. A good example is the development of lenticle browning which is a major storage problem for mangoes. Irradiation treatment has been shown to significantly induce the development of a lenticle disorder in B74 (Calypso™) mangoes (Marques et al., 2016), but this can be successfully managed with harvesting and treating fruit with more advanced maturity. Roberto et al – not published showed that regardless of dose, irradiation treatment of ripening fruit at ~70% yellow skin reduced the lenticle disorder on the ripened fruit by 36 – 47% compared to irradiating unripe green mature fruit at ~10% yellow skin. Irradiation of ripening fruit at 300 – 800 Gy consequently resulted in 74 – 100% marketable fruit at ripe compared to 5 – 59% for irradiation of the green mature fruit. Irradiating ripening fruit also minimised delays in loss of green skin during ripening. B74 fruit sensitivity to the lenticle disorder decreases as fruit ripen and so delaying irradiation treatment until the fruit have partially ripened may be a commercially viable option to reduce quality loss due to lenticle disorder, provided the fruit can be marketed quickly to compensate for a shorter post-treatment shelf-life (in press).

Citrus

While cold treatment protocols have successfully enabled exports of oranges and mandarins to key export markets, the development of chilling injury in response to cold treatment can limit exports in some susceptible citrus types such as lemons. Another market access tool for the Australian citrus industry is irradiation. This sub-component summarises the effects of low dose irradiation on internal quality (TSS and TA), potential injury / disorders following treatment, Vitamin C and consumer aspects following commercial irradiation.

This review is from the recent literature review '*Exploring the potential of low dose irradiation phytosanitary treatments for the Australian citrus industry*' by John Golding and Lluis Palou from the Hort Innovation 'Australian Citrus Postharvest Science Program' (CT15010).

Internal quality

Total soluble solids (TSS) also known as soluble solids content - SSC (% Brix) is a relative measure of the sugar content in citrus fruit. Together with titratable acidity (TA) which is a measure of the acidity or sourness of the fruit, these fruit quality components combine to determine overall fruit taste and acceptability. The effects of low dose irradiation on TSS and TA levels in citrus fruit are presented in Table 8 and show that in general irradiation does not consistently affect TSS or TA in citrus fruit.

Table 8. Summary of the effects of irradiation on total soluble solids - TSS (% Brix) and titratable acidity - TA (% citric acid) in citrus fruit.

Fruit	Dose (Gy)	TSS (% Brix)	TA (% citric acid)	Reference
Grapefruit Rio Red	70, 200, 300, 400, 700	Early season not affected. Later harvest no differences after storage	Early season not affected. Later harvest irradiated higher TA	Patil et al. (2004)
Grapefruit Rio Red	150, 300, 400, 500	No change	No change	Hallman and Martinez (2001)
Orange Navel	200, 400, 600	No difference (except 400 and 600 Gy lower TSS)	No difference, (except at 600 Gy lower TA)	McDonald et al. (2013)
Orange Ambersweet, Hamlin, Navel, Pineapple, Valencia	250, 300, 450	No effect (except decrease in Ambersweet at 300 Gy)	No effect	Miller et al. (2000)
Mandarin Clementine	510, 875	No consistent differences	No consistent differences	Palou et al. (2007a)
Mandarin Clementine	195, 395, 510, and 875	No consistent differences	No consistent differences	Palou et al. (2007b)
Mandarin Fallglo, Minneola, Murcott, Sunburst, Temple	250, 300, 450	No effect (except decrease in Sunburst at 450Gy)	No effect (except decrease in Sunburst and Tangelo at 450Gy, and increase Murcott at 300Gy)	Miller et al. (2000)
Mandarin Seedless Kishu	150, 400, 1,000	No change	No change	Ornelas-Paz et al. (2017)
Mandarin Shatang	200, 300, 400, 500, 600	Up to 30 days storage - no differences	Decrease TA with increasing dose, during storage	Zhang et al. (2014)
Orange Navel	200, 400, 600, 800, 1,000	No change	No change	Noh et al. (2016 a, b)
Orange Marrs	150, 300, 400, 500	No change	No change	Hallman and Martinez (2001)
Lime Tahitian	50, 100, 150 and 200; 250, 750	Response varied with harvest time	Response varied with harvest time	da Silva et al (2016)
Pommelo Sarawak, Chandler	150, 1,000	No consistent effects	No consistent effects	Jain et al. (2017)

Orange

O'Mahony and Goldstein (1987) and McDonald et al. (2013) found a decrease in TSS and TA at irradiation dose levels between 300 and 600 Gy but Miller et al. (2000) did not report changes in TA of oranges treated at irradiation doses of 150 – 450 Gy. McDonald et al. (2013) concluded that the overall changes in combined TSS and TA as shown by changes in BrimA ('Brix minus acid') after 4 weeks of storage, were relatively small (0.31 units). This, combined with the results of their sensory testing, suggested that the effects of irradiation on TSS and TA may have limited importance in terms of flavour.

In a study of low dose irradiation (200, 400, 600, 800 and 1,000 Gy) on imported Navel oranges stored for either 20°C for 12 days or 3°C for 45 days reported no significant effect of irradiation in TSS/TA ratio, total sugar content, reducing sugar content (Noh et al., 2016 a, b). While Hallman and Martinez (2001) found no change in TSS or TA in Marrs oranges treated up to 500 Gy and stored for 21 days at ambient temperature.

Mandarin

Miller et al. (2000) showed that irradiation (150, 300 and 450 Gy) did not generally affect TSS or TA of five mandarin hybrids, Fallglo, Minneola, Murcott, Sunburst, and Temple, with the exception of a decrease in of Sunburst mandarin at 450 Gy and a reduction in TA of Sunburst and Temple at 450 Gy, but an increase at 300 Gy in Murcott. While these few differences may have been statistically different, the effects on overall taste and flavour would be low even with an untrained panel of seven people. Miller et al. (2000) showed the acceptability of juice and pulp flavour was not affected. Sensory and consumer aspects of irradiation on consumer acceptability is discussed in the *Consumer Acceptability Section* (page 28). Ornelas-Paz et al. (2017) further showed no consistent effect of low dose irradiation (150, 400, and 1,000 Gy) on TSS or TA in Seedless Kishu mandarins. While Zhang et al. (2014) showed with Shatang mandarin treated at 200, 300, 400, 500 and 600 Gy, TSS and TA had no significant differences compare to those of the control during the first 2 weeks storage at 4°C, but after this storage time increasing dose reduced TA levels. However there were no significant differences in TSS between irradiated and non-treated fruits after 30 days storage (Zhang et al. 2014). Palou et al. (2007a, b) also showed there were no consistent differences on TSS and TA in Clemenules mandarins after different times in storage where in general, irradiation had no effect on TSS or TA.

Other citrus

Grapefruit

Patil et al. (2004) showed harvest time had a significant impact on the treatment effects of irradiation on Rio Red grapefruit. In early season grapefruit, TSS and TA were not affected due to irradiation or storage, but late harvest grapefruit exposed to irradiation (70 – 700 Gy) retained acidity better than the fruit not exposed to irradiation. Patil et al. (2004) further showed that the initial TSS was the lowest in the late season fruit exposed to the 700 Gy treatments; however, no differences among treatments were observed after storage. Hallman and Martinez (2001) further found no change in TA or TSS in Rio Red grapefruit treated up to 500 Gy and stored for 21 days at ambient temperature.

Lime

The effects of irradiation in the internal quality of Tahitian limes were affected by harvest time ('on' and 'off'-season fruit) and irradiation dose (da Silva et al., 2016). They showed irradiation reduced TSS in fruit from the 'off'-season, but not fruit harvested in the regular harvest period. They also showed higher TA values in the 'off'-season fruits treated with 50 Gy, as compared with untreated fruits (da Silva et al., 2016). Thus in this trial, the interaction of harvest time and irradiation was significant and should be considered.

Pummelo

Jain et al. (2017) showed no consistent effects of 150 and 1,000 Gy irradiation on TSS and TA values in Chandler and Sarawak pummelos stored for 3 weeks at 12 °C and after an additional week at 20 °C. The differences were low and did not affect consumer acceptability of the treatment (Jain et al., 2017).

Injury and disorders

Citrus is relatively sensitive to irradiation and the response to treatment is highly variable and dependent on species, hybrid, and cultivar (Miller et al., 2000). Physical injury can occur at low doses (< 1,000 Gy) and usually occurs in the peel as peel pitting and fruit softening (Wall, 2015). For example Miller et al. (2000) treated ten citrus cultivars grown in Florida, including the five orange [*Citrus sinensis* (L.) Osbeck] cultivars, Ambersweet, Hamlin, Navel, Pineapple, and

Valencia, and the five mandarin hybrids (*Citrus reticulata* Blanco), Fallglo, Minneola, Murcott, Sunburst, and Temple, with low dose irradiation at 0, 250, 300 and 450 Gy, and stored for 14 days at 1 °C or 5 °C plus 3 days at 20 °C, to determine dose tolerance based on fruit injury. They showed that fruit softening of Valencia, Minneola, Murcott, and Temple was dose-dependent, but other cultivars were unaffected. Only Ambersweet, Valencia, Minneola, and Murcott did not develop peel pitting at 150 Gy or higher, whilst all the other cultivars were injured (Miller et al., 2000).

While limited studies have been conducted on the causes of damage, Riov (1975) showed that irradiation induced pitting which may be caused by the accumulation of phenolic compounds in flavedo cells leading to cell death and peel necrosis that manifest as pitting (Figures 3 and 4).

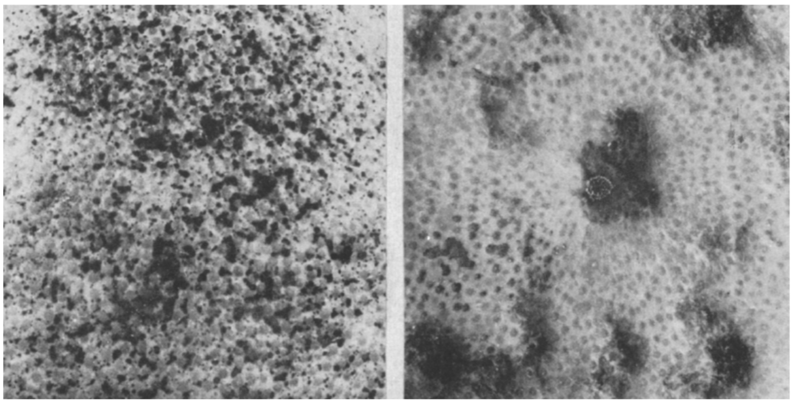


Figure 3. Symptoms of external radiation damage in Marsh Seedless grapefruit peel 7 days after irradiation with 2,400 Gy. Damage symptoms at the stem end (left) and damage symptoms at the stylar end (right).
(from Riov (1975); Radiation Botany 15, 257-260).

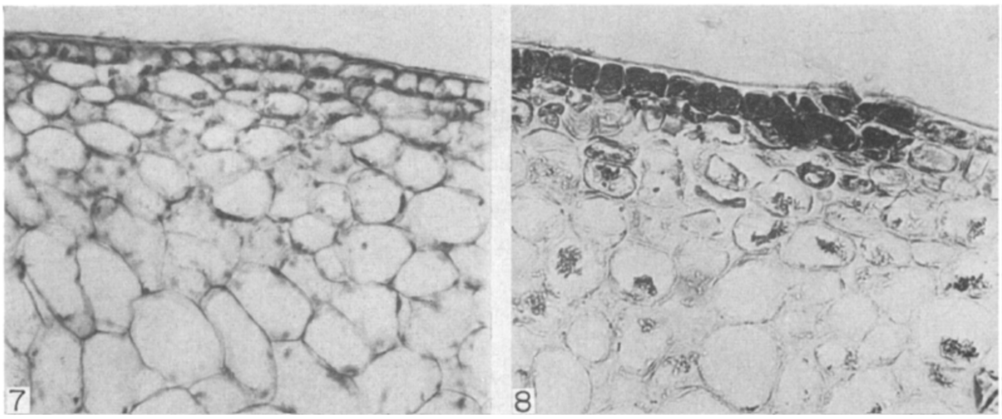


Figure 4. Cross sections in the outer flavedo layers at the stem end of control and irradiated Shamouti orange treated with 2,400 Gy. Untreated control Shamouti orange stained with diazo-safranin (× 290) (left). Irradiated Shamouti orange stained with the GIBBS' reagent (right). Phenolic compounds which accumulate in the outer flavedo layers are seen mainly in the epidermis (× 290). (from Riov (1975) Radiation Botany 15, 257-260).

A summary table of the literature on the effect of irradiation on citrus disorders in presented in Table 9 and shows different types of symptoms that may develop within different cultivars and treatment doses.

Table 9. Effects of irradiation on visual quality of citrus fruit.

Fruit	Dose (Gy)	Injury / Disorder	Reference
Orange Mosambi	250, 500, 1,000, 1,500	Peel disorder in the form of brown sunken areas after 90 days and reduced fruit firmness at > 250 Gy	Ladaniya et al. (2003)
Orange Ambersweet, Hamlin, Navel, Pineapple, and Valencia	0, 250, 300, 450	Fruit softening of Valencia was dose-dependent, but that of all other cultivars was unaffected. Pitting - Hamlin, Navel, Pineapple developed peel pitting injury, but Ambersweet and Valencia did not develop any symptoms.	Miller et al. (2000)
Orange Lane Late	200, 400, 600	Surface pitting and visual damage after treatment with 400 and 600 Gy – see Figure 5	McDonald et al. (2013)
Orange Navel	320-370 and 520-600	Increased brown blemishing and pitting	O'Mahony and Goldstein (1987)
Orange Valencia	300, 500, 750, 1,000	No damage at 750 Gy	Nagai and Moy (1985)
Orange Washington Navel, Valencia	75, 150, 300	No damage up to 300 Gy	Macfarlane and Roberts (1968)
Orange Valencia Late	350, 800	No damage	Betancurt et al. (2007)
Mandarin Fallglo, Minneola, Murcott, Sunburst, Temple	0, 250, 300, 450	Fruit softening of Minneola, Murcott, and Temple was dose-dependent, but that of other cultivars was unaffected. Pitting - Minneola, and Murcott did not develop peel pitting at 150 Gy or higher, whilst all the other cultivars were injured	Miller et al. (2000)
Mandarin Nagpur	250, 500, 1,000, 1,500	No rind disorders up to 1,500 Gy	Ladaniya et al. (2003)
Mandarin Clemenules	195, 395	Slight to moderate rind browning immediately after treatment, but no damage after 12 days cold storage	Alonso et al. (2007)
Mandarin Seedless Kishu	150, 400, 1,000	400 and 1000 Gy promoted browning of the calyx end and fungal infection	Ornelas-Paz et al. (2017)
Mandarin Shatang	200, 300, 400, 500, 600	No effect, but increased decay with high levels	Zhang et al. (2014)
Grapefruit Rio Red	150, 300, 400, 500	No effect	Hallman and Martinez (2001)
Grapefruit Rio Red	70, 200, 400, 700	Early season Rio Red grapefruit was more sensitive to later season fruit, particularly at 700 Gy in the early season fruit. But overall appearance of all fruit was still acceptable as judged by consumers	Patil et al. (2014)
Pumello Chandler, Sarawak	150, 1,000	Peel damage was greater and developed more quickly in irradiated fruit and was more severe when the fruit was stored at ambient	Jain et al. (2017)

Fruit	Dose (Gy)	Injury / Disorder	Reference
		temperature for a week	
Lemon Lisbon	75, 150, 300, 600, 1,000	Peel damage increased with dose. Lemons at a green stage were more severely affected than yellow lemons	Jessup et al. (1992)
Lemon Eureka	500 – 3,000	Some minor peel damage and cavitation at 500 Gy	Maxie et al. (1964)
Lime Tahitian	50, 100, 150 and 200; 250, 750	> 100 Gy caused skin yellowing	da Silva et al. (2016)

Orange

Lane Late navel oranges had increased surface pitting and visual damage after treatment with 400 and 600 Gy (McDonald et al. 2013). Figure 5 shows the typical symptoms of irradiation damage, with brown blemish and pitting in Lane Late navel oranges following treatment at 400 and 600 Gy and storage. Table 10 quantifies the levels of damage in these fruit following treatment and storage. O'Mahony and Goldstein (1987) also found increased brown blemishing and pitting of whole navel oranges irradiated at 300 and 600 Gy. While in another study, Valencia oranges were tolerant to 750 Gy treatment and storage for 7 weeks at 7 °C (Nagai and Moy, 1985). In a comparison of different orange cultivars, Miller et al. (2000) showed that Ambersweet and Valencia oranges tolerated 500 - 600 Gy irradiation, but Hamlin, Navel, and Pineapple cultivars were injured at 150 Gy.

Macfarlane and Roberts (1968) showed treating Washington Navel oranges with less than 300 Gy were commercially acceptable, however injury increased as the dose was increased over the range studied. In addition, the severity of injury depended on the variety and, particularly for Washington Navels, on the part of the season when the fruit was picked and treated (Macfarlane and Roberts, 1968). From a limited data set, early season Washington Navel fruit harvested from coastal NSW was very susceptible to injury, whilst late season fruit was relatively resistant. In a subsequent smaller experiment with Valencia oranges, harvest time made little difference (Macfarlane and Roberts, 1968). Indeed Betancurt et al. (2007) also showed no effect of 350 and 800 Gy irradiation on Late Valencia appearance and fruit quality.

In addition to external appearance, McDonald et al. (2013) detected some internal drying and granulation in Lane Late navel oranges with higher irradiation treatments. They showed that after 3 weeks of storage, 25% and 29% of the fruit treated at doses of 400 and 600 Gy, respectively, showed some degree of segment drying, but none of the control or fruit treated at 200 Gy showed any symptoms. In addition, they showed granulation was present in an average of 17% of the 600 Gy fruit and in none of the other treatments. However the extensive taste panel assessment did not detect any differences changes due to dose or storage time (McDonald et al., 2013). However in other studies, with Clemenules mandarin fruit (Alonso et al., 2007), Fortune hybrid fruit Alonso et al. (2002) and Nagpur mandarins (Ladaniya et al., 2003) there has been no reports of juice loss due to irradiation.

4 weeks at 3 °C 3 weeks at 3 °C + 1 week at 20 °C

Control (0 Gy)

200 Gy

400 Gy

600 Gy

Figure 5. Effect of low dose irradiation on visual quality of Lane Late navel oranges after 4 weeks storage at 3 °C (left) and 3 weeks at 3 °C and one week at 20 °C shelf-life (right) (from McDonald et al., 2013).

Table 10. External damage values for Lane Late navel oranges treated at four different dose levels and evaluated after 1 day, 3 weeks and 4 weeks following irradiation treatment with injury / damage scored using 1–6 scale where 1 = no damage, 4 = moderate damage, 6 = very severe damage. % of fruit rated moderate or above is indicated next to predicted mean score (from McDonald et al., 2013).

External damage score and % of fruit rated 4 (moderate) and above						
Dose (Gy)	**1 day**		**3 weeks**		**4 weeks**	
0	2.0	6.9%	2.1	6.6%	2.0	3.5%
200	1.9	4.5%	2.3	7.3%	2.4	11.1%
400	2.1	10.8%	3.0	33.0%	3.4	50.3%
600	2.1	9.4%	3.6	55.9%	3.8	68.4%

Mandarin

Similar to oranges, the tolerance of mandarins to irradiation is dependent on cultivar and other pre and postharvest factors. Miller et al. (2000) showed that the mandarin hybrids Minneola and Murcott showed tolerance at 500-600 Gy, but peel pitting occurred for Fallglo, Sunburst and Temple cultivars at 150 Gy. Ladaniya et al. (2003) showed the Nagpur mandarin tolerated doses up to 1,000 Gy. While Shatang mandarin was not affected by treatment up to 600 Gy (Zhang et al., 2014).

Alonso et al. (2007) observed a slight to moderate rind browning in X-ray irradiated Clemenules mandarin fruit at both 195 and 395 Gy after two days at 20 °C. However, this damage was not evident after the 12-day cold storage period and this underscores the random nature of these disorders and could be attributed to interactions with other postharvest factors such as the coating used in this experiment (Alonso et al., 2007).

While some cultivars have tolerance to irradiation, some mandarin types are very sensitive to irradiation. For example, Ornelas-Paz et al. (2017) found Seedless Kishu mandarins (*Citrus kinokuni mukakukishu*) treated with 150 Gy developed peel damage and browning of the calyx. This is not the classic pitting damage, but a general browning and senescence of the peel which becomes highly susceptible to fungal damage (Figure 6). The severity of the browning damage increased with irradiation dose, especially for fruit located on the top layer of the cases but browning severity was not objectively evaluated in this study and further studies are needed in this regard.

Figure 6. Irradiation damage on the peel of kishu mandarins after three weeks of storage. (from Ornelas-Paz et al. (2017) Effect of phytosanitary irradiation on the postharvest quality of Seedless Kishu mandarins (*Citrus kinokuni mukakukishu*). *Food Chemistry* 230, 712-720.)

Other citrus

Grapefruit

Treatment of grapefruit with a dose of 300 Gy resulted in minimal injury to the fruit (Spalding and Davis, 1985; Miller and McDonald, 1996). While Hallman and Martinez (2001) demonstrated that Rio Red grapefruit exposed to irradiation doses of up to 500 Gy did not affect appearance compared to untreated fruit. Type and intensity of injury to grapefruit due to low dose irradiation (300 – 900 Gy) has been attributed to time of harvest. Early-season grapefruit, harvested from October to December (northern hemisphere), were more susceptible to scald and less susceptible to rind breakdown, while late-season fruit were more susceptible to rind breakdown after irradiation and storage (Hatton et al., 1982). Patil et al. (2014) further showed early season Rio Red grapefruit was more sensitive to later season fruit, particularly at 700 Gy in the early season fruit. Overall appearance of all fruit was still acceptable as judged by consumers.

Pummelo

The peel damage in Chandler (red flesh) and Sarawak (white flesh) pummelos treated with 150 Gy and 1,000 Gy is described in Figure 7 (Jain et al., 2017). The damage was greater and developed more quickly in irradiated pummelos and became even more severe when the fruit was stored at ambient temperature for one week. However this damage was low and Jain et al. (2017) suggest this could be managed with minimal handling and good temperature control. The quality of irradiated pummelos stored at refrigerated temperature for 3 weeks was similar to untreated pummelos, however, physical handling and exposure to higher temperatures resulted in increased peel pitting of irradiated fruit compared to non-treated fruit. Jain et al. (2017) concluded that irradiation could serve as a potential phytosanitary treatment for Chandler and Sarawak pummelos, provided that the fruit is subjected to minimal handling and not temperature abused.

Figure 7. Peel damage in Chandler pummelo irradiated at 150 Gy after 4 weeks of storage - 3 weeks at 12 °C and one week at 20 °C (from Jain et al. (2017) Effect of phytosanitary irradiation on the quality of two varieties of pummelos (*Citrus maxima* (Burm.) Merr.) *Scientia Horticulturae* 217, 36-47).

Lemon

Lisbon lemons harvested at two different maturity stages (green and completely yellow) which grown in the NSW Central Coast, were treated with 75, 150, 300, 600 and 1,000 Gy (Jessup et al. 1992). They showed that peel damage increased with increasing irradiation dose. Lemons that were harvested at a green stage, were more severely affected than yellow lemons (Table 11). In addition irradiation caused flesh discolouration and cavitation (Table 11), as well as albedo discolouration and toughness, particularly at the higher dose rates (Jessup et al., 1992).

Maxie et al. (1964) treated Eureka lemons with high irradiation treatments (500 – 3,000 Gy), but even at the lower irradiation doses (500 Gy), there was some minor peel damage and cavitation.

Table 11. Effect of low dose irradiation and subsequent storage at 15 °C on damage to Lisbon lemons harvested at either a green or completely yellow stage (from Jessup et al., 1992).

Type of damage to fruit and maturity tested						
	Peel Damage		Flesh discolouration		Cavitation	
	Yellow	Green	Yellow	Green	Yellow	Green
5% lsd	*0.42*		*0.45*		*0.23*	
0	1.0	1.0	1.0	1.0	1.0	1.0
75	1.8	2.3	1.1	1.0	1.0	1.0
100	2.4	3.1	2.0	2.1	1.0	1.0
300	2.6	3.6	2.7	2.1	1.2	1.0
600	2.5	3.1	2.6	2.3	1.3	1.2
1,000	3.0	4.0	3.5	2.5	1.7	1.2

Lime

In a preliminary trial, da Silva et al. (2016) showed 250 and 750 Gy doses negatively affected skin quality and pulp of Tahitian limes. They then used lower doses of irradiation (50, 100, 150, and 200 Gy) and showed doses > 100 Gy caused skin yellowing in harvested fruits and concluded that doses between 50 Gy and 700 Gy caused damage to the quality of lime fruit during storage at room temperature (de Silva et al., 2016).

Vitamin C

Citrus is a rich source of ascorbic acid (AA, vitamin C) and is a major dietary contributor to all age and gender groups in Australia and New Zealand, with the exception of 17-18 year old Australian females (FSANZ 2014). Indeed, citrus fruit provides between 5 to 17% of AA intake of Australians (FSANZ, 2014). Therefore the potential effects of irradiation on vitamin C content of citrus is important. Citrus are not a major source of dietary carotene, thiamin, riboflavin, niacin, folate or vitamins E and B6 in Australia and New Zealand (FSANZ ,2014), therefore this review will focus on the effects of irradiation treatment on AA and carotenes.

Substantial data documents the natural variation in levels of vitamin C in citrus fruit (Lee and Kader, 2000; Magwaza et al., 2017). Extensive natural variation occurs in the vitamin C content in citrus where the main sources of variation are cultivar, season, growing location and orchard management, indeed there is more than four-fold being common between citrus types (Magwaza et al., 2017). In addition, postharvest treatments and storage contribute to decreased levels of vitamin C during storage (Lee and Kader, 2000; Mditshwa et al., 2017).

Vitamin C is widely regarded as a most important water-soluble antioxidant. It includes all compounds exhibiting the biological activity of L-ascorbic acid (AA) plus L-dehydroascorbic acid (DHAA), its oxidation product (Lee and Kader, 2000). However, vitamin C is inherently unstable in solution, with its destruction affected by temperature, light and pH (Eitenmiller et al., 2008). As such, vitamin C is one of the most sensitive vitamins to irradiation, with the effects of irradiation influenced by exposure to oxygen, storage and temperature, as well as the pH of the food matrix or storage medium (Kilcast, 1994). Irradiation results in some AA being converted to DHAA (Kilcast, 1994), however both forms have vitamin C activity (Tsujimura et al., 2008). Therefore, when interpreting findings of irradiation studies it is important to consider that losses due to irradiation may be overestimated if only AA is reported. Hence, total vitamin C (AA plus DHAA) content is a more reliable indicator of post-irradiation vitamin C.

There have been several studies on the effects of irradiation on nutrient composition of orange, mandarin, lemon, lime and grapefruit. The findings of these studies are summarised in Table 12 (FSANZ, 2014) with additional data from the literature.

Orange

In Kau oranges, there was no significant effect of X-ray irradiation at 750 Gy on AA levels. Similarly, total carotenoids did not change with irradiation after two days but increased by 33% after nine days storage (Boylston et al., 2002). In blood oranges, irradiation with 250 and 500 Gy slowed the loss of AA for six weeks storage, resulting in higher AA levels in oranges irradiated with 500 Gy (Khalil et al., 2009).

In Mosambi oranges, AA decreased initially at doses of 1,000 Gy (-22%) and 1,500 Gy (-16%). However, this effect was lost throughout the storage period as all groups exhibited AA losses (0 Gy; -31%. 250 Gy; -26%, 500 Gy; -33%, 1,000 Gy; -4%, 1,500 Gy; -16%) (Ladaniya et al., 2003). As only AA was measured, some of the variability in this data may be through transformation to DHAA. Furthermore, the statistical analyses were limited to ANOVA; results of post-hoc testing were not presented thereby limiting interpretation as dose-effects that cannot be separated.

De Bortoli et al. (2015) reported that low dose irradiation (10, 20, 30, 40, 50, 100, 150 and 200 Gy) had no effect on AA levels in Valencia oranges, however no data or methodology were described, and little impact should be taken from this report.

Noh et al. (2016) and Cho et al. (2015) showed that in general treatment with 200, 400, 600, 800 and 1,000 Gy resulted in statistically lower vitamin C levels in Navel oranges imported into Korea during storage at 3°C and at room temperature (20°C) respectively, but these effects were variable at different storage times.

Mandarin

Irradiation with 75 and 300 Gy had no significant effect on total vitamin C content in Ellendale mandarins, within a week of irradiation or after three weeks storage (Mitchell et al., 1992). Vitamin C levels decreased 10 to 12% in Ellendale mandarins, irrespective of irradiation. In contrast, Imperial mandarins showed no early effects of irradiation, but after three weeks storage the vitamin C levels decreased by 46% in non-irradiated fruit and 69% and 78% in fruit irradiated at 75 and 300 Gy, respectively. At this time, total vitamin C levels were significantly lower in irradiated compared to control mandarins.

Another study measured AA levels in Nagpur mandarins irradiated with 250, 500, 1,000 and 1,500 Gy. Irradiation doses of ≥ 500 Gy decreased AA content by approximately 15% (Ladaniya et al., 2003). However, diminution of AA was not dose-dependent, and AA levels fluctuated throughout the storage period. This variability in AA suggests conversion between AA and DHAA may be occurring. As DHAA was not measured, it is not possible to determine the extent of vitamin C loss in this study.

Clementine mandarin

A study in Clementine mandarins detected no significant change in total vitamin C levels after X-ray irradiation with 510 and 875 Gy (Rojas-Argudo et al., 2012). Similarly, work from the same group using up to 164 Gy in combination with up to 12 days storage showed no significant change in total vitamin C, except for an early increase in total vitamin C in Clementine mandarins irradiated with 54 Gy (Contreras-Oliva et al., 2011). A third study in Clementine mandarins assessed the impact of irradiation in combination with washing / waxing and storage (Mahrouz et al., 2002). In this study, AA levels fluctuated throughout the seven-week experimental period but decreased in all groups during storage. After seven weeks, there was no significant effect of irradiation on AA content (Mahrouz et al., 2002).

Other citrus

Grapefruit

Two studies from the same group showed there was no consistent effect of low dose irradiation on AA and β-carotene levels in grapefruit. In the first study, there was no effect of irradiation with 70 – 700 Gy on β-carotene or total carotenoid levels in Rio Red grapefruit in early harvest fruit after 35 days storage at 10°C (Patil et al., 2004). However, irradiation doses of 200 Gy or higher, significantly reduced vitamin C content after 4 weeks storage at 10 °C in late-season Rio Red grapefruit (Patil et al., 2004).

β-carotene levels increased with storage in early harvest fruit irrespective of irradiation dose, but not in late harvest fruit. A similar study using 300 Gy doses showed no significant change in either AA or β-carotene levels after 4 and 6 days storage (Vanamala et al., 2005). A third study from the same group indicated significant losses of total vitamin C in two cultivars with very high doses of electron-beam irradiation (Girennavar et al., 2008). In this study, fruit were exposed to 1,000, 2,500, 5,000 and 10,000 Gy. These treatments are extreme but showed no significant change in Rio Red grapefruit with 1,000 Gy, but a statistically significant loss in Marsh White grapefruit at the same dose. However, at higher doses, large losses of vitamin C occurred in a dose-dependent manner, with losses of >50% at 10,000 Gy. In contrast, β-carotene levels were unaltered by any dose of irradiation in Rio Red grapefruit. These irradiation doses are ten times the levels used for quarantine treatment and are only presented as a guide for extreme high level treatment.

Lemon

Irradiation with 75 and 300 Gy had no significant effect on total vitamin C content in lemons and stored for up to three weeks. Storage had little effect on vitamin C content in irradiated lemons (+1% and -5% change), while vitamin C content decreased 9% in non-irradiated lemons (Mitchell et al., 1992).

Lime

In limes, AA levels fluctuated during storage, but were decreased initially by doses of ≥500 Gy. AA levels remained lower in limes irradiated with ≥1,000 Gy for 90 days storage (Ladaniya et al., 2003).

Other non-vitamin bioactive compounds

Whilst citrus is a good source of traditional nutrients such as certain vitamins, minerals and fibre, nutritionists have more recently focused on a range of substances called 'non-vitamin bioactive compounds' or phytochemicals. An orange has over 170 different phytochemicals and more than 60 flavonoids which have been shown to have anti-inflammatory and anti-tumour activity as well as inhibiting blood clots and having strong antioxidant activity (Baghurst, 2000). This section reviews the use of low dose irradiation on these compounds.

Irradiation with 30, 54 and 164 Gy did not decrease total antioxidant capacity and total phenolic content in Clementine mandarins, and flavanone glycoside levels were similar or increased in irradiated fruit after 0 and 6 months storage (Contreras-Oliva et al., 2011). Irradiation of Clementines at a mean dose of 300 Gy followed by storage for 49 days at 3 ^{o}C resulted in enhanced synthesis of phenolic compounds, primarily hesperidin as the major flavanone glycoside, and nobiletin and heptamethoxyflavone as the major polymethoxylated flavones. Initially, the content of these flavonoids in peel was significantly lower than in controls but biosynthesis increased between days 14 and 21. The irradiation enhanced content of these flavonoids and of para-coumaric acid, a biosynthetic precursor to the coumarins scopoletin and scopolin, may relate to enhanced resistance to mould decay, while the low irradiation dose and cold storage helped to minimize losses due to pitting of the peel (Oufedjikh et al., 2000). After 12 months storage, small decreases in flavanone glycoside levels occurred in fruit irradiated with 164 Gy (-7% to -12%). However, irradiation of clementine mandarins with 51 and 875 Gy did not alter flavanone glycoside levels after two months storage (Rojas-Argudo et al., 2012).

In grapefruit, effects of irradiation on flavanones were variable; higher doses (400 and 700 Gy) led initially to small reductions in naringin and narirutin in early season fruit, but these changes were lost after 35 days storage, and did not occur in late season fruit (Patil et al. 2004). However, total flavanone levels were increased by irradiation with 70 and 200 Gy after 35 days storage in early season fruit. Lycopene levels were similar between control and irradiated grapefruit ≤1,000 Gy, with the exception of a small decrease (~10%) after 35 days storage in late harvest fruit irradiated with 700 Gy (Patil et al., 2004; Vanamala et al., 2005; Girennavar et al., 2008). Lycopene levels were >25% lower in late harvest compared to early harvest fruit, irrespective of irradiation. Limonin levels in grapefruit were also unaffected by irradiation with <1,000 Gy (Patil et al., 2004).

Table 12. Effects of irradiation on radiation-sensitive nutrients in citrus fruit.
Data primarily complied by FSANZ (2014) with addition of literature (2014).

Fruit	Dose (Gy)	Carotene	Vitamin C	Other components	Analysis method / Reference
Grapefruit	70, 200, 300, 400, 700	No change	No change	Flavonones: variable Lycopene: similar Limonin: no change	AA by HPLC Patil et al. (2004) Vanamala 2005
Grapefruit (≥1,000 Gy)	1,000, 2,500, 5,000, 10,000	No change	Dose-dependent decrease	Flavonoids and lycopene: No change with 1,000 Gy, variable effects with >1,000 Gy	Total vitamin C by HPLC Girennavar et al. (2008)
Lemon	75, 300	n.d.	No change	n.d.	Total vitamin C by derivatization Mitchell et al. (1992)

Fruit	Dose (Gy)	Carotene	Vitamin C	Other components	Analysis method / Reference
Lime Kagzi	0, 250, 500, 1,000, 1,500	n.d.	Variable. Decreased with 1,500 Gy#	n.d.	AA by titration Ladaniya et al. (2003)#
Mandarin Clementine	30, 54, 164, 510, 875	n.d.	No change	Antioxidant capacity, phenolics: no change Flavanone glycosides: no change ≤6 months storage	Total vitamin C by HPLC Rojas-Argudo et al. (2012) Contreras-Oliva et al. (2011)
Mandarin Ellendale	75, 300	n.d.	No change	n.d.	Total vitamin C by derivatization Mitchell et al. (1992)
Mandarin Imperial	75, 300	n.d.	-43%* and -60%* after 3 wk	n.d.	
Mandarin Nagpur	0, 250, 500, 1,000, 1,500	n.d.	Dose-dependent decreases for ≥ 500 Gy#	n.d.	AA by titration Ladaniya et al (2003)#
Orange Lane Late	200, 400 and 600	n.d.	No change	Phenolic content: no change Antioxidant capacity, phenolics: no change	AA by titration McDonald et al. (2013)
Orange Kau	750	+33%* after 9 d	No change	n.d.	AA by titration Boylston et al. (2002)
Orange Navel	200, 400, 600, 800 and 1,000	n.d.	Dependent on storage time	n.d.	Cho et al. (2015) Noh et al. (2016)
Orange Mosambi	0, 250, 500, 1,000, 1,500	n.d.	Immediate decrease with ≥1,000 Gy, but no difference after storage#	n.d.	Ladaniya et al. (2003)#
Orange Valencia	10, 20, 30, 40, 50, 100, 150 and 200	n.d.	No change	n.d.	AA methods not reported De Bortoli et al. (2015)
Orange blood	0, 250, 500	n.d.	AA higher in irradiated fruit after 1-6 weeks storage	n.d.	AA by titration Khalil et al. (2009)

**Significant difference. n.d.; not determined.*
#AA determined, therefore some losses may be due to conversion to DHAA, and statistical analyses limit individual comparisons in this study.

In summary, Food Standards Australia New Zealand (FSANZ, 2014) reviewed the published literature on the effects of phytosanitary of irradiation dose on fresh fruit and vegetables and concluded that low dose irradiation:

- had no effect on carotene levels in fruits and vegetables,
- did not decrease vitamin C levels in the majority of fruits and vegetables,
- had little effect on other non-vitamin bioactive compounds.

In some cultivars of different fruits, vitamin C levels decreased following irradiation. This was also seen in literature on the citrus irradiation treatment (Table 12). However, in the majority of these cases the vitamin C content of irradiated fruit remained within the range of natural variation. In addition, when the effects of these changes were compared to dietary consumption patterns it was evident that these changes were unlikely to impact on dietary vitamin C intakes in Australia and New Zealand. FSANZ (2014) concluded that phytosanitary doses of irradiation do not pose a nutritional risk to the Australian and New Zealand populations and recommended that the data requirements for applications to irradiate fruits and vegetables can be streamlined to focus on data for vitamin C, with requirements for other nutrients to be determined on a case-by-case basis. For citrus, the results above show that different fruit types and cultivars respond differently to irradiation treatments. This calls for the development of cultivar-specific irradiation treatment protocols. Vitamin C is water-soluble, and is sensitive to irradiative degradation, particularly at higher treatment doses (Kilcast, 1994). To reduce vitamin C loss, irradiation treatments could be conducted at low temperatures (Mditshwa et al., 2017).

Consumer acceptability

The consumer acceptability of irradiated fruit is the ultimate determinant of commercial acceptability. There have been limited studies on the trained panel and consumer acceptability of citrus following irradiation. Mc Donald et al. (2013) examined the dose tolerance of Lane Late navel oranges to identify the sensory attributes that maybe affected by the treatment, and determine which changes, if any, influence consumer liking. They showed shows that trained panelists were able to detect increased pitting and visual damage in fruit treated by irradiation at 400 and 600 Gy and was corroborated by the consumer panels, which showed lower liking scores in overall appearance for the irradiated oranges compared to the control fruit. The effect was exacerbated by storage for 3 and 4 weeks (McDonald et al., 2013). Similarly, trained panelists in a study conducted by O'Mahony and Goldstein (1987) found increased brown blemishing and pitting of whole navel oranges irradiated at 300 and 600 Gy. However McDonald et al. (2013) found that overall liking was not affected by irradiation with similar overall liking scores for the control and treated fruit. Although consumers stated that they liked the appearance of untreated fruit significantly more than irradiated fruit, their overall liking of irradiated fruit was no different than the control, although this could be a result of removal of the most heavily pitted fruit from consumer evaluation (McDonald et al., 2013). O'Mahony et al. (1985) also observed that untrained consumers were not able to tell the difference between untreated and irradiated (600 – 800 Gy) navel oranges even though expert judges were able to detect differences in brown blemishing and flavour of irradiated fruit after 5 to 6 weeks in storage. Betancurt et al. (2009) further showed irradiation (350 and 800 Gy) did not affect overall acceptability, appearance or juiciness of Late Valencia oranges after 20 and 40 days of storage as determined by 30 untrained panelists. While Hallman and Martinez (2001) found no differences detected by informal taste panels in Rio Red grapefruit, Marrs oranges, and Dancy tangerines treated up to 500 Gy and stored for 21 days at ambient temperature.

Noh et al. (2006a) evaluated the effects of 200, 400, 600, 800 and 1,000 Gy on Navel oranges and showed that after treatment with continuous storage at 20 ^{o}C for 12 days there was no differences in sensory acceptability of treated fruit. But after storage at 3 ^{o}C for up to 45 days, consumer perception of sweetness and overall acceptability of irradiated samples greater than 600Gy, were negatively affected by irradiation treatment (Noh et al., 2016b). McDonald et al. (2013) also showed there was a significant interaction between age and irradiation treatment suggesting that irradiation stresses the fruit and makes it more sensitive to handling. The Lane Late navel oranges used by McDonald et al. (2013) were commercially packed for the Pacific Rim (high export pack in which fruit are packed so as to place as much fruit as possible in the box). The fruit packs for visual damage evaluation were kept intact for the entire storage period. For other evaluations, fruit was removed from the original packs; this latter sample did not show as much visual damage as the fruit that was tightly packed. In addition, the fruit used in this study were late season navels, which had suffered stress due to a wet winter. This may also have contributed to the greater impact of irradiation. This observation suggests that packing compression in conjunction with the irradiation may enhance bruising of navel oranges. O'Mahony and Goldstein (1987) also observed greater pitting in navel oranges of damp oranges. The effect of handling, packing density as well as time of harvest should be evaluated in future studies.

While fruit softening has been shown not to be affected by irradiation in Late Valencia fruit (Betancurt et al., 2009), it has also been measured to increase (Miller et al., 2000; O'Mahony et al., 1985; McDonald et al., 2013). However this increased softness has not been able to be detected by trained panelists (O'Mahony et al., 1985; McDonald et al., 2013). Although O'Mahony et al. (1985) rated the resistance to bite of the treated oranges to be slightly higher compared to the control. Similarly McDonald et al. (2013) showed that trained sensory panelists were unable to determine differences in internal dryness or granulation among the control and irradiation treatments, even though analytical testing had indicated that there was a positive association of irradiation with segment drying at 400 and 600

Gy and with granulation at 600 Gy. This difference in results could have been due to the fact that the trained panelists were evaluating fruit sections rather than whole slices or that the drying and granulation, although present in a number of the fruit, was fairly minor on a whole fruit basis. The low prevalence of the drying and granulation was also indicated by results from the consumer panels, which found there to be no differences among treatments for either texture or juiciness.

McDonald et al. (2013) also found that the 400 and 600 Gy doses of irradiation enhanced the concentrations of aroma volatiles present in the Lanes Late but again this did not appear to result in a loss in flavor quality given that both the trained and consumer sensory panels found there to be no significant differences in the flavor or overall liking between the control and irradiated fruit. The lack of sensory impact of the increases in volatile concentrations was also noted in sensory panel evaluations of aroma of both whole and cut fruit, which found no differences due to treatment (McDonald et al, 2013). Although there was no sensory impact of the increases in aroma volatiles, these changes indicate that irradiation is inducing metabolic alterations in the fruit that have the potential to alter flavor at higher dose levels (McDonald et al., 2013). Similarly McDonald et al. (2013) showed there was decreased TSS at doses 400 and 600 Gy, these small effects had little impact on flavour. Indeed with other citrus types such as pummelos, while Jain et al. (2017) showed no consistent effects of 150 and 1,000 Gy irradiation on TSS and TA values, these differences were low and did not affect consumer acceptability of the treatments (Jain et al., 2017).

In summary, McDonald et al. (2013) concluded from their study, that while there may be some measurable effects of irradiation on fruit quality (such as aroma volatiles, internal drying/granulation, TA and TSS) these have not been shown to influence perceived flavour as indicated by the trained sensory panel or consumers. However more consumer and sensory work is required to ensure phytosanitary irradiation treatment does not affect consumer eating quality.

Pineapple

Extensive research in Thailand has shown that irradiation (400 – 600 Gy absorbed doses) did not affect the ratio of TSS/TA, antioxidant content, or ascorbic acid concentration, but did delay colour development in Pattavia pineapple fruit stored at 13 °C and 90% RH (Jenjob et al., 2017). Conversely, Trad Si Thong pineapple irradiated with gamma rays at doses 0 (control), 500 and 1,000 Gy, and then stored at 13 °C for 18 days did not affect hue angle of pulp, or disease incidence, but phenolic contents in irradiated fruit were higher than in the control fruit (Uthairatanakij et al., 2013). However, the dose of gamma rays significantly affected the TSS/TA ratio and the antioxidant activity (Uthairatanakij et al., 2013).

One of the major storage problems in pineapple storage is internal browning (IB) or blackheart which is induced by exposure to low temperature, either preharvest or postharvest (Wills and Golding, 2017). While cold treatment induces the development of IB, some studies on product tolerance have shown irradiation can induce IB in Trad Si Thong pineapples (Uthairatanaki et al., 2013). In addition, inconsistency occurs in the incidence and severity of IB symptoms between different experiments in Thailand (Apiradee Uthairatanakij et al., unpublished data).

In a trial to compare the effects of harvest season (i.e. fruit harvested in winter and summer seasons), Jenjob et al. (2017) treated Pattavia pineapple fruit which had been harvested in the summer and the rainy cool (winter) seasons with irradiation at dose levels of 0 and 400 – 600 Gy from a 60 Cobalt source and the fruit stored at 13 °C and 90% RH for up to 21 days. They showed that irradiation did not affect the ratio of TSS/TA, antioxidant content, or ascorbic acid concentration. However, it did delay colour development and also induced internal browning in over 50% of flesh discoloured in fruit stored for 14 days, especially in the fruit harvested in winter. Moreover, harvesting fruit in different seasons had a significant effect on fruit quality after harvest and during stimulated sea shipment storage. Their result showed that irradiation can be used as a phytosanitary treatment with minor changes in eating quality (Jenjob et al., 2017) however IB induced by irradiation depends on seasonal harvesting, fruit maturity and irradiation dose (Jenjob et al., 2017; Uthairatanakij et al., 2013; 2018).

Lychee

There have been studies on the effects of high levels of irradiation (i.e. above 1,000 Gy) reducing postharvest decay (such as Kramer and Kuhn, 1964, Akamine and Goo, 1977). Ilangantileke et al. (1994) found that irradiation at 1,000 Gy followed by storage at 5°C reduced decay and extended the storage life of litchi fruit. However, Akamine and Goo (1977) also reported that doses over 250 Gy caused darkening of the pericarp and levels above 500 Gy affected the organoleptic properties of the fruit. Research in Queensland showed the Tai So lychees irradiated at 0, 75 or 300 Gy and stored for 3 weeks at 5°C showed virtually no effect on any of the physical, chemical or organoleptic parameters investigated (McLauchlan et al., 1992). Incidence of disease caused by Colletotrichum species was reduced by doses of 75 and 300 Gy but unidentified species were increased. They concluded that irradiation of lychees at 75 or 300 Gy may be used for disinfestation purposes with no adverse effects on fruit quality (McLauchlan et al., 1992).

Follett and Sanxter (2003) treated Kaimana·lychee fruit one day after harvest with a minimum absorbed dose of 400 Gy and compared against hot-water immersion at 49°C for 20 minutes. They showed that irradiation was superior to hot-water immersion as a quarantine treatment on the basis of fruit quality maintenance.

McGuire (1997) compared the effects of cold treatment (15 days at 1.1 °C) to phytosanitary irradiation (at 100, 200, or 300 Gy) and showed that Mauritius lychee fruit were more susceptible to decay following irradiation at 300 Gy and 6 days of storage at 5 °C. In addition, both Mauritius and Brewster lychee cultivars also lost firmness after this treatment. The pericarp of irradiated Mauritius fruit became more orange, whereas the flesh of both cultivars became greener. Irradiated Brewster fruit were also less acidic and contained less soluble solids, however sensory evaluations could not differentiate between irradiated and nontreated fruit regardless of cultivar. Therefore McGuire (1997) concluded that the loss of fruit quality was minimal with irradiation treatment.

Passionfruit

There has been little published research on the effects of irradiation as a quarantine treatment on passionfruit quality. Kader (1986) reported that passionfruit are moderately tolerant to ≤ 1,000 Gy irradiation, but provided no data. Another study reported the effects of low dose irradiation on respiration rates in yellow passionfruit (Akamine and Goo, 1971), but no fruit quality or acceptability data on the effects of irradiation were not reported.

In a study of Australian grown passionfruit (*Passiflora edulis*, Sims), Golding et al. (2015) treated Sweetheart passionfruit to gamma irradiation at levels suitable for phytosanitary purposes (0, 150, 400 and 1,000 Gy) then stored at 8 ºC and assessed for fruit quality and total ascorbic acid concentration after one and fourteen days. They showed that irradiation at any dose (≤ 1,000 Gy) did not affect passionfruit quality (overall fruit quality, colour, firmness, fruit shrivel, stem condition, weight loss, TSS levels, TA level, TSS/TA ratio, juice pH and rot development), nor the total ascorbic acid concentration (Golding et al., 2015). The length of time in storage affected some fruit quality parameters and total ascorbic acid concentration, with longer storage periods resulting in lower quality fruit and lower total ascorbic acid concentration, irrespective of irradiation treatment. There was no interaction between irradiation treatment and storage time, indicating that irradiation did not influence the effect of storage on passionfruit quality. The results showed that the application of 150, 400 and 1,000 Gy gamma irradiation to Sweetheart purple passionfruit did not produce any deleterious effects on fruit quality or total ascorbic acid concentration during cold storage (Figure 8). This supports the use of low dose irradiation as a phytosanitary treatment against quarantine pests in purple passionfruit (Golding et al., 2015).

0 Gy 150 Gy 400 Gy 1,000 Gy

Figure 8. External appearance and internal quality of irradiated passionfruit after fourteen days storage at 8 ^{o}C. Fruit were treated with 0 Gy (left), 150 Gy (middle left), 400 Gy (middle right) and 1,000 Gy (right) (from Golding et al., 2015).

Longan

McGuire (1998) compared the effects of cold treatment (15 days at 1.1°C) to irradiation at 100, 200, or 300 Gy and showed that irradiation did not significantly affect susceptibility to decay or injure fruit, nor were firmness or external and interior colour reduced. Irradiated fruit, however, had lower percentages of TSS and acids, with a concomitantly higher pH, but sensory evaluations could not differentiate these fruits from untreated samples. Due primarily to the injurious effects of cold treatment on the longan pericarp, McGuire (1998) concluded that irradiation at 100 to 300 Gy would be preferable for maintaining quality of longans that require quarantine treatment for the eradication of exotic pests and are destined for the fresh market.

Dragon fruit

Dragon fruit (pitaya red flesh) exposed to gamma rays at 400 - 600 Gy before storage at ambient conditions showed that irradiation did not affect either pulp or bract colour (L*, a*, b* values and hue angle) nor TSS content and fruit firmness during storage for 9 days (Uthairatanakij et al., 2018).

Other tropical fruit

Follett (2004) compared the effect of irradiation and heat quarantine treatments on fruit quality out-turns in lychee (*Litchi chinensis*), longan (*Dimocarpus longan*) and rambutan (*Nephelium lappaceum*). For each fruit type, fruit of various cultivars were subjected to (a) hot water immersion at 49 ^{o}C for 20 min or vapor heat at 47.2 ^{o}C, (b) irradiation treatment at a minimum absorbed dose of 250 or 400 Gy, or (c) left untreated as controls. Fruit was then stored at 2 to 5 ^{o}C (lychee and longan), or 10 ^{o}C (rambutan) and quality attributes evaluated after one to three weeks. They showed that the external appearance of fruit treated with hot water immersion (lychee and longan) or vapor heat (rambutan) was generally less acceptable than irradiated or untreated fruits. Overall, under the experimental conditions tested, irradiation was superior to hot water immersion and vapor heat as a quarantine treatment on the basis of fruit quality maintenance (Follet, 2004).

Temperate fruit

Apple

Irradiation effects on apple have been well studied for over 65 years as there are at least 27 different cultivars listed on the IDCT database. The majority of studies have been on Fuji, Golden Delicious, Granny Smith and Red Delicious cultivars at irradiation doses less than 1,500 Gy. There are many studies at higher rates, but they were not included in this review.

Several studies have shown that irradiation reduces apple firmness after treatment (Bramlage et al., 1965; Kang et al., 2016; Kheshtia et al., 2019; Liu et al., 1989; Olsen et al., 1989 and Al-Bachir, 1999) especially at dose rates between 300 and 900 Gy (Drake et al., 1999) or less than 1,000 Gy (Kovacs et al., 1988), or above 1,155 Gy in Chinese apple (Kang et al., 2016). Drake et al. (1999) also found that there was no effect on fruit firmness in Fuji and Granny Smith cultivars when the dose rate was lower than 300 Gy. Irradiation may have an immediate effect on reducing fruit firmness, however the difference between treated and control fruit often decreases with storage time and during ripening (Olsen et al., 1989). In fact, Chuanyao et al. (1993) observed that firmness was higher in Golden Delicious treated at 300 to 900 Gy than in the controls, especially after 48 days storage at 8 to 18 °C (Lui et al., 1989).

Hussain et al. (2008) showed that overall fruit quality can be maintained in three cultivars, Ambri, Golden Delicious and Royal Delicious, when irradiated between 200 and 500 Gy and stored under both ambient (15 °C) and refrigerated (3 °C) temperatures. Furthermore, Lastarria-Tapia and Sequeiros (1985) extended shelf life by 15 days and 30 days in Delicious apples that were irradiated in the range of 500 to 4,000 Gy and stored under ambient (26 °C) and refrigerated (1 °C) temperatures, respectively, when compared to control fruit.

In general, irradiation suppresses ethylene production in many apple cultivars including Fuji treated at 1,148 Gy (Kheshtia, 2019), Gala treated up to 1,230 Gy or with 1-methylcyclopropene (1-MCP) (Fan et al., 2001), Golden Delicious treated at 300 to 700 Gy (Chuanyao et al., 1993), and Jonathan and tree-ripened Granny Smith treated up to 600 Gy (Rigney et al., 1985). The only cultivar where ethylene production slightly increased was in pre-climacteric Granny Smith (Rigney et al., 1985). Inhibition of ethylene production due to irradiation can help to slow ripening and often leads to longer storage life when compared to untreated fruit.

Other physiological trends after irradiation appear to be cultivar dependent. Hou et al. (1989) and Kheshtia et al. (2019) both showed there was an increase in respiration rate of Guoguang apples and Fuji apples, respectively, whereas there was a slight decrease in Rhode Island Greening and Cortland apple cultivars (Smock and Sparrow, 1957).

The optimal dose rate to maintain good colour and visual appearance in Delicious apples was determined to be 2,000 Gy (Lastarria-Tapia and Sequeiros, 1985), and 500 Gy in Guoguang apples (Hou et al., 1989). This rate was similar to what Fante et al. (2015) determined as 'low dose' which was between 500 and 1,500 Gy, however they were more interested in preserving antioxidant activity, ascorbic acid and SSC in Ava apples. Mostafavi et al. (2012) confirmed that a dose rate above 990 Gy can significantly reduce phenolic concentration and antioxidant activity in Red Delicious apples.

Summary. Optimal dose rates to maintain fruit quality in apple cultivars vary between 200 and 2,000 Gy with the extent of quality changes generally cultivar dependent. Very low irradiation dose rates of 75 and 200 Gy result in 100 % mortality of phytosanitary pests. Irradiation treatment often decreases firmness, inhibits ethylene production and increases respiration rates. Storage and shelf life can be extended for some cultivars by using irradiation in combination with other treatments, such as calcium chloride, refrigeration at less than 3 °C or 1-MCP treatment, however this may affect aroma expression during ripening.

Pear

Several studies have shown that the response of pear fruit to irradiation is inconsistent among different cultivars including Anjou, Bartlett, Bosc, Packham's Triumph and William's (as reported in IDCT database). Perez et al. (2009) showed that while a minimum absorbed dose rate of 200 Gy is suitable for controlling Codling moth and Oriental fruit moth in Packham's Triumph, no undesirable effects on fruit firmness, skin colour, TSS, TA and sensory attributes were observed for 8 months storage at 1 °C. On the other hand, Drake et al. (1999) observed a decrease in firmness of Bosc pears coated with a food-grade shellac-based wax prior to irradiation at 0, 150, 300, 600 or 900 Gy, and stored at 1 °C for up to 120 days. The magnitude of the decrease in fruit firmness was dose dependent, however they showed that both Bosc and Anjou cultivars ripened normally after treatment (Drake et al., 1999). They also showed that scald levels increased among irradiated Anjou pears compared to control fruit that was also dose dependent (Drake et al., 1999).

Sea et al. (2015) found similar inconsistencies in Bartlett pear quality resulting from irradiation treatment, although they also accounted for fruit maturity based on early and late harvests. They showed that irradiation treatment did not affect respiration rate, weight loss or TSS in early harvested pears however consumers were less impressed with their visual quality compared to control fruit (Sea et al., 2015). Irradiation increased respiration rate and weight loss, but decreased TSS, in late harvest pears. Furthermore, consumers rated late harvest pears lower for their overall liking, texture, flavour and sweetness compared to control fruit. Irradiation treatment appeared to reduce the rate of fruit quality loss as measured by decreased ethylene production and higher fruit firmness in both early and late harvest pears, which helped delay fruit ripening and restrict bruising and mould development during retail display simulations (Sea et al., 2015) (Figure 9). Maxie et al. (1966) observed that pear harvest maturity is also an important factor as pre-climacteric fruit failed to ripen regardless of treatment.

Hussain et al. (2010) showed that the shelf life of Bartlett and William's pears increased by 8 days and 4 days in mature green pears irradiated at 1,500 Gy and stored at 3 ˚C for 45 and 60 days, respectively. A further 4 days shelf life was added to Bartlett and William's pears when a carboxymethyl cellulose coating was applied prior to irradiation which helps to postpone decay in pears during post-storage ripening (Hussain et al., 2010). In a similar study, Wani et al. (2008) showed that pears irradiated at 1,500 to 1,700 Gy increased shelf life by 8 and 4 days at ambient temperature following storage at 3 ˚C for 30 and 45 days, respectively. However, all these studies were conducted on fruit above the accepted phytosanitary treatment (< 1,000 Gy).

Summary. Findings from research conducted over several decades to determine the effect of irradiation on pears have been inconsistent. Both positive and negative impacts on fruit quality parameters such as firmness, colour, TSS and TA, sensory attributes and rots, as well as shelf life, can be linked to irradiation treatment with these effects differing significantly among cultivars. Low dose rates of 200 to 400 Gy have been shown to control relevant insect pests whereas higher dose rates of 1,500 to 1,700 Gy can assist with extending shelf life, especially when utilised in conjunction with fruit coatings. Harvest maturity and irradiation treatment may also reduce ethylene production during storage, effecting ripening consistency and delaying decay in pears.

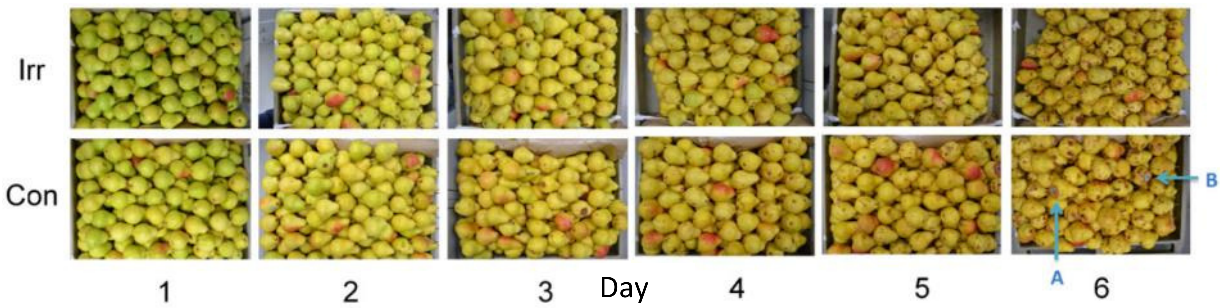


Figure 9. Retail market handling and display simulation of late harvest untreated control (Con) and irradiated (Irr) pears after 1 to 2 weeks storage at 3-5 ˚C followed by ripening at 20 ˚C and 80% RH for 6 days. Arrows indicate mould growth on bruised control pears (from Sea et al., 2015).

Cherries

A review of the effects of irradiation on cherry fruit quality was prepared for the Australian cherry growers through Hort Innovation ('*Review of international best practice for postharvest management of sweet cherries*' - CY17000). This summary presented here is modified from this Hort Innovation review.

The effect of irradiation (< 1,000 Gy) as a market access treatment on fruit quality has shown there are few consistent negative effects of treatment and subsequent cold storage on cherry quality, whereby fruit integrity is generally not affected (Neven and Drake, 2000; QDAF, 2013; Thang et al., 2016). In a comparison of methyl bromide fumigation and low dose irradiation as market access treatments, Thang et al. (2016) showed that the target dose of 400 Gy does not adversely or positively impact cherry quality or shelf-life and can serve as a good alternative to methyl bromide fumigation.

Jessup (1990) showed the quality of NSW grown Ron's Seedling, American Bing, and Lambert cherry was not affected by irradiation doses of 1,000 Gy and similarly Drake et al. (1994) reported that cherry showed minimal quality loss after being irradiated. QDAF (2013) showed that fruit quality was only affected by storage time and not by irradiation. They showed that time in storage had a small impact on the skin colour (lightness values) of the cherry fruit where the fruit became slightly darker in shade during storage but did not detract from the integrity or overall visual appeal of the fruit (QDAF, 2013). The findings suggest that an application of up to 1,000 Gy would not result in any detrimental damage to the quality of cherry fruit.

These results concur with several other studies examining the effects of irradiation and subsequent cold storage on cherry quality, whereby fruit integrity was unaffected (Drake et al., 1994, Kovacs et al., 1995). Drake et al. (1994) also demonstrated that fruit treated to doses of up to 1,000 Gy and stored for up to 21 days exhibited no significant changes in various fruit quality attributes, such as in fruit and stem colour, SSC, TA or sensory characteristics. While not considered low dose for market access treatment, even irradiation doses between 1,000 and 2,500 Gy had no effect on fruit quality attributes such as skin colour or sugar content (Kovacs et al., 1995).

In a fruit storage trial with five different cherry cultivars from Young and Orange districts in NSW (cvs. Kordia, Lapin, Regina, Simone and Skeena) treated with 150 Gy, showed no treatment effect on stem browning, fruit colour, pitting, cracks, splits, bruising, rots, overall acceptability, SSC, TA and SSC/TA ratio (Golding, 2017). Fruit firmness as measured with the Firmtech instrument did detect a treatment effect, whereby treated fruit were softer than untreated fruit. However the small sensory trial showed consumers (*n*=12) were not able to detect these differences in texture and treatment also had no effect on overall acceptability, flavour or appearance (Golding, 2017). In a related trial examining the different dose treatments (150, 400 and 800 Gy) there was little difference in overall fruit quality in treated Lapin cherries compared to those of the untreated control fruit (Figure 10). The different dose treatments had no effect on stem browning, fruit colour, pitting, cracks, splits, bruising, rots, overall acceptability, SSC, TA nor SSC/TA ratio. The only quality parameter found to be affected by treatment was fruit firmness, where Lapin fruit treated at the highest dose (800 Gy) resulted in significantly lower firmness. There was no difference in fruit firmness between the untreated, 150 and 400 Gy treatments (Golding, 2017). However the decrease in fruit firmness observed in both experiments were observed across a range of cultivars, but were not detected by consumers. A decrease in cherry fruit firmness with irradiation has been observed in other studies:

- Drake et al. (1994) Rainier cherries > 600 Gy
- Drake and Neven (1998) Bing cherries from > 300 Gy and Rainer cherries from 600 Gy
- Eaton et al. (1970) Vans cherries at 500 Gy
- Johnson et al. (1965) Bing cherries at 600 to 800 Gy
- Kovacs et al. (1995)
- Neven and Drake (2000) Bing cherries at 300 Gy at treatment and 7 days storage
- Thang et al. (2016) Sweetheart cherries at 400Gy at firmness but not after storage

Whilst other reports have not shown any significant negative effect of irradiation on fruit firmness:

- Jessup (1990) Bing and Lambert cherries up to 300 Gy for 20 days at 1 °C
- QDAF (2012) Stella cherries up to 1,000 Gy for 14 days at 1 °C
- Neven and Drake (2000) Rainier cherries at 300 Gy for up to 14 days storage
- Eaton et al. (1970) Lambert cherries up to 500 Gy and Vans cherries < 500 Gy

Overall low dose irradiation has few negative effects on fruit quality and there is generally more effect of storage time on final fruit quality.

0 Gy (Untreated) | 150 Gy | 400 Gy | 800 Gy

Figure 10. Effect of irradiation treatment (0, 150, 400 and 800 Gy) on appearance of Lapin cherry fruit and two weeks storage at 0 °C with one additional day at 20 °C (unpublished from Golding, 2017).

Effects of irradiation on cherry nutritional content

In general, there are few differences in the nutritional content of cherries treated with low dose irradiation (QDAF, 2013). However it is important to note that different cultivars tested, fruit maturity, growing conditions and management practices all affect nutritional content and care must be taken when comparing studies and treatments. An extensive report on the effects of low dose irradiation on Australian cherries was conducted in 2012 for application to FSANZ to change the food code (QDAF, 2013). This study examined the effect of irradiation at 150, 600 and 1,000 Gy on the nutritional profile and postharvest quality of Stella cherry and showed that low irradiation doses (150 – 1,000 Gy) combined with cold storage overall, did not result in significant differences in cherry nutritional quality (including ash, energy, dietary fibre, fat profile, moisture, sodium, protein, total sugars, sugar profile, Vitamin C (ascorbic acid) and beta-carotene) and postharvest quality after treatment and 14-day storage period. These results supported a successful application to allow low dose irradiation as a market access treatment for Australian cherries.

QDAF (2013) reported that low dose irradiation (< 1,000 Gy) did not cause any detrimental impact for all the nutritional components tested. Indeed storage treatment had a greater impact on sweet cherry nutrition than that of irradiation (QDAF, 2013). After storage for 14 days, reduced Vitamin C (total ascorbic acid) and Vitamin A (beta-carotene) levels and increased protein and ash content and were considered senescence related (QDAF, 2013). After 14 days storage, only minor changes occurred as a result of irradiation, with a slight decline measured in beta-carotene levels at 600 Gy (QDAF, 2013). Similar results were found in a previous study by Akbudak et al. (2008), where ascorbic acid levels in untreated 0900 Ziraat cherry were no different from fruit irradiated at 300 Gy. In that study which investigated storage at six different atmosphere combinations for up to 60 days after being exposed to irradiation, the highest ascorbic acid value was recorded in fruit stored under controlled atmosphere and irradiation. Indeed Akbudak et al. (2008) showed 0900 Ziraat cherry can be stored successfully for more than 60 days under controlled atmosphere following low dose irradiation.

QDAF (2013) also reported there were little or no changes in carbohydrates, glucose and fructose across all irradiation samples and after 14 days cold storage. Similarly, Drake and Neven (1997) found that carbohydrates (sucrose, glucose, fructose and sorbitol) were not influenced by irradiation treatment in Rainier cherry, irradiated between 150 and 900 Gy. In summary, low dose irradiation (< 1,000 Gy) has no significant negative effects on cherry fruit nutrition.

Summerfruit

Peach

The effects of irradiation on peach have been extensively studied over the last 55 years with at least 25 different cultivars listed on the IDCT database with the majority of research being conducted using doses of between 100 and 600 Gy.

Peaches like plums, nectarines and apricots, are climacteric fruit that ripen quickly especially at warmer temperatures hence quality and shelf life can often be compromised with some postharvest treatments (Wills and Golding, 2017). Hussain et al. (2008) studied the effect of high dose irradiation on Elberta peaches (i.e. treatments between 1,000 to 2,000 Gy) and stored at refrigerated (3 ˚C) and ambient (25 ˚C) temperatures for up to 20 days. They showed that irradiation improved the colour development and anthocyanin concentration at both storage temperatures. Irradiation of 1,200 to 1,400 Gy increased storage life by 6 and 20 days for peaches stored under ambient or refrigerated temperatures, respectively. This increase was mainly due to delaying of rot development. Irradiated peaches were also higher in TSS and exhibited less moisture loss.

Similarly, Dhaliwal and Salunkhe (1965) increased storage life by up to 20 days in peaches by using multiple doses of low-level irradiation 1,000 Gy in conjunction with packaging in polyethylene bags and low storage temperatures. Irradiation helped control fungus growth (mainly *Penicillium* and *Rhizopus* sps.) and enabled peaches to be stored for longer periods. On the other hand, Bramlage and Couey (1965) found that irradiation successfully controlled Brown rot but not *Rhizopu*s species. However, Elberta and Suncrest #72 peaches irradiated at 1,000 to 6,000 Gy ripened the fruit by up to five-days earlier and increased the red colour and anthocyanins levels compared to control fruit (Maxie et al., 1966).

Several studies have shown that irradiation decreases fruit firmness in numerous peach cultivars (Bramlage, 1965; Maxie et al., 1966; Khan et al., 1971; Ahmed et al., 1972; Drake et al., 1988; Mi-Seon et al., 2009 and McDonald et al., 2012) particularly directly after treatment (Braddock et al., 1966 and Ahmed et al., 1972). In addition, treatment with higher dose rates makes fruit susceptible to mechanical injury (Maxie et al., 1966). Drake et al. (1988) and Lu et al.

(2006) concluded that at lower dose rates (< 300 Gy) there were minimal effects on peach quality, especially fruit firmness, whereas treatment at higher doses (> 600 Gy) resulted in reduced firmness levels, stimulated ethylene production, accelerated ripening and induced internal breakdown that result in unacceptable consumer peach quality.

In general, irradiation has been shown to have no effect on TSS (Lu et al., 2006), TA (McDonald et al., 2012) or vitamin C content (Mi-Seon et al., 2009) in peaches, but can change pectin activity (Shewfelt et al., 1968) and increase pH, total polyphenol concentration and moisture loss (Lu et al., 2006). Limited sensory tests show that consumers preferred irradiated peaches over untreated fruit (Mi-Seon et al., 2009; McDonald et al., 2012) especially in terms of colour, taste and flavour when treated at lower dose rates (Khan et al., 1971).

Summary. Irradiating peaches at lower dose rates (i.e. 300 Gy) shows promising results for minimising changes in quality, reducing fungal growth, and maximising shelf life whilst still providing consumer appeal. To extend storage life peaches could be packed in suitable polyethylene bags to reduce moisture loss and stored at low temperatures.

Nectarine

Limited research has been conducted on the effects of irradiation on nectarine quality with much of the research conducted at high treatment doses (> 1,000 Gy). Bramlage and Couey (1965) investigated gamma radiation to extend market life in 11 fresh fruits including two nectarine cultivars - Late Le Grand and Sun Grand. The former cultivar involved fruit waxing so will not be discussed in this review. Sun Grand nectarines were separated into two distinct maturities based on either green or yellow background colour and irradiated at 0, 450, 1,250, 2,000 or 3,000 Gy followed by two storage periods of 5 or 7 days at either 3 or 15 °C, and then ripened at 15 °C for 4 or 7 days. While most of the treatment doses were greater than 1,000 Gy, some of the results are relevant to this review. Weight loss was highest, and significantly different from the control, in fruits treated at the highest dose rate, whilst there was no effect of irradiation on fruit firmness or flavour, and brown rot was controlled as well. Maxie et al. (1966) confirmed that flavour and appearance of nectarines was not affected when irradiated at high treatment doses (1,000 to 6,000 Gy), however aroma and texture was less than acceptable. Furthermore, irradiation stimulated the production of ethylene which contributed to the fruit ripening by up to 5 days earlier, and fruit were also redder and softer than the controls.

In a more recent and relevant study Chay et al. (2012) examined the effect of irradiation on postharvest quality of Arctic Snow nectarine treated at 0, 150, 600 or 1,000 Gy, and stored at 4 °C for 21 days. They found minimal treatment effects on fruit quality. Dose rates had no effect on weight loss, fruit firmness, TSS and TA, although a longer storage period reduced fruit flavour (Chay et al. 2012). However, they showed that irradiation treatments contributed to minor pitting and skin browning was observed among 3% of fruit treated at 150 Gy and increased significantly to 20% among fruit treated at 1,000 Gy (Figure 11). Severity of symptoms was relatively low on average and affected a skin surface area of less than 1 cm^2.

Figure 11. ‘Mild’ pitting and browning in Arctic Snow nectarine irradiated at 1,000 Gy and stored at 10 °C for 21 days (from Chay et al., 2012).

Summary. It appears irradiation has minimal effects (positive or negative) on fruit quality of nectarine however limited studies and cultivars have been tested. Nectarines tend to respond more favourably to lower dose rates by exhibiting minimal changes in weight loss, fruit firmness, sugars, acidity and skin disorders.

Plum

Bramlage and Couey (1965) conducted a comprehensive storage trial with Eldorado, Laroda, Santa Rosa and Wickson plum cultivars but the treatment doses were greater than 1,000 Gy (i.e. treatment doses of 1,250 Gy to 5,000 Gy) and therefore not relevant to this review. However more recent studies show that dose rate and storage temperature can affect overall acceptability in mature Santaroza plums (Figure 12) (Hussain et al., 2013). They showed that fruit acceptability generally increased with increasing irradiation dose (i.e., 200, 400, 600, 800, 1,000 Gy) when stored at the higher temperature and these trends were observed, although at slower rates, over the five storage periods of 4, 8, 12, 16 and 20 days (Hussain et al., 2013). As expected, overall acceptability was higher when plums were stored at lower temperatures under refrigerated conditions. They observed that only plums treated at the higher dose rate of 1,500 Gy were still saleable after 20 days of storage at 25 °C, mainly due to significant inhibition of fungal rots which would more than satisfy air freight and subsequent storage and export marketing requirements. Similarly, all irradiated fruit stored at 3 °C for 35 days would still be saleable after the longer storage period and relevant marketing conditions (e.g., simulating a sea freight journey). Incidence or rot development increased with irradiation treatment and peaked at 12% (800 Gy) thus this fruit would not be suitable for marketing.

Viljoen (2011) treated Songold plums with 400, 600 and 800 Gy, and showed that flesh firmness was similar after six weeks storage at various temperatures. As expected, flesh firmness decreased in all fruit after a further five days of ripening at 10 °C, however firmness levels among irradiated fruit were approximately 0.5 kg lower than among control fruit. After storage gel breakdown, although not significantly different between control and irradiated plums, was highly prevalent after five days of ripening in non-irradiated (46%), and irradiated (> 85%) plums. Furthermore, the impact of irradiation on plum moisture loss was clearly observed after six weeks of storage, with higher shrivel incidence resulting from higher dose rates. The other part of the experiment looked at the benefits of applying a ripening inhibitor such as 1-methylcyclopropane (SmartFresh^{SM}) prior to irradiation that yielded significantly higher firmness levels, less gel breakdown and reduced shrivel after the storage period than when compared to the control fruit (data not shown).

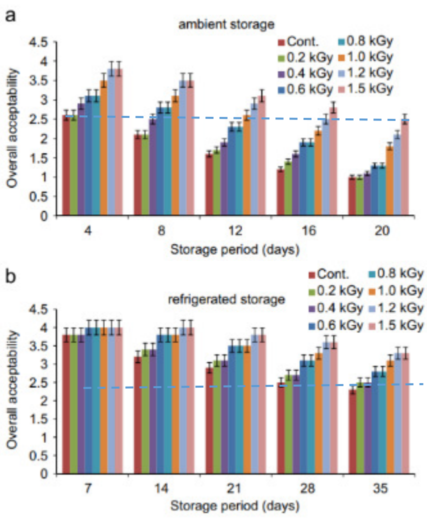


Figure 12. Effect of different irradiation doses (0, 200, 400, 600, 800, 1,000, 1,200 and 1,500 Gy) on overall acceptability (using a 4-point scale, where 4=excellent, 3=good, 2=fair and 1=poor) of cv. Santaroza plums during storage at (a) ambient (25 °C - top) and (b) refrigerated (3 °C - lower) temperatures. Dotted blue line represents saleable fruit. (from Hussain et al., 2013)

Summary. The benefits of higher dose irradiation are obvious for plums stored for shorter periods at ambient temperatures whereas lower doses are satisfactory for fruit stored for longer periods at lower temperatures. Dose rate didn't adversely affect plum quality straight out of cool storage but may affect ripening and flavour in some cultivars. Treatment at 400 Gy most represented control fruit.

Persimmon

There have been few studies on the effects of irradiation as a quarantine treatment on persimmon fruit (Wheeler et al., 1989; Ah et al., 2018; Golding et al., 2020), with other studies conducted on higher irradiation doses above the phytosanitary limit (1,000 Gy maximum). For example, Hachiya persimmons were treated with a range of irradiation doses (1,500 – 3,500 Gy) (Nawito, 2008), but these treatment doses are not representative of any commercial market access treatment.

In a recent experiment that examined the effect of storage time and phytosanitary irradiation treatment on the quality of Australian Jiro persimmon fruit during storage at 15 °C, there was no effect of irradiation treatment on fruit quality (Golding et al., 2020). However respiration rates were higher in treated fruit and indicated some fruit stress caused by the treatment, but this did not translate into lower fruit quality. Indeed, there was no effect of irradiation (i.e. no difference when compared to non-irradiated control fruit) on fruit weight loss, calyx appearance, fruit firmness (objective and subjective), TSS, TA, internal appearance and ethylene production rate (Golding et al., 2020).

While phytosanitary irradiation treatment did not affect fruit colour in Fuyu persimmon (Wheeler et al., 1989 and Ahn, 2018), Golding et al. (2020) showed the fruit skin colour of Jiro persimmons tended to be darker orange / red (Figure 13) but these observed differences between the treatments were not outside commercial acceptability (Figure 14).

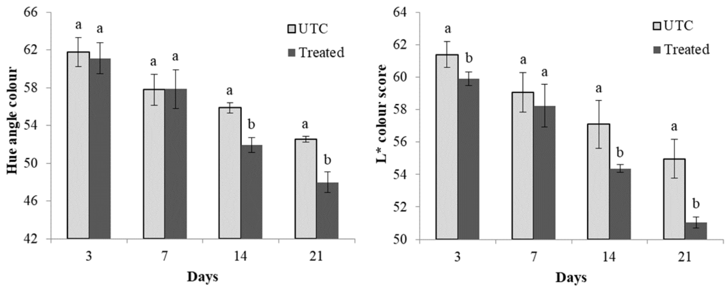


Figure 13. Skin colour parameters (a*, b*, hue angle and L*) of treated and untreated control (UTC) Jiro persimmon fruit during storage at 15 °C for up to three weeks. Data are means (n=3) and standard deviations around the mean are shown in error bars. Values with the same letter within each assessment time are not significantly different at P<0.05 (from Golding et al., 2020)

Figure 14. Untreated control (UTC) (top) and treated (lower) Jiro persimmon fruit after three weeks storage at 15 °C (from Golding et al., 2020)

Skin blemish is a negative consumer attribute and many postharvest phytosanitary treatments can induce skin browning in persimmons (Mitcham et al., 1987). Wheeler et al. (1989) showed Fuyu persimmons treated with 300 and 1,000 Gy in combination with modified atmosphere (MA) bags showed some skin blemish on 1,000 Gy treated fruit stored in MA bags after removal from cold storage (Wheeler et al., 1989). Similar superficial skin blemish was observed with Jiro persimmon fruit during storage at 15 °C from 7 days storage following 769 Gy at a commercial phytosanitary irradiation treatment, but this was assessed as 'minor' level (i.e. with <10% blemish) (Golding et al., 2020).

Due to the low number of studies conducted with commercial irradiation treatments, there are large gaps in our knowledge on the range of irradiation treatment doses, persimmon cultivars, storage treatments etc. which may affect storage quality, market out-turn and consumer acceptability. Further extension to other irradiation treatment doses and persimmon cultivars and storage conditions are needed to confirm these findings on a broader range of persimmon fruit and marketing conditions.

Kiwifruit

Kim et al. (2008) treated Haywood kiwifruit with 100, 300 and 500 Gy and held the fruit at 20∘C for 2 weeks. They showed that while the Vitamin C content and hydrogen donating activity decreased during the storage period, these quality parameters were not reduced by the irradiation process. Similarly total sugar and reducing sugar contents increased as the storage period increased; and these factors were unaffected by irradiation (Kim et al., 2008). The levels of organic acids significantly following irradiation, and all samples had decreases in organic acids over the storage period. Fruit hardness decreased with the storage period and with increasing doses of irradiation. When compared with control samples, the irradiated samples had lower color and overall acceptability scores just after irradiation (week 0) (Kim et al., 2008). However, during the storage period, the irradiated fruit samples had higher scores for smell, taste, texture, and overall acceptability than the control. Kim et al. (2008) concluded that up to 500 Gy is the recommended treatment to maintain overall quality attributes in kiwifruit.

The same Korean research group also examined the effect of higher doses of irradiation (up to 3,000 Gy) on fruit quality and showed that higher doses were able to inactivate the three pathogens of *Botrytis cinerea*, *Diaporthe actinidiae*, and *Botryosphaeria dothidea* in kiwifruit (Kim and Yook, 2009). Irradiated kiwifruits appeared softer compared to non-irradiated kiwifruits. However, the colour and organic acid content of kiwifruits were minimally affected by the irradiation. Irradiated fruits showed a decrease in the TSS content with increasing irradiation dose. Irradiation of kiwifruit up to 3,000 Gy had negative effects on vitamin C content and antioxidant activity, but it contributed to improving sensory quality (Kim and Yook, 2009), but these levels are greater than the phytosanitary dose used for kiwifruit.

Fu and Feng (2003) (as reported in IDCT) treated kiwifruit with irradiation at 0, 300, 600, 900 and 1,500 Gy and after irradiation the kiwifruit were held at 20 ± 2 °C and evaluated at 2, 11 and 20 days for appearance, firmness, vitamin C, soluble solids, total sugar, total acid and taste. The results showed that irradiation had a significant effect on the hardness and the vitamin C content, but had no significant effect on the TSS and total acids. Fu and Feng (2003) reported that irradiated kiwifruit treated with 300 - 1,500 Gy could be preserved 13 days longer than untreated fruit.

The IDCT also reported a variety of studies on the effects of electron beam treatment on kiwifruit (Zhou et al., 2015; Hung et al., 2020). The use of electron beam is not included in this review, but the results of these studies were generally positive in maintaining fruit quality during storage and shelf life.

Table grape

The major limitation with storage of tablegrapes is *Botrytis cinerea* decay. The use of irradiation has been widely examined as a potential decay control method in tablegrapes (Al-Bachir, 1999; de Kock and Hol, 1991). de Kock and Hol (1991) examined the feasibility of using irradiation for the control of postharvest Botrytis bunch rot of table grapes in cold storage. They treated Waltham Cross and Barlinka tablegrapes at 0, 1,500, 2,000 and 3,000 Gy and stored the grapes for 4 weeks at -0.5°C, followed by another week at 10°C and showed that the higher irradiation doses were associated with less *Botrytis cinerea* decay. But these irradiation treatment doses are higher than commercially acceptable. However they did show that even these relatively high irradiation doses had no adverse effect on other aspects of quality (de Kock and Hol, 1991).

Gamma irradiation has been applied to prolong the shelf-life of tablegrapes (Campbell early) grapes where Yun et al. (2008) reported the changes in microbiological, physicochemical, nutritional, and sensory characteristics were investigated during 6 weeks of post-irradiation storage and showed that the 1,000 Gy treatment did not detrimentally affect the nutritional or physical characteristics of grapes, especially when cold storage follows radiation treatment.

Kim et al. (2014) treated Sugraone and Crimson Seedless tablegrapes with 400, 600, and 800 Gy and assessed the effects of irradiation on physicochemical and sensory quality for 3 weeks storage. They observed significant changes in texture and colour with irradiation and age but little visual difference was seen between control and irradiated grapes. They showed that storage had a greater effect on firmness than irradiation for Sugraone grapes. Irradiation also did not significantly affect the SSC/TA ratio, which increased during storage (Kim et al., 2014). The trained panel detected significant changes in the berry texture and rachis colour but rated sweetness and flavour significantly higher for irradiated Sugraone as compared to the control. Consumers liked both the untreated and 800 Gy treated Sugraone grapes, but liked the untreated grapes more for texture. However, there was no difference in liking between irradiated (600 Gy or 800 Gy) and control samples of Crimson Seedless for any attribute (Kim et al., 2014). These results show that there are varietal differences in response to irradiation but the overall maintenance in quality of irradiated grapes during 3 weeks of storage indicates that irradiation can serve as a viable phytosanitary treatment (Kim et al., 2014). Irradiation was also shown to improve the shelf life of two cultivars of Syrian grapes, Helwani and Baladi (Al-Bachir, 1999). However each cultivar responded differently to treatment levels and the author suggested that optimum irradiation dose for reducing fungal decay and extending shelf life in cold storage is related to the thickness of skin, firmness, and hardness of the flesh of the grape berries (Al-Bachir, 1999). These studies indicate that different cultivars of grapes have differing tolerance to irradiation.

A recent local Australian study with Sweet Sapphire™ tablegrape from three different growers within the same growing area (Sunraysia) showed that fruit quality following treatment with phytosanitary irradiation and subsequent storage was not significantly different to other market access treatments (e.g. methyl bromide and cold treatment), but irradiation treatment did result in softer berries (as measured with a texture analyser) for all storage periods (Golding, 2022). An interesting observation from this study was the grower to grower variability in fruit quality in their response to different market access treatments. In this study, three different commercial tablegrape growers / exporters from the Sunraysia regions were used in this trial. These growers were very experienced and large active exporters. However there were differences noted on the effects of the different market access treatments on the different growers' fruit (Figure 15). For example the main and lateral stem condition of Grower B was generally better than other growers.

Figure 15. Effect of phytosanitary irradiation on Sweet Sapphire™ tablegrape appearance in representative fruit samples from Grower A, Grower B and Grower C after three weeks storage at 5 °C and additional shelf life (plus 3 days at 20°C) (from Golding, 2022).

Melon

There have been few reports on the effects of phytosanitary irradiation on the quality of melons. A report in the International Database on Commodity Tolerance (IDCT) from the IAEA report that Wang et al. (1994) treated white honey melons with 0, 200, 400, 700, 100 and 1,600 Gy and held for the melons for up to 150 days. They report that the 100 – 400 Gy irradiation had no effects on fruit colour, aroma, taste and appearance.

While the effects of irradiation on minimally processed fruit and vegetables is outside the scope of this review, the effect of irradiation on the postharvest storage and quality of minimally processed melons has been conducted (Bibi et al., 2006; Boynton et al., 2005, 2006; Zhou et al., 2012). These reports show that irradiation has the potential to maintain fresh-cut product integrity and extending the shelf life of fresh cut melon pieces.

While the results of electron beam treatment are generally not described in this review, Castell-Perez et al. (2004) treated whole and fresh-cut packaged cantaloupes with a linear electron beam accelerator with the single beam (10MeV) fixture. Samples were then stored at 10°C for 0, 4, 8 and 12 days along with control (non-irradiated) samples and tested for colour, texture (firmness), size (density), sugars and carotene content to determine the effect of irradiation dose level (1,000, 1,500 and 3,100 Gy). Results indicated that irradiation of cantaloupes, as whole fruits with doses up to 1,000 Gy, caused no significant changes on the fruit's physical and nutritional quality attributes. Irradiating at higher doses had an undesirable effect on product quality. The fresh-cut packaged cantaloupe may be irradiated up to 1,500 Gy without affecting the product quality attributes. In both cases, carotene content increased slightly as irradiation dose increased. In general, samples irradiated with dose levels between 1,000 and 1,500 Gy showed better quality attributes than non-irradiated samples (Castell-Perez et al., 2004).

Blueberry

Irradiation as a quarantine treatment has been examined on a range of blueberries, however much of this work has been conducted on irradiation doses above 1,000 Gy (Eaton et al., 1970, Miller et al., 1994b, Moreno et al., 2007). There are three main species of blueberry which are commercially grown around the world; highbush (*Vaccinium corymbosum*), lowbush (*Vaccinium angustifolium*), and rabbiteye (*Vaccinium ashei*).

Marissa Wall from United States Pacific Basin Agricultural Research Center, USDA, ARS at Hilo in Hawaii (USA) reviewed the current blueberry literature:

> Wall M.M. (2015) Phytosanitary irradiation and fresh fruit quality: cultivar and maturity effects. *Stewart Postharvest Review* 11(3), pp.1-6.

The following is an amended extract from this review (Wall, 2015).

In an early report by Eaton et al. (1970), six cultivars of highbush blueberries were treated with gamma radiation at doses between 1,000 Gy and 5,000 Gy to extend shelf-life and there was no mention of quarantine treatment. Fruit from four of the six varieties darkened with irradiation treatment. Berries of all varieties softened following irradiation treatment. In general, irradiation at doses exceeding 1,000 Gy caused undesirable changes in colour and texture. However, certain varieties (Bluecrop and Jersey) appeared more tolerant, indicating that the irradiation response is cultivar-dependent (Wall, 2015).

There is only one report of highbush blueberries treated at doses below 1,000 Gy. Blueberries of the cultivar Sharpblue (a southern highbush hybrid) were irradiated with an e-beam source at doses ≤ 1,000 Gy for potential quarantine treatment (Miller et al., 1995b). Berry flavour and texture declined linearly as dose increased, but sensory quality was still deemed acceptable. Weight loss, decay, soluble solids, acidity, skin colour, and waxy bloom were not affected by irradiation at doses less than 1,000 Gy. The authors concluded that Sharpblue berries could be irradiated at doses up to 750 Gy with some decline in sensory quality, but the reductions in flavour and texture should not affect consumer acceptance.

The majority of the blueberry radiation literature pertains to rabbiteye fruit. When rabbiteye berries (cv. Climax) were treated with gamma radiation (750 to 3,000 Gy), doses above 750 Gy adversely impacted flavour within 24 hours of treatment (Miller et al., 1994b). The blueberries softened, and preference scores declined significantly. Irradiation did not affect weight loss, surface colour, powdery bloom, soluble solids, or acidity. Irradiated fruit had more decay than control berries, regardless of dose or storage duration. The results indicate that Climax blueberries tolerated doses less than 750 Gy irradiation. Berry quality was seriously reduced at > 1500 Gy, with increased softening and decay, loss in pulp integrity, and reduced flavour acceptability (Miller et al., 1994b). Later studies confirmed that high doses damaged rabbiteye blueberries (cv. Bonita Blue) (Trigo et al., 2006). Sensory panellists detected undesirable taste at doses greater than 1,000 Gy.

When Climax blueberries were treated with e-beam irradiation at low doses (250 to 1,250 Gy), there was a general trend for the percentage of firm berries to decline as dosage increased above 250 Gy (Miller et al., 1994a). Blueberry firmness, flavour and texture declined as dosage increased (regardless of storage duration). Flavour scores for nonirradiated berries were always higher than for irradiated berries. Fruit treated at doses higher than 750 Gy were consistently rated lowest in flavour. Weight loss, decay, skin colour, soluble solids, acidity, and visual appearance (powdery bloom and shrivelling) were not affected by irradiation dose (Miller et al., 1994a; Trigo et al., 2006). Doses ≥ 1000 Gy were detrimental to the quality of Climax blueberries because of softening, loss of flavour and texture. For another rabbiteye variety (Bonita Blue), blueberries irradiated at 500 and 1000 Gy had equivalent flavour to non-irradiated fruit, but the shelf-life at 4°C was reduced by 8 days, compared to non-irradiated fruit (Trigo et al., 2006).

The response of rabbiteye cultivars, Brightwell and Tifblue, to 500 and 1,000 Gy radiation was generally consistent with those of Climax and Sharpblue (Miller and McDonald, 1996). Irradiation softened Brightwell berries but did not affect the incidence of decay. Weight loss, soluble solids, acidity, and sensory quality were not affected by dose, similar to previous studies. For Tifblue, there was no difference in quality for any attribute, regardless of dose. In general, the blueberry research indicates that highbush and rabbiteye cultivars suffer quality loss following irradiation at doses ≥ 1,000 Gy, but that most cultivars tolerate doses below 750 Gy (Miller and McDonald, 1996).

In another study with northern highbush blueberries (unknown cultivar), e-beam irradiation at doses > 1,100 Gy caused berries to soften substantially during storage at 5 °C (Moreno et al., 2007). Texture, as measured by shear force, decreased significantly with dose, confirming other reports that irradiated blueberries are softer than nonirradiated berries. Examination of blueberry microstructure revealed skin depressions in irradiated fruit. Irradiation at doses > 1,100 Gy was not recommended for blueberries, because of the adverse effect on texture. However, blueberries exposed to 1,600 Gy were acceptable to a sensory panel for overall quality, colour, texture and aroma. There was no effect of irradiation on acidity, moisture content, or juiciness. Irradiated berries (1,000 and 1,600 Gy) were generally darker in colour than controls, with less ascorbic acid but greater total phenolics and antioxidant activity (Moreno et al., 2007, 2008). Moreno and associates also determined the dose distribution within a tray of highbush blueberries exposed to 1,000 to 3,200 Gy irradiation. They confirmed that dose is not uniformly distributed within a pack, because the density is not homogeneous. Dose levels at the bottom of the tray were 18% ± 8% higher than at the top of the tray, suggesting that careful dose mapping must be conducted before commercial treatment of packed blueberries (Moreno et al., 2008).

In a study on the effect of quarantine irradiation doses on Australian blueberry fruit quality, Golding et al. (2014) and Golding et al. (2015) treated blueberry (Northern Highbush, cv Brigitta) with low dose gamma irradiation (0, 150, 400 and 1,000 Gy) and stored at 0 °C for three or ten days to determine the effects of irradiation on fruit quality and nutritional and proximate contents. In general, none of the irradiation doses (≤ 1,000 Gy) significantly affected blueberry fruit quality (overall fruit quality, colour, firmness, weight loss, TSS, TA levels or TSS / TA ratio), or the nutritional or proximate content (ash, carbohydrate, dietary fibre, energy, moisture, protein, sodium, potassium, total sugars, fructose, ascorbic acid, monomeric anthocyanin, citric and malic acids). The length of time in storage affected some fruit quality and nutritional and proximate content parameters (such as overall fruit quality, firmness, weight loss, TA levels, dietary fibre, potassium, ascorbic acid, citric and malic acids), with longer storage periods resulting in lower quality fruit, irrespective of irradiation treatment (Figure 16). No interaction was detected between the effects of irradiation treatment and storage time, indicating that the storage effect was consistent for all irradiation doses on Brigitta blueberry fruit quality. This work was the basis of the FSANZ approval for the use of irradiation as a market access for Australian blueberries (FSANZ, 2017).

0 150 Gy 400 Gy 1,000 Gy

Figure 16. Irradiated Brigitta blueberries after ten days storage at 0 °C. Fruit were treated with 0, 150, 400 and 1,000 Gy (from Golding, 2013).

Other recent studies which have examined lower quarantine doses of irradiation have also demonstrated it does not negatively impact blueberry fruit quality. For example Thang et al. (2016) treated Bluecrop blueberries (*Vaccinium corymbosum*) with 400 Gy and showed that irradiation treatment caused an immediate decrease in firmness without further significant change during storage but there were no significant effects of treatment on consumer liking of any of the attributes. In addition, irradiation resulted in only modest reductions in *Salmonella* and *Listeria* counts and will not contribute significantly to improving safety. Thang et al. (2916) concluded that irradiation did not negatively affect fruit quality during and after storage.

Strawberry

Strawberries were one of the first commodities exposed to irradiation and there are over 20 cultivars recorded on the IDCT database during the last 60 years. Several studies have recently focused on irradiation treatments of less than 1,000 Gy and their effect on postharvest storage performance. In 2020, Korean researchers studied the effects of electron-beam irradiation at 0, 150, 400, 600 or 1,000 Gy on the postharvest quality of Maehyang strawberry which have shown that e-beam treatment resulted in lower microbial levels (i.e., aerobic bacteria, yeasts and moulds), fresh weight loss and decay in a dose-dependent manner during 9 days storage at 15 °C (Yoon et al., 2020). Similar trends in fungi suppression were observed in cv. Tristar (Yu et al., 1995) and gamma-irradiated Festival strawberries (Maraei and Elsawy, 2017), Corona fruit (Majeed, 2014), and in Marquee and Amado strawberries (Figure 17) even when irradiated at 400 Gy (Serapian and Prakash, 2016).

Higher irradiation doses (e.g., 1,000 to 3,000 Gy) have also been studied which tend to increase storage potential by between 2 and 15 days (Majeed 1995; Cooper and Salunkhe 1963; Yu et al., 1995) without significantly affecting fruit quality attributes such as SSC, pH, colour, ascorbic acid and TA. However, tissue breakdown consisting of watery soaked flesh can be expected at the highest dose rate. Similarly, Zegota (1988) showed a shorter period between harvest and irradiation (e.g., no more than 6 to 10 hours) can improve storage performance as compared to longer durations (e.g., 20 to 24 hours), whereas red colour intensity and ascorbic acid levels decreased with increasing dose rate and storage time.

Irradiated strawberries tend to be softer after treatment (Yu et. al., 1995; Johnson et al., 1965) with higher doses increasing the rate of fruit softening. However, these differences diminish with increasing storage time. For example, Serapian and Prakash (2016) found that irradiated strawberries were 20% softer when compared to fumigated strawberries and 23% softer when compared to control fruit, however this had no impact on consumer liking scores in sensory tests (Figure 17) which is contrary to Yu et al. (1995). Irradiation treatment may also be advantageous in slowly increasing anthocyanin and phenolic concentrations and antioxidant activity during storage (Yoon, 2020), but decreasing colour intensity and ascorbic acid concentration at higher dose rates and longer storage times (Zegota, 1988).

Figure 17. Appearance of cv. Marquee (top) and cv. Amado (bottom) strawberries following air freight simulation plus 2 days storage at ambient temperature. The treatments include a control (left), irradiation at 400 Gy (middle) and methyl bromide fumigation (right) (from Serapian and Prakash, 2016).

Summary. In general, the storage performance and marketability of irradiated strawberries appears to be unaffected by irradiation treatment especially at lower dose rates of less than 1,000 Gy and, in particularly at 400 Gy, which seems to have minimal impact on fruit quality, and in fact may extend shelf life by reducing microbial spoilage and improving consumer visual appeal during marketing. As a result, irradiation could serve as a viable option especially compared to methyl bromide fumigation for exporting strawberries by air freight. It is recommended that the optimal irradiation dose should be determined for each export strawberry cultivar.

Raspberry

Similar to blueberries, there have been very few reports on the effects of irradiation on raspberry (*Rubus idaeus*) fruit and nutritional quality (Guimarães et al., 2013; Verde et al., 2013; Golding et al., 2014; Golding et al., 2015).

Guimarães et al. (2013) treated Autumn Bliss raspberries with 500, 1,000 and 2,000 Gy then stored the fruit for 12 days at 1 °C and 95% relative humidity. The results showed that there were some negative affects with the higher treatment doses (i.e. 1,000 and 2,000 Gy) whereas low dose irradiation generally did not affect most fruit quality attributes, (except firmness and weight loss), although there were interactions between storage time and treatment in many quality variables. They also performed microbiological assays (coliforms at 35 and 45 °C, psychrotrophic and filamentous fungi and yeasts) during cold storage and showed lower filamentous fungi and yeast counts in the irradiated fruits, and 2,000 Gy was determined as the most effective dose for microbial control, but this irradiation dose also resulted in increased loss of fruit firmness.

Verde et al. (2013) treated Amira raspberries at 500, 1,000 and 1,500 Gy and measured the bioburden, total phenolic content, antioxidant activity, physicochemical properties such as texture, colour, pH, SSC, and acidity, and sensorial parameters were assessed before and after irradiation and during storage time up to 14 days at 4 ◦C. The main focus of this study was the microbiological aspects where the results showed the inactivation of mesophilic population by one log reduction of microbial load (95% inactivation efficiency for 1,500 Gy), in the surviving population mainly constituted by filamentous fungi (79 – 98%). Irradiation treatment tended to increase the total phenolic content where storage time resulted in a decrease in total phenolics. The same trend was found for fruit antioxidant capacity with storage time. However irradiation induced a significant decrease in firmness compared with nontreated fruit. In addition, irradiated and non-treated fruit presented similar physicochemical and sensory properties during storage time.

In a study on the effect of quarantine irradiation doses on Australian raspberry fruit quality, Golding et al. (2014) and Golding et al. (2015) treated raspberry cv. Maravilla with low dose gamma irradiation (0, 150, 400 and 1,000 Gy) and stored at 0 ^{o}C for three or ten days to determine the effects of irradiation on fruit quality and nutritional and proximate contents. In general, none of the irradiation doses (≤ 1,000 Gy) significantly affected raspberry fruit quality (overall fruit quality, colour, firmness, weight loss, TSS, TA levels or TSS / TA ratio), or the nutritional or proximate content (ash, carbohydrate, dietary fibre, energy, moisture, protein, sodium, potassium, total sugars, fructose, ascorbic acid, monomeric anthocyanin, citric and malic acids). The length of time in storage affected some fruit quality and nutritional and proximate content parameters (such as overall fruit quality, firmness, weight loss, TA levels, dietary fibre, potassium, ascorbic acid, citric and malic acids), with longer storage periods resulting in lower quality fruit, irrespective of irradiation treatment (Figure 18). No interaction was detected between the effects of irradiation treatment and storage time, indicating that the storage effect was consistent for all irradiation doses on Maravilla raspberry fruit quality. This work was the basis of the FSANZ approval for the use of irradiation as a market access for Australian raspberries (FSANZ, 2017).

0 Gy 150 Gy 400 Gy 1,000 Gy

Figure 18. Irradiated Maravilla raspberry fruit after seven days storage at 0 ^{o}C.
Fruit were treated with 0, 150, 400 and 1,000 Gy (from Golding, 2013).

Vegetables

Tomato

Several studies have been conducted over the past 50 years on different tomato cultivars and recorded on the IDCT database. Dose rates range widely between 150 and 4,000 Gy however the majority of recent research has been conducted at < 1000 Gy. Physical, chemical, sensory, nutritional and visual quality have been evaluated at different dose rates and storage temperatures (i.e. 4, 10, 12, 15 and 25 °C).

Chay et al. (2012) found that even though irradiation treatments at 150, 600 and 1,000 Gy decreased tomato firmness by 19% and moisture levels by 3%, the fruit still remained marketable after 14 days storage at 10 °C (Figure 19). Similarly, Loro et al. (2018) found that irradiation at 500, 1,000 and 1,500 Gy soften tomato fruits without degrading ascorbic acid and lycopene content or affecting other quality parameters. Small but significant changes in skin colour, to a deeper shade of red, was attributed more to storage duration rather than irradiation treatment (Chay et al., 2013). TSS remained relatively constant over the storage period (Chay et al., 2012; Akter and Khan, 2012) and TA was unaffected by irradiation but did increase slightly due to storage time.

In terms of sensory attributes, Singh et al. (2016) found that colour, texture and overall acceptability improved with irradiation doses up to 1,500 Gy but showed a significant negative affect at the highest rate (4,000 Gy). Similarly, Adam et al. (2013) observed no significant differences in colour, texture, taste, flavour and overall acceptability for fresh tomato slices irradiated at 250, 500 and 1,000 Gy, and stored for 24 days at 15 °C and 85 - 90% RH, although these fruits were treated at the mature green stage. Furthermore, irradiation doubled the shelf life in cv. Amani tomatoes due to significantly delaying fruit softening and reducing both moisture loss and respiration rate.

An optimal dose rate of 750 to 1,000 Gy was determined by Singh et al. (2016) which can aid in improving shelf life without adversely affecting quality and sensory characteristics of tomatoes. Akter and Khan (2012) also showed that irradiation at 750 Gy in conjunction with storage at 12 °C resulted in the most promising results when factoring in other quality attributes such as firmness loss, TSS and spoilage, and is a practical solution to preventing losses in Bangladesh.

Summary. Irradiation has the potential to double tomato shelf life without adversely affecting other quality and sensory parameters. However, tomato firmness is affected, and even though it is reduced compared to non-irradiated produce, it is still satisfactory for wholesale and retail handling and marketing. At this stage an irradiation dose of 750 Gy in conjunction with 12 °C storage appears to be the best treatment for reducing spoilage of tomatoes after harvest.

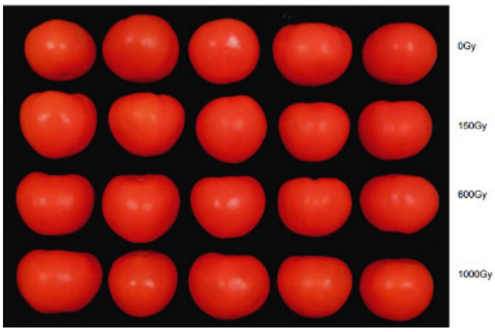


Figure 19. Effect of irradiation on visual quality of tomatoes after 14 days cool storage at 10 °C (from Chay et al., 2012).

Capsicum

Only one study on cv. Five star capsicum from 30 years ago is listed in the IDCT database, however capsicums (and tomatoes) were first approved for phytosanitary treatment in Australia by FSANZ in 2013. This approval was based on the report of Chay et al. (2012) who investigated the effect of low dose irradiation and storage duration on several fruits and vegetables including capsicums. Green capsicums were gamma irradiated at up to 1,000 Gy and then assessed within 1 day and after 3 weeks of storage at 7.5 °C. They showed that fruit firmness declined in storage which was independent to both increasing irradiation dose and storage time (Chay et al., 2012). Capsicums softened due to moisture loss which was significantly higher in capsicums treated at 1,000 Gy when compared to 0, 150 and 600 Gy. Chay et al. (2012) showed that the levels of TSS increased by 10% to 4.5 °Brix over the trial period and between the lower and higher dose rates whereas changes in TA levels increased only slightly by 0.02% to 0.13%, depending on the phytosanitary treatment. Degreening (i.e., development of red pigment) occurred over the storage period but was only minor at 2%, and not linked to irradiation treatment, whereas capsicums dosed at over 600 Gy were slightly dark greener than the two lower dose rates according to skin colour measurements.

In another study, Mitchell et al. (1992) found similar trends in quality changes within red and green capsicums when irradiated at less than 300 Gy, however changes were affected more by the storage time rather than the irradiation treatment. Both studies found that small quality changes were observed at low dose rates but more so at the higher rate.

Summary. Limited research has been conducted on capsicums however it appears that storage time of approximately 3 weeks at 'retail' temperatures has more of an impact on vegetable quality than dose rates, especially at levels less than 600 Gy. Storage at a lower temperature would potentially extend the shelf life beyond 3 weeks which would make this crop more suitable for export.

Asparagus

Limited work has been conducted on irradiation of asparagus with only four studies appearing in the IDCT database. Asparagus possesses a high respiration rate which makes it susceptible to water loss and quality changes during handling at elevated temperatures as occurs during fumigation. Fumigation is generally conducted within the importing country such as in Japan, however mixed loads treated at higher rates and in conjunction with less than ideal post-treatment temperature management result in reduced quality and shelf-life.

Previous research from Lescano et al. (1993) on asparagus packed in polystyrene foam, wrapped in polyvinylchloride (PVC) film and irradiated at 0, 1,000, 1,500 and 2,000 Gy and stored at 3 ± 2°C and 92 ± 5 % RH showed that the higher treatment dose rates increased market life. During 53 days of storage, flavour and colour were maintained, whereas spear growth (i.e. bract and length), microbial spoilage and moisture loss were delayed. In this research and as reported by Langerak (1971a and 1972), packaging helped to reduce dehydration, and created a controlled atmosphere around the produce that helped to delay senescence in the spears. Minimal differences were also observed in gradual weight loss between the control and irradiated product during the storage period. Colour changes from early on after treatment and the appearance of rust spot in control samples after two weeks of storage suggest asparagus quality may benefit from irradiation. Maxie et al. (1971) also found that even a low dose rate of 250 Gy helped control fruit fly and increase shelf life in 19 out of 20 fruits and vegetables, including asparagus. Linares (1990) report that moisture loss was slightly higher in the untreated (i.e., control) asparagus at 15%, when compared to product irradiated at 1,500 Gy with a moisture loss of 11%, and a similar trend observed by Zhen-Xin et al. (2001). Furthermore, ascorbic acid concentration was shown to decrease by 38% and 22% with higher dose rates of 1,500 and 2,000 Gy, respectively, when compared to the control (57%) after 30 days of storage. However Zhen-Xin et al. (2001) observed the opposite result although the storage time used in this study was significantly shorter at 15 days.

The majority of studies so far have been conducted using irradiation doses well in access of 1,000 Gy, or are more than 20 years old. However Agriculture Victoria is conducting a storage trial on asparagus using different packaging liners (i.e., perforated and MAP), and irradiated at 400 Gy (January 2022).

Summary. Given asparagus is currently exported without packaging in 5 or 10 kg wooden or plastic crates, this high value product has the potential to benefit greatly from irradiation to improve temperature management during the treatment process, and in conjunction with packaging treatments to help prevent moisture loss, irradiation could help extend the storage potential and improve or at least maintain export quality.

CONCLUSION

Fresh fruit and vegetables are still living after harvest and are perishable with limited storage and shelf life. There are a range of commercial technologies such as refrigeration which maintain product quality through the supply chain (Wills and Golding, 2017). However the introduction of irradiation as a commercial phytosanitary market access treatment requires the integration into current handling systems without negatively impacting on product quality.

Irradiation treatment breaks chemical bonds in DNA and other molecules in both the quarantine pest and the product, thereby sterilizing the pest or preventing it from achieving sexual maturity (Barkai-Golan and Follett, 2017). However what effects does this irradiation process have on product quality, consumer acceptance, nutritional quality, and eating quality?

This report reviewed the published scientific literature and unpublished reports of phytosanitary irradiation to give clear information on the effects of irradiation on product quality following treatment and export. A lot of older scientific literature has been conducted using doses that are above the current phytosanitary limits (i.e. above 1,000 Gy). This is because it has been shown that high dose irradiation (> 1,000 Gy) can inhibit postharvest decay and have some food safety benefits (Barkai-Golan and Follett, 2017), but these higher doses are not suitable for phytosanitary treatment and this review examined the effects of low-dose irradiation treatment (< 1,000 Gy).

It is interesting to note that while the effects of irradiation on product quality has been widely studied in many major horticultural crops, there have been relatively few studies on other major crops (e.g. melons and many vegetables). This is in part due to the use of irradiation, historical research efforts around the world and hosts of quarantine pests. For example where phytosanitary irradiation has been recently accepted for trade, more research has been completed. Subsequently, countries such as the USA and Australia have become leaders in phytosanitary irradiation research. However, it is interesting to note that many countries such as Thailand and China have shown increased interest in phytosanitary research. Further engagement between leading international research providers and regulators would benefit the adoption of phytosanitary R&D.

The results of this review showed that there are few negative consistent effects of phytosanitary irradiation on fruit and vegetable quality, however these limited examples can impact consumer acceptability. For example, a known quality attribute affected by irradiation is softening in many fruit. However, this observation is in part due to the sensitivity of the objective instruments (specialist texture analyers) used by researchers, and differences in fruit firmness attributes are often not detected by consumers (Golding, 2018). Given this caveat, fruit softening can be a commercial out-turn issue for irradiated produce and more needs to be understood and managed to ensure it does not become an export barrier for the supply chain and consumers.

Most of the research reviewed in this report has been descriptive, generally only treating a single batch of fruit at one time. While these trials have compared irradiation treatments and untreated control fruit, the inferences which can be drawn from these descriptive trials are limited, i.e. the results only reflect a single batch on that one harvest / treatment time. Indeed most of this research has not employed the use of sensory panels or consumer acceptance studies following irradiation treatment and simulation of supply chain storage conditions. More sensory and consumer research would further validate the findings of treatment / simulated storage trials.

The vast majority of phytosanitary research has been descriptive with no attempt to examine other factors which may affect fruit quality out-turn. It can be argued that this limited research scope of much of the previous research is limiting our understanding, management and commercial application of phytosanitary irradiation. There have been very few studies which have attempted to understand the combination of pre- and postharvest factors that contribute to irradiation impacts on product quality.

A good example of practical R&D to support the application of phytosanitary treatments was examining the effect of maturity on a storage disorder in mango. Irradiation treatment was shown to induce the development of a lenticle disorder in B74 (Calypso™) mango (Marques et al., 2016), however it was subsequently shown that this disorder can be successfully managed with harvesting and treating fruit with a more advanced maturity (Roberto not published). Similarly, the outcomes of phytosanitary irradiation in Pattavia pineapple has been shown to be influenced by seasonal harvesting, fruit maturity and irradiation dose (Jenjob et al., 2017; Uthairatanakij et al., 2013; 2018). While there is potentially some negative quality issues associated with phytosanitary irradiation, these examples show it is possible to manage the pre and postharvest factors to minimise these effects to facilitate trade. Unfortunately the pre- and postharvest factors which influence end-point quality are often unknown and with very little research undertaken to understand and minimise these effects.

RECOMMENDATIONS

The review of published and unpublished literature has identified some short- and longer-term recommendations to improve the commercial outcomes of phytosanitary irradiation treatment:

1. Demonstrate the efficacy of phytosanitary irradiation treatment to maintain the quality for Australian horticultural products through domestic and export supply chains

Quantify the effects of phytosanitary treatment and storage on a range of important horticultural products to overcome any potential technical barriers to poor quality. This will be done through both laboratory-based storage trials and through commercial supply chains.

1a. Laboratory trials. Conducting laboratory based storage trials allow for tight control of treatment and storage conditions. Simulating different domestic and export supply chains allow for testing different transport and retail conditions at different times of the growing season. This should include sensory, consumer acceptability assessments and nutritional analysis. Controlled replicated laboratory trials will be published in peer-reviewed international scientific journals. This will allow for the continued international acceptance of phytosanitary irradiation in both regulatory and commercial negotiations.

1b. Quantifying the effects of phytosanitary treatment through commercial supply chains will give industry, exporters and importers confidence to use consistently use irradiation as a market access treatment.

Priority crops: summerfruit, blueberry, lemon, vegetables, melons, kiwifruit.

2. Understanding the basis for the action of irradiation and maintenance of fruit quality following irradiation

With few exceptions such as Melo et al. (2021), all of the current product tolerance literature to irradiation has been descriptive with no attempt to understand the mechanisms of tolerance and intolerance to irradiation treatment. Indeed the underlying molecular mechanisms of fruit ripening and senescence and response to stress are poorly understood. However comparative transcriptomic approaches are beginning to reveal the molecular mechanisms and improving our understanding of fruit responses to stress. For example we recently developed a conceptual model elucidating the molecular mechanism of browning development in apple fruit in response to stress (Li et al., 2022). Melo et al. (2021) examined the effect of irradiation on gene expression of enzymes related to ethylene and α-farnesene in Granny Smith apples following irradiation and showed irradiation treatment may reduce superficial scald in Granny Smith apples through inhibition of gene expression of enzymes related to ethylene and α-farnesene biosynthesis. Understanding the molecular basis of the positive and potentially negative effects of irradiation on fruit quality (including nutritional changes) will improve our options to manage fruit quality following treatment through the supply chain.

Priority crops: apple and blueberry.

3. Identify and understand the pre- and postharvest factors which effect product tolerance to phytosanitary treatment

While there may be some occasional sub-optimal effects of irradiation on final fruit quality following treatment and through the supply chain, the review identified that there is the potential to identify and understand some of the contributing factors which could potentially be managed to maintain quality through the supply chain. For example pre-harvest differences between grower, cultivar, regions, harvest maturity, etc. have all been identified as contributors to final fruit quality following phytosanitary treatment (Recommendation 1). These factors need to be clearly identified and qualitied across different seasons and growing conditions. However the identification and management of the effects of irradiation on fruit quality has rarely been conducted. The few examples of preharvest factors affecting fruit tolerance include the effect of growing season on internal browning in pineapples (Jenjob et al., 2017) and harvest maturity in Calypso™ mangoes (Dr. Roberto Marques, QDAF - *in press*). There needs to be systematic examination of pre-harvest factors on postharvest quality outcomes.

In addition, postharvest factors have been shown to affect the product response to irradiation. For example, the use of modified atmospheres and other standard postharvest technologies (such as modified atmosphere storage) have been shown to interact and maintain fruit quality after treatment and through the supply chain (Wills and Golding, 2017). There are few examples of mediating potentially phyto-toxic responses in horticultural produce. Ortiz et al. (2018) showed the negative effects of methyl bromide treatment in blueberries could be countered with the application of the ethylene action inhibitor 1-methylcyclopropene (1-MCP) and concluded that pre-treatment with 1-MCP may be useful to alleviate methyl bromide-induced deterioration in blueberry. It is necessary to identify standard postharvest management factors such as the use of edible coatings, modified atmospheres, 1-MCP which could be integrated into current handling systems to reduce any potential negative effects of irradiation treatment, maintain product nutrition and extend the storage and marketing life of treated horticultural produce.

Priority crops: lemon, tablegrapes, summerfruit, blueberry, vegetables.

4. Develop management strategies to improve the quality outcomes of Australian exports which use phytosanitary irradiation

Having identified the potential pre- and postharvest factors associated with improved quality (and potentially negative effects) of irradiation (Recommendation 3), it is essential to systematically integrate these management factors to maintain quality after treatment and through the supply chain. The effects of the different interactions of pre- and postharvest factors are often not captured in market access R&D due to the complex nature of these interactions. Indeed current R&D into the effects of irradiation on fruit quality has been limited to single experiments with individual batches of fruit. However it is the successful management of these factors which will determine the success of the application of phytosanitary irradiation treatment. This therefore requires the systematic evaluation of replicated robust laboratory and commercial trials to assess these interactions to optimise pre-harvest, treatment and postharvest handling conditions to maintain final commercial and product eating quality. For example the systematic assessment of harvest maturity, treatment and optimal storage conditions on different batches of fruit from different growing conditions will identify optimal pre- and postharvest treatment and storage conditions.

Priority crops: lemon, tablegrape, summerfruit, blueberry, vegetables.

5. Comparison of different commercial market access treatments on produce quality and eating quality

Irradiation is one of the many commercial market access treatments available for industry to access export markets. Other phytosanitary treatments include cold treatment, methyl bromide fumigation, vapour heat treatment etc. These different end-point treatments have their own commercial and market benefits and challenges. However there are few side-by-side comparisons of these different market access treatments on product quality and eating quality. We have recently completed a preliminary study on comparing commercial cold treatment, irradiation and methyl bromide treatment on blueberries, cherries, tablegrapes and lemons (Golding, 2022). This research showed the effects of the different market access treatment on fruit quality and also illustrated the grower-to-grower variability. More robust comparisons of the different market access treatments will give industry and exporters the confidence to use irradiation and as a consistent market access treatment.

Priority crops: summerfruit, apple, blueberry, vegetables.

6. Develop and implement crop specific best practice guidelines for the commercial use of irradiation as a phytosanitary market access treatment

The successful commercial application of phytosanitary irradiation treatment requires consistent outcomes of excellent fruit quality out-turns, which also minimises any potential negative quality issues. The delivery of these consistent outcomes requires the application of robust best practice guidelines. These guidelines need to be developed and tested to ensure the consistent supply of treated product. The practical guidelines will outline pre and postharvest management factors to optimise fruit quality and storage life. These best practice guidelines will be developed on commercial commodities with extensive use of irradiation.

Priority crops: mango, tablegrape, blueberry.

Within the scope of this current Project (Section 1.3b), it is recommended to explore *Recommendation 1* to give industry confidence to use phytosanitary treatment. It is proposed to work with key industries to quantify the effects of phytosanitary treatment and storage to identify and overcome any potential technical barriers to poor quality.

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