FOOD STANDARDS
Australia New Zealand
Te Mana Kounga Kai – Ahitereiria me Aotearoa

Nutritional impact of phytosanitary irradiation of fruits and vegetables

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1 Table of Contents

1 Executive Summary

Low level ionising irradiation can be used as a phytosanitary treatment for insect pest control on fruit and vegetables. FSANZ has previously assessed the safety and nutritional impact of using ionising irradiation for phytosanitary purposes on various tropical fruits as well as tomatoes and capsicums, and found that doses of ≤1 kGy do not present a safety or nutritional risk to Australian and New Zealand consumers. It is expected that in the near future FSANZ will receive a number of applications to irradiate a variety of other fresh fruits and vegetables for quarantine purposes.

The objectives of this review were to:

- assess the impact of phytosanitary doses of irradiation on the nutritional quality of fruit and vegetables by:
  - Investigating the natural variability in vitamin levels in a range of fruits and vegetables
  - Documenting changes in vitamin composition of fruits and vegetables following irradiation with up to 1 kGy
  - Considering the dietary implications of any reduction in vitamin levels following phytosanitary doses of irradiation (up to 1 kGy).
- Make recommendations to amend data requirements for irradiation of fruits and vegetables.

Extensive natural variation occurs in the nutrient composition of individual fruit and vegetable types. The main sources of variation are cultivar, season, growing location and degree of ripeness. Post-harvest storage and processing also affect nutrient composition. Fruits and vegetables are rich sources of vitamin C and carotenes. Substantial data documents the natural variation in levels of these nutrients, with differences of more than ten-fold being common between cultivars.

Phytosanitary doses of irradiation typically range from 0.15 to 1 kGy. At these doses there is no effect of irradiation on macronutrients or minerals. However, the effect on vitamins is less clear, with vitamins A, C, E and thiamin being most sensitive to irradiation. Fruits and vegetables generally have high levels of carotenes and vitamin C but are not major contributors to intakes of vitamin E or thiamin, therefore this review focused on vitamin C and carotenes. Review of the published literature demonstrated that phytosanitary doses of 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 some fruits vitamin C levels decreased following irradiation. 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. As carotene levels were unaffected by phytosanitary doses of irradiation it can also be concluded that carotene intakes would not be compromised.

From these data it can be concluded that phytosanitary doses of irradiation do not pose a nutritional risk to the Australian and New Zealand populations. It is therefore 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.

2 Terminology and abbreviations

AA	Ascorbic acid (reduced form)
β-carotene	pro-vitamin A carotenoid
β-carotene equivalents	Estimated using the following formula: β-carotene (µg) + α-carotene/2 (µg) + β-cryptoxanthin/2 (µg)
Carotene	Non-oxygenated carotenoid
Carotenoid	Hydrocarbon pigments synthesised by plants
DAFF QLD	Department of Agriculture, Fisheries and Forestry, Queensland
DHAA	Dehydroascorbic acid (oxidised ascorbic acid)
HPLC	High pressure liquid chromatography
Retinol equivalents[1]	Calculation of total vitamin A activity of a food. Estimated using the formula: retinol (µg) + (β-carotene/6 + α- carotene/12 +β-cryptoxanthin/12 (µg))
Total vitamin C	Value represents both AA and DHAA

[1] For an alternate approach, calculating Retinol Activity Equivalents (RAE), please see the "DRI Essential Guide to Nutrient Requirements" (2006), available at http://www.nap.edu/openbook.php?record_id=11537&page=170

3 Background

Food irradiation is currently permitted for specific commodities under Standard 1.5.3 of the Food Standards Code. These include:

- herbs, spices and herbal infusions with up to 30 kGy to control bacterial contamination and sprouting, and for pest disinfestation
- tomatoes, capsicum, breadfruit, carambola, custard apple, litchi, longan, mango, mangosteen, papaya, rambutan and persimmon with up to 1 kGy as a phytosanitary measure to control pest infestation.

Following a comprehensive review, the Australian Pesticides and Veterinary Medicines Authority has decided to suspend some of the current uses of dimethoate and fenthion. For a number of years, these two pesticides have been the treatment of choice for phytosanitary purposes on a range fruit and vegetables. As a result of this decision, FSANZ is expecting to receive applications to permit the use of irradiation of a range of raw fruit and vegetables for phytosanitary purposes. In contrast to pesticide treatment, an effective end point of irradiation for phytosanitary control is preventing an insect's ability to emerge from its larval stage or rendering the adults incapable of reproduction. Typically, an effective irradiation dose for fruit fly is 0.15 kGy, and up to 1 kGy for some *Lepidoptera* species (Diehl 1995).

3.1 Regulatory Context and Objectives

To date, applications for fruit irradiation approvals have been assessed on a case-by-case basis. To conform with existing data requirements, information has been provided on the impact of irradiation on a selected range of nutrients. However, these data requirements may impose greater cost on applicants and FSANZ than is required to assess potential nutritional quality of irradiated fruits and vegetables.

The objectives of this review were to:

- assess the impact of phytosanitary doses of irradiation on the nutritional quality of fruit and vegetables by:
    - Investigating the natural variability in vitamin levels in a range of fruits and vegetables
    - Documenting changes in vitamin composition of fruits and vegetables following irradiation with up to 1 kGy
    - Considering the dietary implications of any reduction in vitamin levels following phytosanitary doses of irradiation (up to 1 kGy).

- Make recommendations to amend data requirements for irradiation of fruits and vegetables.

This review includes recent unpublished data on the effects of phytosanitary doses (≤1 kGy) of irradiation on nutrient composition (specifically that of the irradiation-sensitive vitamin C and carotenes) of whole fruits and vegetables. Different types of fruits and vegetables currently treated with dimethoate and fenthion were also included, as well as other fruit and vegetables for which phytosanitary irradiation may be used. For this reason, pome, stone, berry, citrus and tropical fruits, as well as cucurbit and fruiting vegetables were included as they can potentially be hosts for fruit fly.

Other vegetables such as root and tuber vegetables, brassicas, leafy vegetables and legumes are unlikely to be irradiated in Australia or New Zealand for phytosanitation, and have therefore not been considered in this literature review. While citrus fruit are also unlikely to be irradiated (communication from Steritech), they have been included as they are a potential fruit fly host, and also have high levels of radiation-sensitive nutrients.

4 Natural variation in vitamin content of fruits and vegetables

Fruits and vegetables are a rich source of antioxidant vitamins, in particular vitamin C and pro-vitamin A carotenes, and to a lesser extent, vitamin E. Fruits and vegetables also make a major contribution to dietary intake of folate and vitamin B6 (through banana consumption), but only limited contribution to thiamin, riboflavin and niacin intake. Vitamins C and E, carotenes and thiamin are sensitive to irradiation, but as fruits and vegetables make major contributions to vitamin C and carotene intakes this review will focus on these micronutrients.

To collate quantitative data about the natural variation of vitamin levels in fruits and vegetables, published data were searched using EBSCOHost and food composition tables from Australia, New Zealand and the USA. References and data were cross-checked with the Food Composition Database for Biodiversity developed by the Food and Agriculture Organisation (Stadlmayr et al. 2011). Full details are presented in Appendix 1, and the major findings summarised below.

4.1 Cultivar

Cultivar refers to different cultivated varieties of the same plant. For each fruit or vegetable there are numerous cultivars, each with different physical, chemical and genetic characteristics. For example, apples can be red, yellow or green-skinned and may mature

early or late in the growing season. Similarly, peaches come in many varieties and even those similar in appearance can have very different physiochemical properties. Examples of the effect of cultivar on vitamin content are given below:

- In apricots, vitamin C levels varied more than five-fold between 15 cultivars (Hegedüs et al. 2010), and carotenoid levels varied more than 10-fold between 37 varieties (Ruiz et al. 2005)
- In a study of 31 apple cultivars grown in Belgium, vitamin C ranged from 7-26 mg/100 g with higher levels reported in late-harvest cultivars (Davey and Keulemans 2004)
- In kiwifruit, vitamin C levels ranged from 26-185 mg/100 g in green-fleshed cultivars, and 64-206 mg/100 g in yellow-fleshed cultivars (Nishiyama et al. 2004)
- In seven capsicum cultivars, vitamin C ranged from 75-202 mg/100 g and β-carotene levels ranged from 2-1187 µg/100 g (Howard et al. 2000).

4.2 Environment

Growing location and season affect nutrient composition. Seasonal variation can occur at two levels. Firstly, produce harvested at different times within a 12-month period may have different nutrient composition. Secondly, produce grown in the same season in consecutive years may differ. The effect of within- and between-season variation is usually less than that of cultivar, but can still lead to large variations. For example:

- In tomatoes, a Spanish study found that vitamin C levels were up to 95% lower in the same cultivar grown in a glasshouse during the autumn/winter season compared to spring/summer. In contrast, β-carotene levels were generally higher in winter-grown tomatoes (Roselló et al. 2011)
- In raspberries, vitamin C content varied by more than two-fold within the same cultivar over three consecutive growing seasons (Pirogovskaia et al. 2012)
- In Valencia oranges, β-carotene levels varied 1.6-fold over three consecutive growing years, with levels varying by up to 6-fold between different geographic growing locations (Dhuique-Mayer et al. 2009).

The physical location of crops or orchards also influences vitamin levels in fruits and vegetables. Climatic conditions, altitude and soil quality are the main variables between different growing locations. Growing conditions, such as the use of greenhouses, can also influence vitamin levels. Examples of the effects of growing location include:

- In mangoes of the same cultivar, but grown in different locations, β-carotene levels varied by 30-160% and vitamin C levels by 20% (Manthey and Perkins-Veazie 2009)
- In bananas, vitamin C levels varied by more than 2.5-fold between growing locations (Wall 2006)
- In tomatoes, the effect of growing location is cultivar-dependent. Vitamin C and β-carotene levels were similar in two different locations for some cultivars, and varied by nearly two-fold for other cultivars (Roselló et al. 2011)
- In Elstana strawberries grown in different conditions (tunnel, open field or greenhouse), vitamin C content varied by up to 3.4-fold (Pincemail et al. 2012)
- In gala apples, vitamin C levels are approximately 20% lower in shaded compared to sun-exposed fruits (Li et al. 2009).

4.3 Ripeness

As fruits mature and ripen, they undergo a number of biochemical changes, with ripe fruit typically having higher water content, decreased starch and increased sugar levels, reduced acidity, and altered pigment profile compared to unripe fruit. As a part of the ripening process the vitamin and pro-vitamin content of fruits changes. In general, carotenoid levels increase during ripening, as indicated by the colour change that typically accompanies ripening. The effect of ripening on vitamin C levels vary between fruit and cultivar type, with reports of increased, decreased or no change in vitamin C content. Examples of the effects of ripening on nutrient content of fruits and vegetables include:

- In mangoes, β-carotene levels increased by up to nine-fold with ripening (Vásquez-Caicedo et al. 2005)
- In plums, total carotenoids increased by more than four-fold during ripening, whereas vitamin C levels increased only 20% (Khan et al. 2009)
- In capsicum, β-carotene levels increased between two and 19-fold during maturation, while vitamin C increased by approximately 20% (Howard et al. 2000)
- In a study of three tomato cultivars, vitamin C levels increased 1.3- to 2-fold during maturation and ripening (Periago et al. 2009)
- In pears, vitamin C levels decreased approximately three-fold during on-tree maturation (Franck et al. 2003).

4.4 Post-harvest storage

Fruits and vegetables continue to ripen after harvest. Further storage can also affect vitamin levels, with vitamin C susceptible to storage-associated diminution in some fruits and

vegetables. Storage conditions influence vitamin changes, with temperature and atmospheric conditions being important considerations. For example:

- Long-term cold storage of apples can result in loss of up to 90% of vitamin C (Bhushan and Thomas 1998). Short-term storage at room temperature also decreases vitamin C by 35–75% (Davey and Keulemans 2004; Kevers et al. 2011)
- Vitamin C levels in oranges decreased by 22–27% following 6 months storage (Erkan et al. 2005)
- Storage effects in tomatoes are variable. Short-term ambient storage decreased vitamin C by 12–34% in four cultivars, but levels increased 16% in another cultivar (Molyneux et al. 2004). Storage conditions are important. Vitamin C increased in tomatoes stored for 15 days at cool temperatures, but there were losses of 15% of vitamin C in tomatoes stored at 25°C (Vinha et al. 2013)
- In strawberries, vitamin C levels increased by nearly 30% when stored for 20 days in normal air, but decreased by up to 13% in high CO_2 atmosphere (Shin et al. 2008).

4.5 Processing

Some fruits and vegetables commonly undergo post-harvest processing. For example, berries which have a short shelf-life are commonly frozen or canned. Vegetables such as tomatoes and capsicums are also regularly consumed cooked. These processing techniques can also alter vitamin contents. For example:

- Up to 50% of vitamin C is lost from tomatoes after baking for 45 minutes, or following processing to tomato paste (Abushita et al. 2000; Gahler et al. 2003)
- Capsicum preserved by freezing lost 40% of vitamin C content, but blanching prior to freezing attenuated loss to 13% (Martínez et al. 2005)
- In frozen berries, vitamin C levels are reduced by around 30%. Greater losses are associated with canning, with vitamin C reduced by around 75% (see section 1.3 of Appendix 1).

The majority of published data focuses on the variability in vitamin C and β-carotene levels in fruits and vegetables. However, the same factors are likely to influence levels of other vitamins. For example, folate levels in strawberries and tomatoes differ between cultivars and with growing year, ripeness, storage and processing (Strålsjö et al. 2003; Iniesta et al. 2009).

4.6 Analytical methods

Vitamin C content can be assessed by a variety of techniques, including direct titration with iodine, derivatization, enzymatic analysis, capillary electrophoresis and liquid chromatography (Eitenmiller et al. 2008). In general, titration is the method most prone to error as other constituents of fruit and vegetables may also produce a colour change through reduction of the coloured indicator dye, and the colours present in fruit and vegetable extracts may also interfere with the assay. In addition, titration only measures reduced AA, and not DHAA, which also has vitamin C activity. However, the usefulness and reliability of the titrimetric method can be enhanced by performing a solid phase extraction step which removes interfering substances and also enables measurement of DHAA. Derivatization methods measure total vitamin C following oxidation of AA to DHAA; measurement of both can be achieved by subtraction. DHAA is then quantified following a condensation reaction which generates a fluorescent product. Enzymatic conversions of AA to DHAA can also be coupled to the derivatization method. More recently, capillary electrophoresis and high pressure liquid chromatography (HPLC) have been used for vitamin C analysis, with both techniques having a high sensitivity and reliability. DHAA needs to be reduced before capillary electrophoresis, enabling a subtractive determination of both AA and DHAA. In contrast, HPLC enables simultaneous measurement of AA and DHAA.

Carotenoid analysis is usually performed using either spectrophotometry or HPLC. Spectrophotometric analysis is limited as it is not able to discriminate between pro-vitamin A carotenoids and the other carotenoids, and can also give erroneous values due to interference from chlorophyll. In contrast, HPLC separates the carotenoids and their isomers, enabling a more detailed and accurate analysis.

In addition to the considerations below, it should be noted that all analytical measurements have a degree of uncertainty associated with them. Measurement uncertainty for vitamin analysis is typically more than 10% of a reported value (Phillips et al. 2007).

For estimating vitamin C concentrations in fruit, there is generally good agreement using different analytical methods. For example, similar ranges of AA content were reported for:

- Apples using titration and HPLC
- Raspberries using liquid chromatography-mass spectrometry, a commercial assay kit and titration
- Citrus fruits using HPLC and titration.

In studies of strawberries, the reported AA levels appeared higher in studies using titration methods compared to HPLC or enzyme analysis. However, given the variability between

cultivars and effects of growing location, it is unclear if this variation is attributable to methodological differences or the result of natural variation.

It is more difficult to directly compare carotenoid data between studies as these data may be reported as β-carotene equivalents, total carotenoids, retinol equivalents or in other forms. However, the reported range of β-carotene levels in apricots was ~3-fold higher in a study using HPLC compared to spectrophotometry. HPLC analyses give more detailed information on carotenoid identity, and have less interference from other pigments. The extraction of carotenoids is an important step in analysis, and methodological differences in extraction as well as variation between the cultivars study may have contributed to inconsistencies between studies.

4.7 Summary

Multiple environmental factors and cultivar selection influence vitamin content of fruits and vegetables. As environmental factors are difficult or impossible to control, there is considerable variability in naturally occurring levels of vitamins, even within fruit of the same cultivar. Table 4.1 summarises the range of vitamin values reported in published literature and food composition tables for common fruits and selected vegetables. Post-harvest handling and storage can also significantly impact nutrient composition of fresh produce. Together, these factors cause large variation in the vitamin content of fruits and vegetables that are consumed by the Australian and New Zealand populations.

Table 4.1 Concentration range of selected vitamins in fruits and vegetables*

	Fruit or vegetable	β-carotene (µg/100 g)	Vitamin C (mg/100 g)	Folates (µg/100 g)	Vitamin E (mg/100 g)
Pome fruit	**Apple**	0–19	<1–35	0–3	0.1–1.3
	Pear	0–20	3–30	7	0–0.5
Stone fruit	**Apricot**	197–5170	3–16	6–9	0.9–1.2
	Peach	38–477	4–15	3–4	0.7–1.3
	Nectarine	12–362	4–14	5	0.8
	Cherry	26–56	7–25	4–6	0.1–0.4
	Plum	147–417	3–11	5	0.3–0.8
Berry fruit	**Strawberry**	0–6	23–185	12–96	0.3–0.4
	Blueberry	8–39	4–13	6–12	0.5–0.9
	Raspberry	0–28	7–41	21–34	0.4–0.9
Citrus fruit	**Orange**	46–6900	40–63	17–43	0.2–0.5
	Mandarin	56–19800	24–58	0–36	0–0.4
Tropical fruit	**Mango**	310–3900	12–135	43	0.9–1.3
	Banana	23–75	3–19	10–33	0.1–0.2
	Pineapple	10–60	17–68	5–19	<0.1
	Litchi	0	21–36	NA	NA
	Guava	380	129–248	NA	NA
Other fruit	**Kiwifruit**	43–54	26–206	25–39	0.9–1.5
	Melon[#]	30–1960	5–50	19–21	<0.1–0.1
	Watermelon	20–427	11–24	0–3	<0.1–0.1
	Grape	0–91	0–7	0–4	0.2–0.5
Vegetables	**Tomato**	60–3500	1–72	2–42	0.3–0.7
	Capsicum	117–930	24–202	10–85	0–4.0
	Cucurbit[f]	59–2710	2–30	0–41	0–1.4

*Detailed data on natural variations are in Appendix 1. [#]Melon includes both rockmelon (cantaloupe) and honeydew melon. [f]Cucurbit includes pumpkin, zucchini and cucumber.

5 Nutrient sensitivity to irradiation

Numerous independent reviews have been published on the effects of irradiation on food (World Health Organization 1981; World Health Organization 1994; World Health Organization 1999; 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). Nutrient loss can be minimised by the use of appropriate processing techniques, such as low temperatures and

oxygen-free conditions (World Health Organization 1994; Diehl 1995), however the applicability of these conditions to whole fruits and vegetables may be limited.

5.1 Macronutrients and minerals

There has been no demonstrated effect of irradiation up to 1 kGy 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.

5.2 Vitamins

There is a general hierarchy of vitamin sensitivity to irradiation, with vitamins A, C, E and thiamin being most sensitive (Figure 1) (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 focussed on these nutrients.

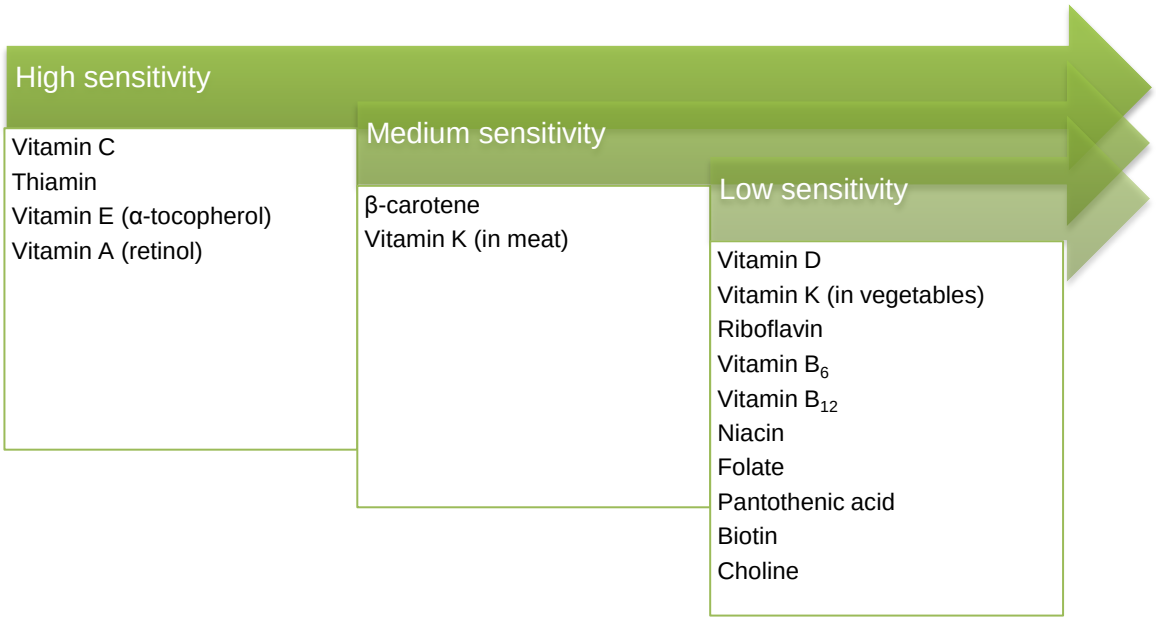

Figure 1: General sensitivity of vitamins in food to irradiation (modified from Kilcast 1994)

5.2.1 Vitamin A

Vitamin A as retinol is not present in plant foods, but the pro-vitamin A carotenoid β-carotene, as well as the less active α- and γ-carotenes and β-cryptoxanthin, are found in many fruits and vegetables. The predominant dietary source of carotenes in Australia and New Zealand is from orange vegetables. In fruits and fruiting vegetables, carotene levels usually increase with ripening as indicated by colour development. Irradiation may affect carotene levels through effects on fruit or vegetable ripening. Produce in which ripening is delayed by irradiation include tropical fruits, plums, pears, tomatoes and capsicum (Thomas 1986a; Thomas 1986b; Lacroix et al. 1993). In contrast, ripening of peaches and nectarines is stimulated by irradiation (Thomas 1986a). However, the effect of irradiation on ripening can vary between cultivars (Thomas and Beyers 1979). Therefore, irradiation can result in lower carotene levels after storage, due to differences in rate of ripening. For this reason, caution should be applied when interpreting changes in carotene levels after irradiation.

5.2.2 Vitamin C

Vitamin C is a water-soluble vitamin. The major dietary sources of vitamin C in Australia and New Zealand populations are fruit and vegetable juices and drinks, potatoes, citrus fruits and brassica vegetables. 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.

5.2.3 Vitamin E

Vitamin E is a lipid-soluble antioxidant vitamin with high sensitivity to irradiation. Vitamin E sensitivity to irradiation is dependent on temperature, oxygen and exposure to air (Diehl 1995). The main dietary sources of vitamin E in Australia and New Zealand include meat, cereals, fats and oils, cakes and biscuits. In addition, fruits and vegetables contributed up to 11% and 16% of vitamin E intakes respectively, but this includes vitamin E from sources such as oils in vegetable dishes. Furthermore, in the New Zealand surveys, potato, kumara

(also known as sweet potato) and taro contributed between 6 and 13% of vitamin E intake. However, none of the individual fruit and vegetable groups made a >5% contribution to vitamin E intake. Overall, vitamin E is derived in small amounts from a wide variety of foods in the Australian and New Zealand diets. In Australian and New Zealand children, apples contributed up to 4% of dietary vitamin E intake. In adults, stone fruits and tomatoes each contributed up to 3% of vitamin E intake. With the exception of these produce, the fruit and vegetable sources of vitamin E are unlikely to be irradiated for phytosanitary purposes. It is therefore unlikely that phytosanitary irradiation of fruits and vegetables would significantly affect vitamin E intakes in the Australian and New Zealand populations.

5.2.4 Thiamin

Thiamin is sensitive to irradiation, but the major dietary sources of this vitamin are bread, milk, meat, breakfast cereals, yeast and yeast-, vegetable- or meat-based extracts. Vegetable dishes and potato and kumara contributed up to 12% and 10% of thiamin intake in Australian and New Zealand populations, respectively. However, potato and potato dishes and products are the predominant source of thiamin from fruits and vegetables in the Australian and New Zealand diet. As such, the sub-categories of fruiting vegetables, tomato and tomato products, and other vegetables did not make a major (>5%) contribution to thiamin intake. As it is these groups that include the vegetables likely to be irradiated for phytosanitary purposes, it is therefore unlikely that thiamin intakes would be adversely affected by irradiation of fruits and vegetables.

5.3 Other non-vitamin bioactive compounds

Fruits and vegetables are rich sources of non-vitamin bioactive compounds. The two main classes are polyphenols and carotenoids without vitamin A activity, with both generally having antioxidant activity. There are >8000 polyphenols, and these compounds can be classified as flavonoids, phenolic acids, polyphenolic amides and other phenols. Flavonoids can be further categorised as isoflavones, neoflavones, chalcones, flavones, flavanols, flavanones, flavanonols, proanthocyanidins and anthocyanidins (Tsao 2010). Similarly, carotenoids are a broad class of compounds, which can be classified as xanthophylls (for example lutein and zeaxanthin) and carotenes (such as lycopene).

These compounds do not have recommended daily intakes and less is known about the level of intake within Australia and New Zealand. Similarly, less is known about the sensitivity of these compounds to irradiation, but given the diversity of compounds the degree of

sensitivity is likely to be varied. Throughout this review, the effects of irradiation on these compounds are discussed where data were available.

5.4 Summary

Fruits and vegetables are an important dietary source of vitamins A and C. The pro-vitamin A carotenoid, β-carotene, and vitamin C exhibit medium- and high-sensitivity to irradiation, respectively. Minerals and macronutrients have low sensitivity to irradiation doses of ≤1 kGy, but the effect of these doses on other carotenoids and polyphenols is less clear. Therefore, it is important to review the current knowledge of the effects of irradiation up to 1 kGy on β-carotene and vitamin C. Where data were available, comment was made on the effects of irradiation on other bioactive compounds.

6 Effects of irradiation on carotenoids, vitamin C and other bioactive compounds in fruit and vegetable groups

Published data were searched using electronic databases as described in Appendix 2. The majority of studies identified assessed the effects of irradiation on carotenoids and vitamin C, with some also investigating other bioactive compounds. For some fruits and vegetables, unpublished (raw) data were made available to FSANZ in 2012 by DAFF QLD. These data are also reviewed. For clarity, the data have been reviewed by fruit and vegetable type.

6.1 Pome fruits

Studies on the effects of irradiation of pome fruits were found for whole and sliced apples, and are summarised in Table 6.1.

Whole apples

A study of four apple cultivars assessed vitamin C levels after irradiation with 0.1, 0.2, 0.4 and 0.6 kGy after 1, 2, 4 and 6 months of cold storage (Bhushan and Thomas 1998). In non-irradiated fruit, vitamin C levels ranged from 1.5-3.3 mg/100 g at harvest, 0.9-1.5 mg/100 g after 1 month, and 0.4-1.5 mg/100 g after 6 months; AA decreased by 30-89% in non-irradiated apples during storage. The effect of irradiation was cultivar-dependent. In Royal Delicious apples, irradiation at all doses attenuated the storage-associated decrease in vitamin C content, with levels being 21% to 146% higher than time-matched non-irradiated controls. After one month, irradiation decreased vitamin C content in Red Delicious and Rich-A-Red apple cultivars -15% to -40% and -61% to -66% compared to non-irradiated apples,

respectively. However, after 6 months storage, both varieties (Red Delicious and Rich-A-Red) had significantly higher vitamin C levels in irradiated compared to non-irradiated controls (+10 to +158%). The effects in Golden Delicious apples were more variable, but the overall pattern demonstrated preservation of vitamin C in irradiated apples with advanced storage (+1% to +43%).

In unpublished data from DAFF QLD (2012), irradiation of Red Delicious apples with 0.15, 0.6 and 1.0 kGy had no effect on β-carotene levels. Total vitamin C levels were unchanged immediately after irradiation (control; 0.9 mg/100 g, irradiated; 0.8–1.0 mg/100 g). However, after 28 days cold storage total vitamin C decreased by 25% and 51% in apples irradiated with 0.6 and 1.0 kGy compared to non-irradiated apples. It should be noted that in these analyses, AA data were at or below the limit of detection.

Sliced apples

Another study assessed the effect of irradiation on vitamin C levels in sliced apples. There was no significant effect of irradiation at 0.5 or 1.0 kGy on vitamin C levels either initially or after 1, 2 or 3 weeks storage (Fan et al. 2005). Vitamin C levels did decrease 40-50% in apple slices after one week, irrespective of irradiation, with levels relatively stable after that. In another study, the effect of irradiation prior to drying apple slices was examined. This study used higher doses (1.5–6 kGy), with data presented graphically. The results indicate decreased vitamin C content with increased irradiation (Wang and Chao 2003). However, this study is of limited regulatory value as the doses used are >1 kGy, the effects of drying and irradiation were not studied separately, and there is some uncertainty over the presentation of data; graphical data did not match text or figure legends.

Table 6.1 Effect of irradiation on radiation-sensitive nutrients in apples

Fruit	Dose	Carotene	Vitamin C (compared to non-irradiated)		Analysis method / Reference
			After 1 month	After 6 month	
Apple (Golden Delicious)	0.1, 0.2, 0.4, 0.6 kGy	n.d.	0.1 kGy; -17%* 0.2 kGy; no change 0.4 kGy;+20%* 0.6 kGy; no change	0.1 kGy; no change 0.2 kGy; no change 0.4 kGy; +43%* 0.6 kGy; +29%*	AA by titration. Bhusan 1998
Apple (Red Delicious)	0.1, 0.2, 0.4, 0.6 kGy		0.1 kGy; -17%* 0.2 kGy; -40%* 0.4 kGy; -40%* 0.6 kGy; -38%*	0.1 kGy; +38%* 0.2 kGy; +118%* 0.4 kGy; +13%* 0.6 kGy; +158%*	
Apple (Royal Delicious)	0.1, 0.2, 0.4, 0.6 kGy		0.1 kGy; +38%* 0.2 kGy; +42%* 0.4 kGy; +34%* 0.6 kGy; +45%*	0.1 kGy; +123%* 0.2 kGy; +17%* 0.4 kGy; +114%* 0.6 kGy; +154%*	
Apple (Rich-A-Red)	0.1, 0.2, 0.4, 0.6 kGy		0.1 kGy; -61%* 0.2 kGy; -61%* 0.4 kGy; -66%* 0.6 kGy; -65%*	0.1 kGy; +10%* 0.2 kGy; +16%* 0.4 kGy; +12%* 0.6 kGy; +56%*	
Apple	0.15, 0.6, 1.0 kGy	No change	0.15 kGy; no change 0.6 kGy; -25% after 14 d 1.0 kGy; -51%* after 14 d		β-carotene and Total vitamin C by HPLC DAFF QLD, 2012
Apple (sliced)	0.5, 1.0 kGy	n.d.	No change		AA by HPLC. Fan 2005

*significant difference. n.d.: not determined

6.2 Stone fruit

Limited studies have been published on the effects of irradiation on nutrient composition of stone fruit. The available published and unpublished data are summarised in Table 6.2. Mitchell et al. (1992) assessed the effect of irradiating nectarines and peaches, but vitamin C analyses were not performed for irradiated fruit due to low levels in control fruit (<10 and <5 mg/100 g, respectively) (Mitchell et al. 1992).

Unpublished data from DAFF QLD (2012) tested the effects of irradiation with 0.15, 0.6 and 1.0 kGy on apricot, cherry, peach and plum. Fruits were assessed one day after irradiation, and after 14 (apricot and cherry), 21 (nectarine), 28 (peach) or 35 (plum) days cold storage. In apricot, peach and plum there was no significant effect of irradiation at any dose on total vitamin C or β-carotene levels. Similarly, in white nectarines there was no significant effect of irradiation on AA, while β-carotene levels were below the limit of detection in all fruit. In cherries irradiated with 0.6 kGy, total vitamin C and β-carotene levels decreased by 46% and 17%, respectively, after 14 days storage. In contrast, there was no effect of irradiation with 0.15 kGy or 1 kGy on total vitamin C or β-carotene levels in cherries. Some of the other

analyses showed a similar pattern (glucose, energy) in the 0.6 kGy treated cherries, but the reason for these inconsistent results was unclear. For all these analyses, total vitamin C data were at the lower detection limit of the assay, and were considerably lower than values reported in nutrient data tables.

Whole apricots

In fresh apricots irradiated at 0.5 and 1.0 kGy, the β-carotene concentration increased after 10 days storage (Egea et al. 2007). In the same study there was a significant decrease of approximately one-third in AA content in apricots irradiated with 1.0 kGy after 3 days storage, and although levels remained lower throughout the 13 day experimental period, they were not significantly different to controls at day 7, 10 or 13. There was no difference in AA levels between apricots irradiated with 0.5 kGy and non-irradiated controls. Total vitamin C data were not reported in this study; therefore it is uncertain whether the decrease observed was a result of AA oxidation or destruction.

Dried apricots

In dried apricots, irradiation with 1-3 kGy had no effect on total vitamin C levels immediately or after 6 months of storage (Hussain et al. 2011). After 12 and 18 months, total vitamin C levels were significantly higher in fruit irradiated with ≥2 kGy (5-6% and 20-23%, respectively). These differences were attributed to irradiated apricots maintaining lower moisture content. During the 18 month storage period, AA levels decreased 59% in non-irradiated controls, and 46-55% in irradiated fruit. β-Carotene levels exhibited a dose-dependent increase immediately after irradiation in dried apricots (1 kGy; +10%, 3 kGy; +29%). During 18 months storage, β-carotene levels decreased ~30% in control and irradiated fruit, but remained significantly higher in fruit irradiated with all doses. However, the applicability of these data to fresh fruit is limited due to the important influence of water content on effects of irradiation (Diehl 1995).

Cherries

Irradiation of cherries with 0.3 kGy did not significantly affect AA levels either immediately after irradiation, or after cold storage of 30 and 60 days, or 60 days cold storage followed by 2 days at 20°C (Akbudak et al. 2008). In contrast, irrespective of irradiation, storage decreased AA levels by a mean of 51% (30 days), 58% (60 days) and 65% (60 days cold, 2 days 20°C) under normal atmospheric conditions. Losses of AA were diminished by controlled atmosphere during storage, but this effect was also unaffected by irradiation.

Other non-vitamin bioactive compounds

In fresh apricots, there was no effect of irradiation on antioxidant capacity (Egea et al. 2007). Irradiation of dried apricots with 3 kGy increased total phenols and flavonoids (Hussain et al. 2013). Akbudak et al. (2008) examined anthocyanin levels in cherries following irradiation and storage. In non-irradiated fruit, anthocyanin levels increased during storage under normal atmospheric conditions. This increase was attenuated in irradiated fruit, with anthocyanin levels 21% lower than non-irradiated cherries (Akbudak et al. 2008).

Table 6.2 Effects of irradiation on radiation-sensitive nutrients in stone fruit

Fruit	Dose	Carotene	Vitamin C	Other components	Analysis method / Reference
Apricot	0.5 and 1.0 kGy	No change	1 kGy; -30%* at day 3, no significant difference after 7 d	Antioxidant capacity: no change	AA by HPLC. Egea 2007
Apricot	0.15, 0.6, 1.0 kGy	No change	No change	n.d.	β-carotene and total vitamin C by HPLC DAFF QLD, 2012
Apricot (dried)	1.0, 1.5, 2.0, 2.5, 3.0 kGy	+10%* to +30%*	No change ≤6 mo. 12 mo; ≥2 kGy +5%* 18mo; ≥2 kGy +20%*	3 kGy; phenols: +12%* flavonoids: +16%*	β-carotene and total vitamin C by HPLC. Hussain 2011 Hussain 2013
Cherry	0.3 kGy	n.d.	No change	Anthocyanins: -21%	AA by spectrophotometry Akbudak 2008
Cherry	0.15, 0.6, 1.0 kGy	0.15, 1.0 kGy; no change 0.6 kGy; -6 to -17%	0.15, 1.0 kGy; no change 0.6 kGy; -39%* to -46%*	n.d.	β-carotene and total vitamin C by HPLC DAFF QLD, 2012
Peach	0.15, 0.6, 1.0 kGy	No change	No change	n.d.	
Plum	0.15, 0.6, 1.0 kGy	No change	No change	n.d.	
Nectarine	0.15, 0.6, 1.0 kGy	Not detected	No change	n.d.	AA by titration, β-carotene by HPLC DAFF QLD, 2012

*significant difference. n.d.: not determined

6.3 Berry fruit

Few recent studies have examined the effects of irradiation on the nutrient content of berries. A number of studies were conducted on radiation-preservation of strawberries between 1959 and 1970. As reviewed by Thomas (1986), the results were variable (Thomas 1986a). Using doses ranging from 0.9 to 5 kGy, two studies found a decrease in AA, three found no or

minor changes, three demonstrated increased AA levels after storage, while another study found that AA levels were unaltered in irradiated strawberries, but increased in controls. These studies include a mix of reviews, conference abstracts and journal articles published in English, Japanese and Korean. Further consideration was not given to these studies due to their age, difficulty in obtaining original articles, uncertainty over analytical methods used and the use of doses generally >1 kGy.

Blueberries

Irradiation significantly decreased AA content after 3 days when all irradiated blueberries (1.1, 1.6 and 3.2 kGy) were compared to non-irradiated controls (Table 6.3, Moreno et al. 2008). However, when stratified by irradiation dose, there was no significant difference between blueberries irradiated with 1.1 kGy and controls at either day 3 or 7, and by day 14 AA levels were significantly higher in fruit exposed to 1.1 kGy (12.5 *vs.* 10.0 mg/100g). Additionally, despite lower levels at day 3, there was no significant difference in AA content between blueberries irradiated with 1.6 or 3.2 kGy and non-irradiated controls at day 7 and 14. This transient decrease may be attributable to conversion to DHAA which was not measured in this study.

Strawberries

In strawberries, irradiation with 2 and 3 kGy led to dose-dependent decreases in total vitamin C and AA levels compared to controls both immediately after irradiation, and after 5 and 10 days storage. Four varieties of strawberries were studied, with all exhibiting similar changes in total vitamin C levels in response to irradiation. When these strawberry varieties were irradiated with 1 kGy, total vitamin C was 86–103% of control at day 0, 89–105% at day 5 and 93–98% at day 10 (Table 6.3, Graham and Stevenson 1997).

In unpublished data from DAFF QLD (2012), the effects of 0.15, 0.4, 1.0, 2.0, 2.5 and 3.0 kGy on total vitamin C content of Albion strawberries was assessed. Irradiation with 0.15–1.0 kGy had no effect on total vitamin C in strawberries, either immediately or after 14 days. Irradiation with ≥2.0 kGy decreased total vitamin C by 18–26% initially, but levels increased with storage and were no longer significantly different to non-irradiated strawberries at 14 days (Table 6.3).

Other non-vitamin components

In blueberries, irradiation with 1.1 kGy either had no effect or increased (after 14 days) total phenolic content (Moreno et al. 2008). Similarly, antioxidant activity was similar between control and 1.1 kGy irradiated blueberries. A study in strawberries identified a dose-

dependent increase in one of four phenolic compounds, and decreases in three of four phenolic compounds studied, however statistical analyses of the data were not included (Breitfellner et al. 2003).

Table 6.3 Effects of irradiation on radiation-sensitive nutrients in berry fruit

Fruit	Dose	Carotene	Vitamin C	Other components	Analysis method / Reference
Blueberry	1.1, 1.6, 3.2 kGy	n.d.	1.1 kGy: -17%* to +26% 1.6 kGy: -34%* to +30%* 3.2 kGy: -33%* to -4%	Phenolics; similar or increased	AA by titration Moreno 2008
Strawberry	1, 2, 3 kGy	n.d.	1kGy: -14% to +5% 2 kGy: -21% to +9% 3 kGy: -23 to -4%	n.d.	Total vitamin C by HPLC. Graham 1997
Strawberry	0.15, 0.4, 1.0, 2.0, 2.5, 3.0 kGy	n.d.	≤1 kGy; no change ≥2 kGy; -18%* to -26%* after irradiation, no change after 14d	n.d.	Total vitamin C by HPLC DAFF QLD, 2012

*Significant difference. n.d.: not determined.

6.4 Citrus fruit

There have been a number of 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 6.4.

Orange

In Kau oranges, there was no significant effect of x-ray irradiation at 0.75 kGy on AA levels. Similarly, total carotenoids did not change with irradiation after 2 days, but were increased 33% after 9 days storage in irradiated oranges (Boylston et al. 2002). In blood oranges, irradiation with 0.25 and 0.5 kGy attenuated the loss of AA during 6 weeks storage, resulting in higher AA levels in oranges irradiated with 0.5 kGy (Khalil et al. 2009).

In Mosambi oranges, AA decreased initially at doses of 1.0 kGy (-22%) and 1.5 kGy (-16%). However, this effect was lost throughout the storage period as all groups exhibited AA losses (0 kGy; -31%. 0.25 kGy; -26%, 0.5 kGy; -33%, 1.0 kGy; -4%, 1.5 kGy; -16%) (Ladaniya et al. 2003). As only AA was measured, some of the variability in these 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 cannot be separated.

Mandarin

Irradiation with 0.075 and 0.3 kGy had no significant effect on total vitamin C content in Ellendale mandarins, within a week of irradiation or after 3 weeks storage (Mitchell et al. 1992). Vitamin C levels decreased 10-12% in Ellendale mandarins, irrespective of irradiation. In contrast, Imperial mandarins showed no early effects of irradiation, but after 3 weeks storage vitamin C levels decreased 46% in non-irradiated fruit and 69% and 78% in fruit irradiated at 0.075 and 0.3 kGy 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 0.25, 0.5, 1.0 and 1.5 kGy. Irradiation doses of ≥0.5 kGy 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 0.51 and 0.875 kGy (Rojas-Argudo et al. 2012). Similarly, work from the same group using up to 0.164 kGy 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 0.054 kGy (Contreras-Oliva et al. 2011). A third study in clementine mandarins assessed the impact of irradiation in combination with washing / waxing and storage. In this study, AA levels fluctuated throughout the 7 week experimental period, but decreased in all groups. After 7 weeks, there was no significant effect of irradiation on AA content. In contrast, the washing and waxing procedure significantly decreased AA with a 65% reduction in non-irradiated fruit and a 49% decrease in irradiated fruit (Mahrouz et al. 2002).

Grapefruit

Two studies from the same group indicate no significant effect of low dose irradiation on AA and β-carotene levels in grapefruit. In the first study, there was no effect of irradiation with 0.07-0.7 kGy on β-carotene or total carotenoid levels in Rio Red grapefruit in either early or late harvest fruit, or after 35 days storage (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 used 0.3 kGy doses and again 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 higher doses of electron-beam irradiation (Girennavar et al. 2008). In this study, fruit were exposed to 1, 2.5, 5 and 10 kGy. The presentation of data in this paper is graphical and indicates no significant change in Rio Red grapefruit with 1 kGy, but a statistically significant loss in Marsh White grapefruit at the same dose. Estimation of loss from the graph suggests a ~10% decrease, but in the text the change is reported as -0.8% and -1.3% in Marsh White and Rio Red fruit, respectively. These inconsistencies limit the regulatory use of this paper. However, at higher doses, large losses of vitamin C occurred in a dose-dependent manner, with losses of >50% at 10 kGy. In contrast, β-carotene levels were unaltered by irradiation in Rio Red grapefruit at any dose.

Lemon and lime

Irradiation with 0.075 and 0.3 kGy had no significant effect on total vitamin C content in lemons up to 3 weeks after irradiation. 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).

In limes, AA levels fluctuated during storage, but were decreased initially by doses of ≥0.5 kGy. AA levels remained lower in limes irradiated with ≥1.0 kGy during 90 days storage (Ladaniya et al. 2003).

Other non-vitamin bioactive compounds

Irradiation with 0.03, 0.054 and 0.164 kGy 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). Gamma-irradiation of clementines at a mean dose of 0.3 kGy 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 0.164 kGy (-7% to -12%). However, irradiation of

clementine mandarins with 0.51 and 0.875 kGy did not alter flavanone glycoside levels after 2 months storage (Rojas-Argudo et al. 2012).

In grapefruit, effects of irradiation on flavanones were variable; higher doses (0.4 and 0.7 kGy) 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 0.07 and 0.2 kGy after 35 days storage in early season fruit. Lycopene levels were similar between control and ≤1 kGy irradiated grapefruit, with the exception of a small decrease (~10%) after 35 days storage in late harvest fruit irradiated with 0.7 kGy (Patil et al. 2004; Vanamala et al. 2005; Girennavar et al. 2008). Lycopene levels were >25% lower in late compared to early harvest fruit, irrespective of irradiation. Limonin levels in grapefruit were also unaffected by irradiation with <1 kGy (Patil et al. 2004).

Table 6.4 Effects of irradiation on radiation-sensitive nutrients in citrus fruit

Fruit	Dose	Carotene	Vitamin C	Other components	Analysis method / Reference
Grapefruit	0.07, 0.2, 0.3, 0.4, 0.7 kGy	No change	No change	Flavonones: variable Lycopene: similar Limonin: no change	AA by HPLC. Patil 2004 Vanamala 2005
Grapefruit (≥1 kGy)	1, 2.5, 5, 10 kGy	No change	Dose-dependent decrease. See text for details.	Flavonoids and lycopene: No change with 1 kGy, variable effects with >1 kGy	Total vitamin C by HPLC. Girennavar 2008
Lemon	0.075, 0.3 kGy	n.d.	No change	n.d.	Total vitamin C by derivatization. Mitchell 1992
Lime (Kagzi)	0, 0.25, 0.5, 1.0, 1.5 kGy	n.d.	Variable. Decreased with 1.5 kGy[#]	n.d.	AA by titration. Ladaniya 2003[#]
Mandarin (Clementine)	0.03, 0.054, 0.164, 0.51, 0.875 kGy	n.d.	No change	Antioxidant capacity, phenolics: no change Flavanone glycosides: no change ≤6 months storage	Total vitamin C by HPLC. Rojas-Argudo 2012 Contreras-Oliva 2011
Mandarin (Ellendale)	0.075, 0.3 kGy	n.d.	No change	n.d.	Total vitamin C by derivatization. Mitchell 1992
Mandarin (Imperial)	0.075, 0.3 kGy	n.d.	-43%* and -60%* after 3 wk	n.d.	
Mandarin (Nagpur)	0, 0.25, 0.5, 1.0, 1.5 kGy	n.d.	Dose-dependent decreases for ≥0.5 kGy[#]	n.d.	AA by titration. Ladaniya 2003[#]
Orange (Kau)	0.75 kGy	+33%* after 9 d	No change	n.d.	AA by titration. Boylston 2002
Orange (Mosambi)	0, 0.25, 0.5, 1.0, 1.5 kGy	n.d.	Immediate decrease with ≥1 kGy, but no difference after storage[#]	n.d.	Ladaniya 2003[#]
Orange (blood)	0, 0.25, 0.5 kGy	n.d.	AA higher in irradiated fruit after 1-6 weeks storage	n.d.	AA by titration. Khalil, 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,

6.5 Tropical fruit

Irradiation with 0.15-1 kGy is already permitted for bread fruit, carambola, custard apple, longan, litchi, mango, mangosteen, papaya (paw paw), rambutan and persimmon. A large number of studies are published on the effects of irradiation on tropical fruit, and in particular mango (see Table 6.5). However, data were not available on the nutritional impact of irradiation on avocado and banana.

Pineapple

Three studies have assessed the nutritional impact of irradiation of pineapple. There was no significant effect of irradiation with 0.15 kGy on AA levels in whole-fruit; AA levels decreased ~20% with 22 days ambient storage in both irradiated and non-irradiated fruit (Susheela et al. 1997). Similarly, irradiation with 2 kGy did not significantly affect total vitamin C or carotenoid levels in fresh-cut pineapples (Hajare et al. 2006a). Carotenoid levels were stable over the 12 day storage period, whereas total vitamin C levels decreased ~40% in both non-irradiated and irradiated sliced pineapple. In the third study, irradiation of cut pineapple with 1 and 2 kGy had no effect on vitamin C after 1 day, with levels variable throughout the storage period (Perecin et al. 2011). After 3 days, vitamin C levels were lower in irradiated fruit (1 kGy; -25%, 2 kGy; -42%), but there was no significant difference between irradiated and control samples at any other time. Fluctuations in vitamin C levels occurred throughout the study period. It is unclear from the methods of this paper whether total vitamin C or AA was measured; if DHAA levels were not measured this could account for the variability in vitamin C data.

Mango (Kensington Pride)

A number of studies have assessed the effects of irradiation on carotenes and vitamin C in mangoes. Mitchell et al. found no effect of irradiation with up to 0.6 kGy on carotene content of Kensington Pride mangoes (Mitchell et al. 1990). Irradiation of Kensington Pride mangoes with 0.075 and 0.3 kGy did not significantly affect total vitamin C or DHAA levels. Irradiation with 0.6 kGy increased DHAA levels, and reduced total vitamin C in comparison to mangoes irradiated with 0.75 and 0.3 kGy, but not compared to controls (Mitchell et al. 1992).

Mango (Tommy Atkins)

Irradiation of Tommy Atkins mangoes with 1.0, 1.5 and 3.1 kGy found no difference in either total carotenoid or β-carotene levels immediately after irradiation (Reyes and Cisneros-Zevallos 2007). After 18 days storage, carotenoid levels increased in non-irradiated mangoes, but not in irradiated mangoes. However, the difference in total carotenoid and β-carotene levels were only significantly lower in fruit irradiated with 3.1 kGy. In another study of Tommy Atkins mangoes, carotenoid content fluctuated, with no clear effect of irradiation at 1.0, 1.5 and 3.1 kGy (Moreno et al. 2007). Carotenoid levels increased in control fruit after 5 and 10 days, but then decreased after 21 days. Irradiation with 1.0 and 1.5 kGy initially increased carotenoid levels, and at day 21 levels remained higher than non-irradiated mango in the 1.0 kGy group, but were lower in the 1.5 kGy treated mangoes. Carotenoid levels in mangoes irradiated with 3.1 kGy were initially no different to control, but were higher at day 21 (Moreno et al. 2007).

For vitamin C, there was no effect of irradiation of Tommy Atkins mangoes with 1.0 and 1.5 kGy at day 0, but AA levels decreased 22% after irradiation with 3.1 kGy. After 18 days storage, AA levels decreased by 25% in control and 32-54% in irradiated mangoes, with levels significantly lower in mangoes irradiated with 3.1 kGy (Reyes and Cisneros-Zevallos 2007). Greater AA diminution was observed by Moreno et al., despite the same irradiation conditions and similar storage conditions. Data were not presented for AA at day 0, but by day 5 AA levels were 50–59% lower in irradiated fruit. After 21 days, AA levels were 75% lower in the 1.0 kGy group, and 96% lower than non-irradiated fruit in the 1.5 and 3.1 kGy-treated mangoes (Moreno et al. 2007). Both studies measured AA and not DHAA, and this may account for some or all of the large decrease in AA reported in this mango cultivar. Furthermore, the greater loss of AA reported by Moreno may be due to the use of the titration method which is less reliable and more prone to error than HPLC which was used in the Reyes study.

Mango (Zebda)

In Zebda mangoes, carotenoid levels were similar between control and irradiated fruit (0.5–1.5 kGy) with levels increasing over 30 days in all groups (El-Samahy et al. 2000). In the second study, processed mangoes were used, and the effect of steaming prior to irradiation of mango pulp was investigated. Carotenoid levels were more stable in pulp steamed prior to irradiation, and steaming attenuated storage-associated decreases in both irradiated and control pulp (Youssef et al. 2002). At day 0, irradiation led to a small but significant increase in carotenoids (+4%), but this effect was lost by day 15, and after 30 days carotenoid levels were 5–11% lower in irradiated pulp. As post-hoc testing was not performed in this study, it was not possible to assess the effects of individual irradiation doses.

Effects of irradiation on vitamin C were also mixed in Zebda mangoes. In whole fruit, AA levels were initially reduced by irradiation with 0.5-1.5 kGy, but the rate of AA decline was markedly higher in non-irradiated fruit. However, limited reporting of results of statistical analyses limit interpretation of this study (El-Samahy et al. 2000). In a subsequent study from the same group, there was a more gradual decline of AA content in non-irradiated mango pulp. In this study, the effects of irradiation with 0.5-2.0 kGy appeared dose-dependent with AA levels lowest in mangoes irradiated with 2.0 kGy (Youssef et al. 2002). AA values were similar in mango pulp from control and 0.5 kGy-treated samples, while irradiation with 1.0 kGy led to a 5-10% decrease. AA levels in 2.0 kGy-treated fruit were ~20% lower than controls. Again, limited reporting of statistics restricts the interpretation of these data, and the

use of mango pulp rather than whole fruits limits the applicability of these results to irradiation for phytosanitary purposes.

Mango (other cultivars)

Another two studies assessed the effect of 0.56-0.92 kGy irradiation on mangoes. In the first study, Keitt mangoes were irradiated with 0.64-0.92 kGy. There was a significant decrease in AA content initially, and after 9 and 15 days in irradiated mangoes (Lacroix et al. 1990). AA and DHAA levels fluctuated throughout the storage period in both irradiated and non-irradiated fruit, and the absence of error bars on the graphical data limit interpretation of this study. Similarly, AA and DHAA levels fluctuated in the 30-35 days following irradiation of Nahng Clahng Wahn mangoes with 0.56, 0.63 and 0.70 kGy (Lacroix et al. 1993). Absence of statistical analyses limits the interpretation of this study.

Papaya

Three studies of papaya (pawpaw) have found no effect of irradiation doses ranging from 0.075-0.75 kGy on vitamin C content (Lacroix et al. 1990; Mitchell et al. 1992; Boylston et al. 2002). Similarly, irradiation with 0.75 kGy did not change carotenoid content of papaya (Boylston et al. 2002).

Litchi

In litchi, irradiation with 0.075 or 0.3 kGy had no effect on total vitamin C or DHAA either initially or after 3 weeks storage in Tai So variety (Mitchell et al. 1992). Another study found a cultivar-dependent response, with China litchi having similar or increased total vitamin C levels after irradiation with 0.3 or 0.5 kGy after 1 and 12 days (Hajare et al. 2010). In the Shahi cultivar, irradiation with 0.3 kGy initially increased total vitamin C content by 12%, but after 12 days total vitamin C was 20% lower compared to controls. Irradiation with 0.5 kGy decreased total vitamin C content by ~30% at both times.

Guava

Irradiation of two guava cultivars with 0.25 kGy had no effect on vitamin C content after 8 days storage at room temperature, or 22 days cold storage (Singh and Pal 2009). In the same study, irradiation with 0.5 and 1.0 kGy significantly decreased vitamin C content by 3–11% and 15–25% in Lucknow-49 guavas, and 8–16% and 21–34% in Allahabad Safeda guavas, respectively. In another study, the effect of irradiation on vitamin C content of individual fruits was assessed. In the first experiment, guava were halved, with one half irradiated with 2 kGy and the other half not treated. The results varied between individual fruits, with vitamin C content decreased by 0–6% in five fruits, however the range of vitamin

C concentration in non-irradiated fruit was >3-fold (26-83 mg/100 g) (Kabbashi et al. 2012). In the second part of the study, two whole guava were irradiated with 2 kGy, and a 13% decrease in vitamin C content was observed (Kabbashi et al. 2012). In a third study, low dose irradiation (0.05 and 0.1 kGy) appeared to increase vitamin C contents 3-10% after 4–12 days, but doses of 0.15 and 0.25 kGy appeared to decrease vitamin C by 7-13% from 8–12 days compared to non-irradiated guava (Pandey et al. 2010). However, the absence of results of statistical analyses to compare effects limits the regulatory use of this study.

Custard apple

In custard apples, AA levels were generally higher in fruits irradiated with ≤1 kGy, and remained so throughout a 12 day storage period (Chouksey et al. 2013).

Other non-vitamin bioactive compounds

Bromelain extract is a mixture of proteases that is frequently derived from pineapple stems but can be found in most parts of the fruit. Its enzymatic activity is inactivated in canned and juiced pineapple. Irradiation with up to 2 kGy did not alter bromelain activity in fresh pineapples (Bhattacharya et al. 2009). In Tommy Atkins mangoes, levels of phenolics were similar or increased in mangoes irradiated with 1 kGy, both immediately and up to 21 days after irradiation (Moreno et al. 2007; Reyes and Cisneros-Zevallos 2007). Antioxidant capacity fluctuated throughout storage, but levels were generally similar between irradiated and control mangoes (Moreno et al. 2007). Also in Tommy Atkins mangoes, the content of other carotenoids (violoxanthin and neoxanthin derivatives) were similar between 1 kGy-irradiated and control mangoes immediately after irradiation, and while levels tended to be lower in irradiated mangoes after 18 days, the majority of these changes were not significant. In Zebda mangoes, one study demonstrated irradiation with 0.5-2.0 kGy enhanced the storage-associated increase in phenolics (Youssef et al. 2002), while an earlier study indicated higher phenolic levels only in the first 20 days of post-irradiation storage (El-Samahy et al. 2000). In litchi, irradiation with 0.3 and 0.5 kGy had no effect on flavonoids in Shahi cultivar, but in China cultivar there was a reported decrease in flavonoids with 0.5 kGy at day 1 and 20, but not at day 10 and 28 (Hajare et al. 2010).

Table 6.5 Effects of irradiation on radiation-sensitive nutrients in tropical fruit

Fruit	Dose	Carotene	Vitamin C	Other components	Reference
Custard apple	0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75 kGy	n.d.	≤1.0 kGy; increased >1 kGy; no change	n.d.	AA analysis method unclear. Chouksey 2011
Guava	0.25, 0.5, 1.0 kGy	n.d.	0.25 kGy: no effect 0.5 kGy: -3% to -16%* 1.0 kGy: -15%* to -34%*	n.d.	AA by titration. Singh 2009
Litchi	0.075, 0.3, 0.5 kGy	n.d.	Tai So and China cultivars: no change Shahi cultivar: 0.3 kGy: +11%* at 1d, -20%* at 12d 0.5 kGy: -30%*	Flavonoids: Shahi; no change China; variable	Total vitamin C by derivatization. Mitchell 1992 Hajare 2010
Mango (Keitt)	0.64-0.92 kGy	n.d.	Levels fluctuate; ~10-30% lower at day 1 and 9-15	n.d.	AA and DHA, method unclear. Lacroix 1990
Mango (Kensington Pride)	0.075, 0.3, 0.6 kGy	No change	No change compared to control	n.d.	Total vitamin C by derivatization, carotenes by spectrophotometry. Mitchell 1990 Mitchell 1992
Mango (Tommy Atkins)	1.0, 1.5, 3.1 kGy	Variable	1.0 kGy: no change 3 kGy; -22% to -51%* (Reyes) 1.0-3.1 kGy: -50%* to -96%*	Phenolics: no change Antioxidant capacity: no change Other carotenoids: no change 0 d, trend to decrease at 18 d	AA and carotenoids by HPLC. Reyes 2007 AA by titration. Moreno 2007
Mango (Zebda)	0.5, 0.75, 1.0, 1.5, 2.0 kGy	No change or variable	Variable, but effect of irradiation less than storage	Phenolics: levels increase	Carotenoids by spectrophotometry and AA by titration El-Samahy 2000 Youssef 2002
Papaya (pawpaw)	0.075, 0.3, 0.75, 0.75-0.95 kGy	No change	No change	n.d.	AA and DHA, method unclear. Lacroix 1990, Total vitamin C by derivatization. Mitchell 1992, AA by titration. Boylston, 2002
Pineapple (whole)	0.15 kGy	n.d.	No change	n.d.	AA by titration. Susheela 1997
Pineapple (cut)	1, 2 kGy	No change	No change overall; *transient decrease in one study*	Bromelain: activity preserved	Carotenoids by spectrophotometry Hajare 2006 Vitamin C by titration. Perecin 2011 Bhattacharya 2007

*Significant difference. n.d.: not determined.

6.6 Other fruit

Published data were not identified for the effects of irradiation on honeydew melon and watermelon. Effects of irradiation on grapes, melons, kiwifruit and persimmons are summarised below and in Table 6.6.

Grapes

A study of three grape cultivars assessed the effects of irradiation with 2, 2.5 and 3.5 kGy, as well as the combined effect of a hot water dip (50°C, 5 min) with irradiation at 1 kGy (Thomas et al. 1995). AA levels were measured both immediately and after storage at different temperatures. In Thompson seedless grapes, irradiation with 2 kGy decreased AA by 28% to 41% compared to non-irradiated grapes. The combination of hot-water dip and 1 kGy irradiation had a similar effect on AA, with decreases of 13% to 60%; however, it is not possible to separate the effects of irradiation from that of the heat-treatment on AA levels in this group. In another two cultivars, grapes were irradiated with 2.5 and 3.5 kGy and AA measured after 1 and 56 days storage at 10°C. In Sonaka grapes, irradiation at both doses initially increased AA by 13-18%, but after storage levels were ~13% lower in irradiated fruit. Tas-A-Ganesh grapes showed the opposite pattern, with AA levels initially 7-10% lower in irradiated grapes, but AA levels were 8-11% higher after 56 days storage. It is important to note that no statistical analyses were presented in this paper, thereby limiting the interpretation of these results. Unpublished data from DAFF QLD (2012) found no significant effect of irradiation with 0.15, 0.6 and 1.0 kGy on total vitamin C or β-carotene levels in grapes either one day after irradiation or after 50 days storage at 0°C.

Melon

Irradiation of muskmelon (rockmelon, cantaloupe) with 0.5 and 1.0 kGy had no significant effect on vitamin C levels in fruit studied from four harvests over two consecutive years (Lalaguna 1998). Similarly, irradiation of fresh-cut rockmelon with 0.5 Gy had no significant effect on AA levels after 1, 3 and 7 days (Fan et al. 2006).

Unpublished data from DAFF QLD (2012) found no significant effect of irradiation with 0.15, 0.6 and 1.0 kGy on vitamin C content of rockmelon and honeydew melon, either one or 14 days after irradiation. Similarly, β-carotene levels were not significantly changed in irradiated rockmelon. In contrast, β-carotene levels were significantly decreased in irradiated honeydew melon one day after irradiation, but after 14 days storage there was no significant difference and levels tended to be higher in irradiated compared to non-irradiated melons.

Kiwifruit

Irradiation of mature, unripe kiwifruit with 1 and 2 kGy had no effect on AA levels, but levels decreased significantly with 3 kGy (~10%) (Kim and Yook 2009). After 1-3 weeks storage, AA levels increased in all fruit, but were significantly lower in all irradiated fruit compared to non-irradiated fruit. However, in this study only AA levels were measured; the small differences in AA content between irradiated and control fruit could be due to conversion to DHAA. Antioxidant activity was similar between control and irradiated kiwifruit throughout the storage period, with the exception of a small (<10%) but significant decrease immediately after irradiation with 2 and 3 kGy.

Persimmon

Irradiation of persimmons with 0.075 and 0.3 kGy had no effect on total vitamin C content either immediately or after 3 weeks storage; vitamin C increased ~2-fold with storage in both control and irradiated persimmons (Mitchell et al. 1992).

Table 6.6 Effects of irradiation on radiation-sensitive nutrients in grapes, kiwifruit, persimmon and rockmelon.

Fruit	Dose	Carotene	Vitamin C	Other components	Reference
Grapes	1 (+heat), 2, 2.5, 3.5 kGy	n.d.	-60% (1 kGy + heat) to +18% *no statistical analyses*	n.d.	AA by titration. Thomas, 1995
Grapes	0.15, 0.6, 1 kGy	No change	No change	n.d.	β-carotene and total vitamin C by HPLC DAFF QLD, 2012
Honeydew melon	0.15, 0.6, 1 kGy	Decreased after 1d in 0.6 and 1.0 kGy. No change after 14d.	No change	n.d.	β-carotene by HPLC and AA by titration DAFF QLD, 2012
Kiwifruit	1, 2, 3 kGy	n.d.	Approximate change: 1 kGy; 1wk; -18%* 2wk; -4%*, 3wk; -8%*	Antioxidant activity: no change	AA by titration. Kim 2009
Persimmon	75, 300 Gy	n.d.	No change	n.d.	Total vitamin C by derivatization. Mitchell 1992
Rockmelon	0.5, 1.0 kGy	n.d.	No change	n.d.	Total vitamin C, method unclear Lalaguna 1998 AA by HPLC. Fan 2006
Rockmelon	0.15, 0.6, 1 kGy	No change	No change	n.d.	β-carotene by HPLC and AA by titration DAFF QLD, 2012

*Significant difference. n.d.: not determined.

6.7 Cucurbit vegetables

Few studies have been conducted into the effects of irradiation on nutrient composition of cucurbit vegetables. One study irradiated zucchini with 0.075 and 0.3 kGy, but as vitamin C levels were low in non-irradiated zucchini (<10 mg/100 g), no data were reported for irradiated zucchini (Mitchell et al. 1992). In sliced cucumber, irradiation with 2 kGy had no significant effect on vitamin C; levels were variable in both control and irradiated cucumbers (Hajare et al. 2006b).

Unpublished data from DAFF QLD (2012) in zucchini, showed no significant effect of irradiation with 0.15, 0.6 and 1 kGy on total vitamin C levels, either one or seven days after irradiation. β-carotene levels were not significantly different in irradiated compared to non-irradiated zucchini at either time-point.

No literature was found on the effects of irradiation in pumpkin. Carrots are another orange vegetable with high β-carotene content. Irradiation of carrots with 2 kGy had no significant effect on either β-carotene or total vitamin C content up to 16 days after irradiation (Hajare et al. 2006b).

6.8 Fruiting vegetables

Fruiting vegetables include capsicum, tomato, chilli, eggplant and corn. Studies on the effects of irradiation on eggplant and fresh chilli were not found through the literature search. Studies reporting the effects of irradiation on capsicum, tomato and corn are summarised below and in Table 6.8.

Capsicum

Irradiation of capsicums with 0.075 and 0.3 kGy had no significant effect on carotene or AA content (Mitchell et al. 1990; Mitchell et al. 1992). Another study assessed the effects of irradiation with 1, 2, and 3 kGy on cut capsicum; minimal changes were observed in AA and carotenoid levels, however the absence of statistical analyses limit the interpretation of data from this study (Ramamurthy et al. 2004).

Tomato

Mathew et al. (2007), irradiated tomatoes in modified atmosphere packaging with 1, 2, 3 and 4 kGy followed by 21 days storage (Mathew et al. 2007). AA levels increased in all groups; levels plateaued after 14 days in non-irradiated tomatoes, and after 21 days the AA content

reached a similar level in tomatoes irradiated with 1 and 2 kGy. Levels were approximately 25% lower after 21 days in tomatoes irradiated with 3 and 4 kGy compared to non-irradiated tomatoes (Mathew et al. 2007). A number of earlier studies assessed effects of irradiation on tomatoes, but the interpretation and regulatory use of these studies is limited due to single point data, absence of statistical analyses or insufficient information reported (Abdel-Kader et al. 1968; Villegas et al. 1972; El-Sayed 1978; Al-Wandawi et al. 1983).

In a study of cut tomatoes irradiated with 1 kGy, there was no immediate effect of irradiation on AA levels, but after 14 days AA was 23% lower in irradiated compared to non-irradiated tomato slices (Fan and Sokorai 2008). A similar study of cut tomatoes irradiated with 1 kGy found no significant difference in either total carotenoid or AA levels after 1 and 3 days (Mohácsi-Farkas et al. 2006).

In a previous application to FSANZ, unpublished data on irradiation or red tomatoes and green capsicums were provided by DAFF QLD (2012). Irradiation of firm ripe tomatoes and fresh green capsicum with 0.15, 0.6 and 1.0 kGy had no significant effect on vitamin C or β-carotene contents either 1 day, 14 days (tomatoes) or 21 days (capsicum) after irradiation (FSANZ 2013).

Corn

For corn, only one study was identified, in which frozen corn was irradiated. Irradiation with 1.8 and 4.5 kGy had no effect on carotenoid levels initially, or over 12 months storage (Fan and Sokorai 2007). In contrast, AA levels were reduced by both doses and at all time-points; overall losses ranged from -7% to -25% and -21% to -33% with 1.8 and 4.5 kGy irradiation doses, respectively. AA decreased ~2.5% per month in both control and irradiated samples. As samples had been frozen prior to irradiation there is limited relevance of this study to the use of irradiation for phytosanitary purposes.

Other non-vitamin bioactive compounds

In tomatoes irradiated with 1, 2, 3 and 4 kGy, lycopene accumulation over 21 days storage were lower than non-irradiated controls, and at the end of storage levels were significantly lower than control in tomatoes irradiated with 3 and 4 kGy (Mathew, 2007). No data on the effects of irradiation on lutein or zeaxanthin in corn were identified.

Table 6.8 Effects of irradiation on radiation-sensitive nutrients in fruiting vegetables

Fruit	Dose	Carotene	Vitamin C	Other components	Reference
Capsicum	0.075, 0.15, 0.3, 0.6, 1 kGy	No change	No change	n.d.	Total vitamin C by derivatization, carotenes by spectrophotometry. Mitchell 1990, 1992 β-carotene and total vitamin C by HPLC DAFF QLD, 2012
Corn (frozen)	1.8, 4.5 kGy	No change	1.8 kGy: -7% to -25%* 4.5 kGy: -21% to -33%*	n.d.	AA by HPLC, carotenes by spectrophotometry Fan, 2007
Tomato (cut)	1 kGy	No change	No change after 1–3 d -23%* after 14 d	n.d.	Total vitamin C by HPLC. Fan 2008a AA by HPLC Mohácsi-Farkas 2006
Tomato (whole)	1, 2, 3, 4 kGy	n.d.	After 21 d: 1, 2, kGy: no change 3, 4 kGy; approx. -25%*	Lycopene lower in irradiated	AA by titration, lycopene by spectrophotometry Mathew 2007
Tomato (whole)	0.15, 0.6, 1 kGy	No change	No change	n.d.	β-carotene and total vitamin C by HPLC DAFF QLD, 2012

*Significant difference. n.d.: not determined.

6.9 Other vitamins

Studies in meat and animal feeds demonstrate vitamin E is highly sensitive to irradiation, but it is present only in low levels in almost all fruits and vegetables (see Section 4.2.3). In reviewing the literature, a few papers were identified where vitamin E levels were assessed in irradiated vegetables and chestnuts. Thiamin is also highly sensitive to irradiation. Not surprisingly, given fruits and vegetable are not significant contributors to thiamin intake, data on thiamin levels in irradiated fruit and vegetables were lacking. For completeness, the vitamin E (tocopherol) data are summarised here.

In baby-leaf spinach, irradiation with 0.5-2.0 kGy had no effect on vitamin E (as α-tocopherol) levels in one spinach cultivar, while in another cultivar α-tocopherol levels decreased by 12% following irradiation with 2 kGy. There was no significant effect of irradiation with doses ≤1 kGy (Lester et al. 2010). In cut tomatoes, irradiation with 1 kGy led to an apparent 40% decrease in tocopherol levels are 1 and 3 days; however the absence of statistical analyses in this report limit its interpretation (Mohácsi-Farkas et al. 2006).

Some published data were also identified for the effects of irradiation on vitamin E content of chestnuts. These are included here due to the paucity of available data in fruits and vegetables. In these studies, irradiation with up to 6 kGy using electron-beam irradiation had no significant effect on total tocopherol levels (Carocho et al. 2012). A similar study from the same group using γ-irradiation up to 0.54 kGy found total tocopherol levels increased in irradiated chestnuts (Fernandes et al. 2011). Mushrooms γ-irradiated at 1 kGy showed a significant decrease in α-tocopherol but significant increases in γ- and δ-tocopherols (Fernandes et al. 2013).

6.10 Summary of data for phytosanitary irradiation doses

In this literature review, the effects of irradiation on pome, stone, berry, citrus, tropical, other fruits, cucurbit vegetables and fruiting vegetables were assessed. In the previous sections the effects of all doses of irradiation were discussed for the purpose of completeness. Here, the effects of phytosanitary doses of 0.15-1.0 kGy on whole fruit only are summarised.

6.10.1 Fruit

Ten published papers reported on the effects of phytosanitary doses of irradiation on carotene content of whole fruit. Published data were available for stone, citrus and tropical fruits, and unpublished data were available for pome and stone fruit as well as grapes and melons. As summarised in Table 6.9, the published data indicate no losses of carotenes in fruit irradiated with ≤1 kGy. Unpublished data in honeydew melons indicated a transient decrease in β-carotene soon after irradiation, but given the low levels of β-carotene, and that levels were similar following storage this does not pose a nutritional risk. From these studies, it can be concluded that phytosanitary doses of irradiation does not lead to a decrease in carotene levels in fruits. Similarly, the data available on other bioactive compounds such as flavonoids and phenolics, indicate that phytosanitary doses of irradiation do not cause diminution of these compounds in fruits.

Twenty nine published studies were identified in which the effects of phytosanitary doses of irradiation on vitamin C content in whole fruits were assessed. The effects of irradiation on vitamin C content were dependent on the type and cultivar of fruit, the dose of irradiation and the subsequent handling of the irradiated fruits. Overall, there was no consistent pattern in the sensitivity of fruits to irradiation. In the following chapter, the fruits in which losses of

vitamin C were reported are considered in relation to natural variation and dietary vitamin C intake data.

When interpreting findings of diminished vitamin C, it is important to consider the method of vitamin C analysis, both in terms of its reliability and what is actually measured. Vitamin C can be measured as reduced AA or total vitamin C (both reduced AA and its oxidised form, DHAA). As conversion between the reduced and oxidised forms can occur within fruits, and also within humans following consumption, the most reliable measure of vitamin C content is total vitamin C (AA plus DHAA). In the studies reporting vitamin C loss, there was no evident pattern for the method of analysis used. Three studies used HPLC, three used titration, two used derivatization, and the method of analysis was unclear for one study. However, of the nine studies that found decreased vitamin C content, four reported only AA levels. In these studies, the actual loss of vitamin C may be less than reported, as DHAA has similar vitamin C activity (Eitenmiller et al. 2008; Tsujimura et al. 2008).

Table 6.9 Summary of data for effect of phytosanitary doses (≤1 kGy) on fruit*.

Fruit	Carotene	Vitamin C	Other compounds
Pome	1 study • Apple: no change (unpublished)	2 studies • Apple: -13% after 1 month, then +48-57% after 2-6 mo • Apple: -25% to -51% after 14 d (unpublished)	Not determined
Stone	2 studies • Apricot: no change • Apricot, cherry, peach, plum: no change (unpublished)	3 studies • Apricot: -26% after 3 d, no change after 7 d • Cherry: no change • Apricot, peach, plum: no change. Cherry: variable (unpublished)	2 studies • Apricot: no change in antioxidant capacity • Cherry: -21% anthocyanins
Berry	Not determined	2 studies • Strawberry: -14% to +5% • Strawberry: no change (unpublished)	1 study • Blueberry: phenolics similar or increased
Citrus	3 studies • Grapefruit: no change (2 studies) • Orange: +33% after 9 d	8 studies • Grapefruit: no change (2 studies) • Lemon, mandarin (Ellendale): no change, mandarin (Imperial): -43% to -60% after 3 wk • Lime, orange, mandarin: appear to decrease but study is limited by only AA measurement and limited statistical analysis • Mandarin (clementine): no change (2 studies) • Orange: no change • Blood orange: AA higher in irradiated fruit after 1-6 weeks storage	5 studies • Grapefruit: transient decrease in flavones in early season fruit, no change lycopene and limonin (3 studies) • Mandarin (clementine): no change (2 studies)
Tropical	6 studies • Mango (Kensington pride): no change • Mango (Tommy Atkins): no change or increased (2 studies) • Mango (Zebda): no change (2 studies) • Pawpaw: no change	14 studies • Custard apple: no change • Guava: -3% to -34% • Litchi (Shahi): -20% to -30%; Litchi (China and Tai So): no change (2 studies) • Mango (Keitt): fluctuate, -10% to -30% at day 1 and 9-15 • Mango (Kensington Pride): no change • Mango (Tommy Atkins): no change after 0, 18 d • Mango (Tommy Atkins): -50% to -76% after 5-15 d • Mango (Zebda): no change (2 studies)	4 studies • Litchi: no change in flavonoids • Mango (Tommy Atkins): no change or increase in phenolics, effect on total antioxidant activity variable • Mango (Zebda): similar or increased phenolics (2 studies)

Fruit	Carotene	Vitamin C	Other compounds
		• Pawpaw: no change (3 studies) • Pineapple: no change	
Other	1 study (unpublished) • Grape: no change (unpublished) • Honeydew melon: decreased after 1d, no change after 14d (unpublished) • Rockmelon: no change (unpublished)	5 studies • Grape: no change (2 studies, 1 unpublished) • Honeydew melon: no change • Kiwifruit: -4% to -18% after 1-3 wk (approximate change) • Persimmon: no change • Rockmelon: no change (2 studies, 1 unpublished)	Not determined

*For details and references see individual sections in Chapter 5

6.10.2 Vegetables

Limited data were available for the effects of irradiation on whole vegetables. Similar to fruits, the available data indicate that carotene content is relatively stable in irradiated vegetables. Vitamin C levels also appeared stable in irradiated cucurbit and fruiting vegetables. In addition to these vegetables, γ-irradiation with 1 kGy of broccoli, carrots, celery, cilantro, parsley, red cabbage, green onions and romaine lettuce did not significantly affect vitamin C content. However, vitamin C losses were significant after irradiation of iceberg, green and red leaf lettuce, and spinach at days 1 and 14 (Fan and Sokorai 2008a). While some differences were noted in vitamin C and lycopene levels in irradiated tomatoes at early time-points of storage, these changes appear to be secondary to delayed ripening rather than destruction of these nutrients.

Table 6.10.2 Summary of effects of phytosanitary doses of irradiation (≤1 kGy) in vegetables.

Vegetable	Carotene	Vitamin C	Other compounds
Cucurbit	1 study • Zucchini: no change (unpublished)	1 study • Zucchini: not determined due to low levels in control • Zucchini: no change (unpublished)	No data
Fruiting vegetables	2 studies • Capsicum: no change • Tomato and capsicum: no change (unpublished)	3 studies • Capsicum: no change • Tomato: lower rate of accumulation, but no difference after 21 d • Tomato and capsicum: no change (unpublished)	1 study • Tomato: delayed accumulation of lycopene

An application to use phytosanitary doses of irradiation on tomatoes and capsicums has recently been approved. Little additional data were found in this literature review that would change the earlier conclusion that the available data indicate no loss of either carotenes or vitamin C. Lycopene levels were lower in irradiated tomatoes, but this may be due to a slower rate of lycopene accumulation in tomato associated with delayed ripening.

There is limited data available on the effects of irradiation on cucurbit vegetables and other fruiting vegetables. However, the similarity of findings in tomatoes and capsicums, as well as fruits, indicate that phytosanitary doses of irradiation are unlikely to have a greater effect on nutrient composition than that which occurs with vegetable variety or the effects of growing conditions and location or with storage.

7 Nutritional implications of phytosanitary doses of irradiation

Overall, the weight of evidence indicates that irradiation of fruits and vegetables with up to 1 kGy would not affect dietary carotene intake in Australian and New Zealand populations. Similarly, the majority of studies found no effect of phytosanitary doses of irradiation on vitamin C levels in fruits and vegetables. However, losses were reported in some studies. As a conservative approach, these losses are now considered case-by-case in the context of:

- dietary intakes of vitamin C in Australia and New Zealand, and
- natural variation in vitamin C levels.

Dietary analyses were performed to determine major dietary contributors to vitamin C intake in Australian and New Zealand populations. The contributions of fruits and vegetables to vitamin C intake, and the methods of dietary assessment are detailed in Appendix 3. The food groups contributing most to vitamin C intake in Australia and New Zealand are fruit juices and drinks, citrus fruits, potatoes and brassica vegetables. Importantly, data from the nutrition surveys demonstrated that mean vitamin C intakes exceed both the Estimated Average Requirement (EAR) and Recommended Daily Intakes (RDI) for all population groups. Furthermore, vitamin C intake at the 5^{th} percentile also exceeded the EAR and RDI in all groups. These data demonstrate that vitamin C intake is adequate in the Australian and New Zealand populations, even in people with the lowest intake levels.

7.1 Apples

Vitamin C levels are low in apples. Pome fruit do not make a major contribution to dietary vitamin C intake in the majority of Australian and New Zealand population groups. However, pome fruits do contribute to 5-6% of dietary vitamin C intake in:

- 5–8 year old children in New Zealand and
- 9–13 year old children in New Zealand.

Vitamin C content of apples is susceptible to large losses during storage and processing. For example:

- Vitamin C levels decreased by 35–75% in apples stored 7-10 days at room temperature (Davey and Keulemans 2004; Kevers et al. 2011)
- Vitamin C levels decreased by 19–90% in apples during three to nine months cold storage (Bhushan and Thomas 1998; Davey and Keulemans 2004)
- Vitamin C was not detected in apples baked for 30 minutes at 190°C (NUTTAB).

Irradiation of apples had a variable effect on vitamin C. One month after irradiation, vitamin C levels decreased by up to 66%. The extent of vitamin C loss was more strongly associated with cultivar rather than irradiation dose. However, following 6 months post-irradiation storage, vitamin C levels were on average 57% higher than non-irradiated apples. Furthermore, the vitamin C content of irradiated apples remained within the range of vitamin C levels reported for normal fruit (see Appendix 1).

Combined with dietary intake data, the available evidence indicates irradiation of pome fruits would not have a significant effect on vitamin C intakes in Australia and New Zealand.

7.2 Apricots and Cherries

Stone fruits do not make a major contribution to dietary vitamin C intakes in Australia or New Zealand. While some significant losses of vitamin C were reported in irradiated apricots and cherries, the effects were inconsistent:

- Egea et al. (2007) reported no effect of irradiation with 0.5 kGy on vitamin C levels. However, irradiation with 1.0 kGy decreased AA levels by approximately one-third after 3 days. After 7-14 days, AA levels were no longer significantly different to levels in non-irradiated apricots.
- Unpublished data from DAFF QLD (2012) showed no effect of irradiation on vitamin C in apricots. However, the vitamin C levels in this study were approximately ten-fold lower than the level expected for apricots.

- Unpublished data from DAFF QLD (2012) reported a decreased in vitamin C content in cherries irradiated with 0.6 kGy, but not 0.15 or 1 kGy. As detailed in section 5.2, the 0.6 kGy treatment group appeared aberrant.

In the Egea study, the lowest levels of AA reported in irradiated apricots was approximately 3 mg/100 g. This value falls within the range reported for different apricot cultivars, albeit at the lower end of the range. Total vitamin C levels were not reported, meaning it is possible that the reduction in AA was associated with conversion to DHAA. Furthermore, during the post-irradiation storage period, AA levels were not significantly different between control and irradiated fruits after 7 days.

The available data suggests some diminution of vitamin C is possible in apricots. However, the inconsistencies between studies, and the fact that following storage differences were not significant, indicate that the effect of such losses is likely to be small. Taken together with the dietary intake data, it can be concluded that irradiation of stone fruit would not have significant impact on vitamin C intakes in Australia and New Zealand.

7.3 Strawberry

Despite having relatively high vitamin C levels, berries are not major contributors to vitamin C intake in Australia and New Zealand. Irradiation of strawberries with up to 1 kGy:

- Had no effect on vitamin C levels in the Albion cultivar (DAFF QLD, 2012)
- Decreased total vitamin C by 14% in Hapil strawberries and 11% in Pantagruella strawberries immediately after irradiation, but differences between control and irradiated strawberries decreased with storage (Graham and Stevenson 1997)
- In Cambridge Vigour and Cambridge Favourite strawberries, total vitamin C values in irradiated fruits remained within 10% of the value in non-irradiated controls (Graham and Stevenson 1997).

Vitamin C levels in irradiated strawberries ranged between 46–93 mg/100 g. These values fall well within the range of values reported for non-irradiated strawberries, which extends from 23–185 mg/100 g. Furthermore, vitamin C levels in frozen and canned strawberries decrease to below 41 mg/100 g. Together with the nutrient intake data, it is evident that irradiation of strawberries would not impact vitamin C intakes in Australia and New Zealand.

7.4 Kiwifruit

In national dietary surveys, kiwifruit are included in the “other fruit” category, along with fruits such as melons and grapes. Other fruit make a major contribution to vitamin C intake as follows:

- 6% of vitamin C intake in 2–3 year old male Australians
- 5% of vitamin C intake of 4–8 year old female Australians
- 7% of vitamin C intake of 14 year old females in New Zealand
- 6% of vitamin C intake of 50–69 year old females in New Zealand
- 9% of vitamin C intake of females aged 70 or over in New Zealand

Irradiation of kiwifruit with 1 kGy decreased AA content by approximately 4–18% compared to non-irradiated kiwifruit (Kim and Yook 2009). However, in this study, vitamin C content of irradiated kiwifruit remained over 200 mg/100 g, which is at the high end of the range of natural variation. As such, these changes in vitamin C content of irradiated kiwifruit would not compromise vitamin C intakes in Australia or New Zealand.

7.5 Mandarin

Citrus fruit are a major dietary contributor to vitamin C in all age and gender groups in Australia and New Zealand, with the exception of 17-18 year old Australian females. In these population groups, citrus fruit (excluding juice) provide 5-17% of vitamin C intake.

The effects of irradiation on vitamin C content of mandarins were cultivar dependent. In Clementine and Ellendale mandarins, there was no effect of irradiation on vitamin C content, even following post-irradiation storage. Small vitamin C losses were reported in Nagpur mandarins following irradiation with 0.5–1.0 kGy. In this cultivar, the AA content of irradiated mandarins ranged from 18–22 mg/100 g, and 20-25 mg/100 g in non-irradiated mandarins (Ladaniya et al. 2003). However, in Imperial mandarins:

- Vitamin C levels were unaffected immediately after irradiation with up to 0.3 kGy.
- After 3 weeks storage, vitamin C levels decreased by 46% in non-irradiated mandarins.
- After 3 weeks storage, vitamin C levels decreased by 69% and 78% in mandarins irradiated with 0.075 and 0.3 kGy, respectively. Vitamin C content was 43% and 60% lower in irradiated compared to non-irradiated mandarins following storage (Mitchell et al. 1992).

The initial vitamin C levels in Imperial mandarins were considerably lower than those in Ellendale mandarins used in the same study, and the levels reported for other mandarin cultivars. Specifically, vitamin C levels were:

- 14 mg/100 g in Imperial mandarins, decreasing to 5 mg/100 g after 3 weeks storage and 2 mg/100 g after irradiation and storage
- 38 mg/100 g in Ellendale mandarins
- 24-58 mg/100 g for other cultivars, as reported in food composition tables and published literature (see Appendix 1).

Together, these data indicate that vitamin C content of Imperial mandarins is lower than other cultivars, and is vulnerable to losses through both storage and irradiation. The quantitative effect of storage on vitamin C levels was greater than that of irradiation.

As citrus fruits are a major dietary source of vitamin C, consideration should be given to the cultivar type in assessing the impact of nutrient losses in irradiated citrus fruits. However, oranges are more widely consumed than mandarins, and the data in oranges indicated no loss of vitamin C with irradiation. Furthermore, a number of mandarin cultivars are available in Australia and New Zealand. Together, it is likely that losses of vitamin C following storage of some irradiated mandarin cultivars would not compromise adequate vitamin C intake in Australian and New Zealand populations.

7.6 Mango

Tropical fruits contribute 5-6% of dietary vitamin C intake in females aged over 50 years and Australian males aged over 70 years and less than this for all other age groups. Importantly, the “tropical fruit” category includes banana and pineapple, which are widely consumed in Australia and New Zealand.

Effects of irradiation on vitamin C content in mangoes were cultivar-dependent. No or limited vitamin C loss were reported for Kensington Pride and Zebda cultivars, while data for Keitt and Nahng Clahng Wahn mangoes were variable. Furthermore, in Zebda mangoes. vitamin C levels were higher in irradiated fruit after storage. However, the effects of irradiation of Tommy Atkins mangoes were inconsistent. Data from two separate studies conducted at the same university reported:

- No effect of irradiation with 1 kGy on vitamin C levels, either initially or after 18 days storage. In this study AA levels decreased 25% and 32% in control and irradiated

mangoes, respectively. AA content of irradiated mangoes ranged from 14–20 mg/100 g (Reyes and Cisneros-Zevallos 2007).

- In mangoes irradiated with 1 kGy, AA levels decreased by 50% and 79% after 5 and 21 days storage, respectively. AA content of irradiated mangoes ranged from 4–8 mg/100 g (Moreno et al. 2007).

In both these studies, mangoes were irradiated with electron-beam ionising radiation in the same facility and with the same irradiation protocol. However, the method of AA analysis was different, with the first study using HPLC and the second using titration. As titration is considered to be more error-prone (see section 4.2.2), it is possible that this difference in methodology may have contributed to the conflicting results.

The vitamin C content reported for mangoes ranges from 12-135 mg/100 g. The majority of studies of irradiated mangoes report vitamin C levels within this range. When considered with the dietary consumption data, it is evident that irradiation of mangoes is unlikely to compromise vitamin C intake in the Australian and New Zealand populations.

7.7 Guava and litchi

Guava is included in the tropical fruit group. As detailed above, these fruits only make a small contribution to vitamin C intake in some population groups. In the nutrition surveys, litchi is included in the other fruit category, which contributes 5–9% of vitamin C intake in some population groups (see Appendix 1).

Guavas have very high vitamin C content, with over four-fold more vitamin C than oranges. However, they are not commonly consumed fruits and therefore would only make a minor contribution to vitamin C intakes in some individuals. In irradiated guavas, vitamin C levels:

- Decreased 3–24% in Lucknow-49 cultivar and
- Decreased 8–34% in Allahabad Safeda cultivar.

For both cultivars, larger losses occurred with the higher irradiation dose (1 kGy). The lowest vitamin C levels were observed following storage of irradiated guava at 27°C, with the lowest value being 103 mg/100 g. This value is below the lowest level reported in the literature for non-irradiated guava, which was 129 mg/100 g. However, even with these losses, irradiated guava retain a high level of vitamin C.

The effects of irradiation on litchi were cultivar-dependent. In litchi:

- Irradiation with up to 0.3 kGy had no effect on vitamin C in the Tai So cultivar (Mitchell et al. 1992)
- Vitamin C levels were similar or increased after irradiation with up to 0.5 kGy in the China cultivar
- Vitamin C levels decreased 20–30% following irradiation with up to 0.5 kGy in the Shahi cultivar.

In litchi, irradiation with 0.075 or 0.3 kGy had no effect on total vitamin C or DHAA either initially or after 3 weeks storage in Tai So variety (Mitchell et al. 1992). Another study found a cultivar-dependent response, with China litchi having similar or increased total vitamin C levels after irradiation with 0.3 or 0.5 kGy after 1 and 12 days (Hajare et al. 2010). In the Shahi cultivar, irradiation with 0.3 kGy initially increased total vitamin C content by 12%, but after 12 days total vitamin C was 20% lower compared to controls. Irradiation with 0.5 kGy decreased total vitamin C content by ~30% at both times.

Given the seasonal intake patterns of tropical fruits and the diversity of fruits within this class, it is highly unlikely that irradiation of the tropical fruits such as guava or litchi would significantly decrease vitamin C intakes in Australia and New Zealand.

7.8 Other considerations

Proportion of produce

In assessing the nutritional impact of irradiation, it is important to consider the proportion of fruits and vegetables that will undergo irradiation treatment. This proportion of irradiated produce will vary depending on fruit or vegetable type, season and geographic regions (for example, state or territory). It is beyond the scope of this review to provide quantitative estimates of the proportion of irradiated produce that may be consumed by various populations. However, these calculations could be performed on a case-by-case basis and were undertaken for the application to irradiate tomatoes and capsicums (FSANZ 2013).

Cumulative effects

In addition, consideration should be given to any cumulative effects on dietary intakes if approval is given to irradiate more and more types of fruits and vegetables. Vitamin C is the nutrient most vulnerable to diminution following irradiation and which is present in important levels in fruits and vegetables. However, given the inconsistency in the effect of irradiation and the influence of factors such as cultivar on vitamin C stability, the risk of systematic losses of vitamin C across the food chain is small. Furthermore, the major dietary sources of

vitamin C are fruits and vegetables that are unlikely to be irradiated (citrus, potato, brassicas), and juices or beverages which are less likely to be irradiated for phytosanitation. Lastly, vitamin C intakes in Australia and New Zealand are adequate, and would remain so even with diminished vitamin C intakes. Therefore, while cumulative effects of small vitamin C losses are theoretically possible, they are, in reality, highly unlikely to adversely affect the adequacy of vitamin C intakes in Australia and New Zealand.

7.9 Summary

Vitamin C levels vary greatly between different cultivars of the same fruit, and are also influenced by growing location and climatic conditions. Significant losses of vitamin C occur during storage of many fruits, and while in some cases irradiation appeared to accelerate these losses, in other cases irradiation attenuated storage-associated depletion of vitamin C. Lastly, common processing of fruits, such as canning, freezing and drying are associated with large losses of vitamin C.

Studies of phytosanitary doses of irradiation indicate that this process is not usually associated with significant losses of vitamin C in fruit. When taking all these factors into consideration, it is evident that any impact of irradiation on vitamin C content in fruit has no more detrimental effect than that which occurs under normal growing, storage and handling conditions. Furthermore, under most circumstances, the vitamin C content of irradiated fruit still lies within the range reported for different cultivars of the same fruit. Finally, as vitamin C intakes exceed the RDI in >95% of Australian and New Zealand populations, irradiation of fruits and vegetables does not pose a risk to adequate vitamin C intakes in these countries.

8 Conclusions and recommendations

The quality of the evidence base for the effects of irradiation on fruits and vegetables is variable. The majority of studies assessed the effects of irradiation on vitamin C, with the results dependent on dose, species, cultivar and post-irradiation handling. A number of studies also investigated the effects of irradiation on carotenes in a variety of fruits and vegetables but depletion was not observed. Only a few studies reported the effects of irradiation on polyphenols and other carotenoids, and the effects of irradiation on these compounds remains an area of uncertainty.

8.1 Recommendations for risk assessment of irradiated fruits and vegetables

The data reviewed indicates that irradiation with doses of ≤1 kGy did not adversely affect nutrient composition of the fruits and vegetables included in this literature review. While some individual studies found losses of vitamin C, the extent of these losses rarely exceeded the natural variation between cultivars, or that which occurred with storage or processing. It is therefore reasonable to assume that other fruits and vegetables within these classes would show similar stability of nutrient composition in response to phytosanitary doses of irradiation. Considering the diversity of fruits for which data were available, this assumption could be extended to all fruits.

In addition to the evidence from the literature, FSANZs' dietary modelling demonstrates that the fruits considered within the review are among the major fruit contributors to vitamin C intakes in Australia and New Zealand. It is therefore reasonable to conclude that irradiation of other types of fruits would not adversely affect dietary vitamin C and carotene intakes in Australia and New Zealand.

Only limited data were available for the effects of irradiation on whole vegetables, and only fruiting and cucurbit vegetables were included in this review. Therefore, some uncertainty remains as to the effects of irradiation on the nutrient composition of other vegetables, such as roots and tubers, leafy vegetables, brassicas and legumes. At this stage it would appear unlikely these vegetables would be irradiated for phytosanitary purposes; for this reason the data available on these vegetables were not reviewed here. However, if an application to irradiate these vegetables were submitted, further assessment of the impact of irradiation on these vegetables would be required.

8.2 Considerations for other vitamins and other bioactive compounds

Limited data were available for the effects of irradiation on vitamin E in fruits and vegetables, and these data are not directly relevant to irradiation for phytosanitary purposes due to either the nature of the commodity (baby spinach, chestnuts), or the form of commodity (cut tomatoes). Irradiation with ≤1 kGy did not reduce tocopherol levels in spinach or chestnuts, but losses were observed in cut tomatoes. However, the limited contribution of fruits and vegetables to vitamin E intake indicate that any irradiation-associated losses of vitamin E would not compromise adequate dietary intakes in Australia and New Zealand.

The effects of phytosanitary doses of irradiation on other bioactive compounds in fruit are summarised in Tables 6.9. Twelve studies reported on the effects of irradiation with ≤1 kGy on antioxidant capacity, polyphenols and non-vitamin A carotenoids in fruit, and one study in

tomatoes reported on lycopene levels. Anthocyanin levels in cherries and lycopene levels in tomatoes were lower in irradiated fruits after storage. However, these differences may be secondary to irradiation slowing the rate of accumulation of these compounds, rather than through destruction. In the ten other studies reporting on other bioactive compounds in irradiated fruit, there were no significant losses of these compounds.

8.3 Recommendations for data requirements

It has previously been established that low-dose irradiation does not alter macronutrient or mineral composition of fruits and vegetables. Therefore, future applications for permission to irradiate fruits and vegetables with ≤1 kGy should not require data on macronutrients or minerals.

Furthermore, it is only vitamins A, C, E and thiamin that show high sensitivity to irradiation. Overall, the literature reviewed here does not report any systematic losses of vitamin C or carotene in fruits and vegetables irradiated with ≤1 kGy. The literature consistently reports no loss of carotenes following phytosanitary irradiation. Therefore, it should not be necessary to further assess the effects of irradiation on carotenes in applications to irradiate fruits and vegetables with ≤1 kGy. However, data should be provided if the irradiation dose exceeds 1 kGy.

Fruits and vegetables are not major contributors to vitamin E or thiamin and data should only be provided for these nutrients in the small range of fruits and vegetables that contain important levels.

The data on vitamin C in its entirety indicates relative stability in fruits and vegetables undergoing irradiation. However, the losses reported by some studies indicate data on vitamin C should be included in applications to irradiate fruit and vegetables, particularly given fruits and vegetables are a major dietary source of vitamin C. For vitamin C data to be interpretable, it is recommended that measurement of total vitamin C be the minimum requirement, but it is preferable to have data on both AA and DHAA. In addition, given the influence of cultivar on vitamin C stability, any data provided should be generated on the appropriate cultivars.

Less data are available for the effects of irradiation on non-vitamin bioactive compounds, such as polyphenols and the carotenoids without vitamin A activity. Compared to the micronutrients, less is known about how these compounds contribute to human health and

the levels of intake that are required and/or beneficial. This would be of relevance to fruits and vegetables which have high levels of these compounds, for example anthocyanins in blueberries. It is therefore suggested that data be provided for these compounds where appropriate.

To obtain meaningful data on the effects of phytosanitary doses of irradiation of fruits and vegetables, studies should include analysis of:

- non-irradiated controls
- relevant irradiation doses (for example ranging from 0.15 to 1.0 kGy)
- post-irradiation storage of control and irradiated commodities
- use of the cultivar(s) that will undergo phytosanitary irradiation.

This will enable appropriate conclusions to be drawn about the impact of irradiation on the nutrient composition of fruits and vegetables as supplied in Australia and New Zealand.

More extensive data may be required under certain circumstances. For example, fruits or vegetables that have atypical compositions may require a case-by-case consideration of the data required for a comprehensive nutrition assessment. Similarly, the data requirements for applications to use higher doses of irradiation, or irradiation for a different technological purpose, may vary and should be considered if such an application arises.

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Appendix 1

Natural variation of carotene and vitamin C in fruit and vegetables and contribution to dietary intake

Appendix 2

Search strategies

Appendix 3

Dietary sources of vitamin C