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Preharvest and postharvest factors influencing vitamin C content of horticultural crops

Seung K. Lee [1], Adel A. Kader *

Department of Pomology, University of California, Davis, CA 95616, USA

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Abstract

Vitamin C, including ascorbic acid and dehydroascorbic acid, is one of the most important nutritional quality factors in many horticultural crops and has many biological activities in the human body. The content of vitamin C in fruits and vegetables can be influenced by various factors such as genotypic differences, preharvest climatic conditions and cultural practices, maturity and harvesting methods, and postharvest handling procedures. The higher the intensity of light during the growing season, the greater is vitamin C content in plant tissues. Nitrogen fertilizers at high rates tend to decrease the vitamin C content in many fruits and vegetables. Vitamin C content of many crops can be increased with less frequent irrigation. Temperature management after harvest is the most important factor to maintain vitamin C of fruits and vegetables; losses are accelerated at higher temperatures and with longer storage durations. However, some chilling sensitive crops show more losses in vitamin C at lower temperatures. Conditions favorable to water loss after harvest result in a rapid loss of vitamin C especially in leafy vegetables. The retention of vitamin C is lowered by bruising, and other mechanical injuries, and by excessive trimming. Irradiation at low doses (1 kGy or lower) has no significant effects on vitamin C content of fruits and vegetables. The loss of vitamin C after harvest can be reduced by storing fruits and vegetables in reduced O_2 and/or up to 10% CO_2 atmospheres; higher CO_2 levels can accelerate vitamin C loss. Vitamin C of produce is also subject to degradation during processing and cooking. Electromagnetic energy seems to have advantages over conventional heating by reduction of process times, energy, and water usage. Blanching reduces the vitamin C content during processing, but limits further decreases during the frozen-storage of horticultural products.

Keywords: Ascorbic acid; Dehydroascorbic acid; Vitamin C; Nutritional quality

1. Introduction

The most important vitamin in fruits and vegetables for human nutrition is vitamin C. More than 90% of the vitamin C in human diets is supplied by fruits and vegetables (including potatoes). Vitamin C is defined as the generic term for

* Corresponding author. Tel.: +1-530-7520909; fax: +1-530-752 8502.

E-mail address: aakader@ucdavis.edu (A.A. Kader).

[1] Present address: Division of Plant Science, Seoul National University, Suwon, 441-744, Korea.

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all compounds exhibiting the biological activity of L-ascorbic acid (AA). AA is the principal biologically active form but L-dehydroascorbic acid (DHA), an oxidation product, also exhibits biological activity. Since DHA can be easily converted into AA in the human body it is important to measure both AA and DHA in fruits and vegetables for vitamin C activity. However, it has been noted that when reporting vitamin C levels, many workers have not taken into consideration DHA. In many horticultural crops DHA represents less than 10% of total vitamin C but DHA tends to increase during storage (Wills et al., 1984).

Vitamin C is required for the prevention of scurvy and maintenance of healthy skin, gums and blood vessels. Vitamin C is also known to have many biological functions in collagen formation, absorption of inorganic iron, reduction of plasma cholesterol level, inhibition of nitrosoamine formation, enhancement of the immune system, and reaction with singlet oxygen and other free radicals. Vitamin C, as an antioxidant, reportedly reduces the risk of arteriosclerosis, cardiovascular diseases and some forms of cancer (Harris, 1996).

AA is present in plant tissues undergoing active growth and development, and the amount of AA varies among species and cultivars. Some horticultural crops accumulate very high levels, e.g. the fruit of acerola (*Malpighia glabra* L.), also known as Barbados cherry or West Indian cherry, contains over 1% of its fresh weight in AA (Loewus and Loewus, 1987). Citrus fruits and potatoes are known to be the most important sources of vitamin C in the Western diet because of the large quantities consumed (Ball, 1998). A high recommendation of 100–200 mg/day has been suggested, since stress in modern life is known to increase the requirement for vitamin C.

Vitamin C is most sensitive to destruction when the commodity is subjected to adverse handling and storage conditions. Losses are enhanced by extended storage, higher temperatures, low relative humidity, physical damage, and chilling injury. AA is easily oxidized, especially in aqueous solutions, and greatly favored by the presence of oxygen, heavy metal ions, especially Cu^{2+}, Ag^{+}, and Fe^{3+}, and by alkaline pH and high temperature. DHA can be reduced to AA by reducing agents and also can be irreversibly oxidized to form diketogulonic acid, which has no vitamin C activity (Parviainen and Nyyssonen, 1992). Ascorbate oxidase has been proposed to be the major enzyme responsible for enzymatic degradation of AA. Ascorbate oxidase is a copper-containing enzyme that oxidizes AA to DHA in the presence of molecular oxygen (Saari et al., 1995). Ascorbate oxidase is associated with rapidly growing regions in the plant and occurs bound to cell walls as well as a soluble protein in the cytosol. Under stress, such as pathogen or chemical exposure, ascorbate oxidase levels were increased (Loewus and Loewus, 1987).

Many pre- and postharvest factors influence the vitamin C content of horticultural crops. Large genotypic variation in vitamin content was reviewed by Stevens (1974) and Harris (1975). Other preharvest factors include climatic conditions and cultural practices (Somers and Beeson, 1948; Lee, 1974; Harris, 1975; Mozafar, 1994; Weston and Barth, 1997). All these factors are responsible for the wide variation in vitamin C content of fruits and vegetables at harvest. Maturity at harvest, harvesting method, and postharvest handling conditions also affect the vitamin C content of fruits and vegetable (Kader, 1988). Processing methods and cooking procedures can result in significant losses of vitamin C (Fennema, 1977). Despite many investigations in the area of nutrition, knowledge about pre- and postharvest changes in vitamin C content of fruits and vegetables is inadequate. This review paper includes a brief overview of how preharvest conditions, harvesting, and postharvest handling procedures influence vitamin C content of fruits and vegetables.

2. Variation among species and cultivars

While there have been many studies on the AA content of fruits and vegetables, relatively few have been reported on the content of the two forms of vitamin C, AA and DHA. The wide variation in the content of AA and DHA among different species of fruits and vegetables are shown in Tables 1 and 2, respectively. Persimmons and peppers show the highest amount of vitamin C among their groups. In general cruciferous vegetables contain higher content of AA and sulfur compounds than non-cruciferous vegetables. Total sulfur content correlated well with the AA content of vegetables (Albrecht et al.,

Table 1
Vitamin C content (mg/100g FW) of some fruits

Commodity	AA	DHA	Total	References
Banana (fresh)	15.3	3.3	18.6	Vanderslice et al. (1990)
Blackberry (fresh)	18.0	3.0	21.0	Agar et al. (1997)
Blackberry (20% CO_2, 9 days at 1°C)	16.5	3.0	19.5	Agar et al. (1997)
Black current (fresh)	86.0	6.0	92.0	Agar et al. (1997)
Black current (20% CO_2, 20 days at 1°C)	61.0	3.0	64.0	Agar et al. (1997)
Cantaloupe (fresh)	31.3	3.0	34.3	Vanderslice et al. (1990)
Grapefruit (fresh)	21.3	2.3	23.6	Vanderslice et al. (1990)
Kiwifruit (fresh)	59.6	5.3	64.9	Agar et al. (1999)
Kiwifruit (slices, 6 days at 10°C)	39.4	12.1	51.5	Agar et al. (1999)
Lemon (fresh)	50.4	23.9	74.3	Mitchell et al. (1992)
Mandarins (fresh)	34.0	3.7	37.7	Mitchell et al. (1992)
Orange (California)	75.0	8.2	83.2	Vanderslice et al. (1990)
Orange (Florida)	54.7	8.3	63.0	Vanderslice et al. (1990)
Persimmon (fresh)	110.0	100.0	210.0	Wright and Kader (1997)
Persimmon (12% CO_2, 5 days at 5°C)	122.0	87.0	209.0	Wright and Kader (1997)
Raspberry (fresh)	27.0	2.0	29.0	Agar and Streif (1996)
Raspberry (20%CO_2,+2% O_2, 9 days at 1°C)	22.0	5.0	27.0	Agar and Streif (1996)
Strawberry (fresh)	60.0	5.0	65.0	Agar et al. (1997)
Strawberry (20% CO_2, 20 days at 1°C)	27.0	34.0	61.0	Agar et al. (1997)

Table 2
Vitamin C content (mg/100g FW) of some vegetables

Commodity	AA	DHA	Total	References
Broccoli (fresh)	89.0	7.7	96.7	Vanderslice et al. (1990)
Broccoli (boiled)	37.0	2.6	39.6	Vanderslice et al. (1990)
Cabbage (fresh)	42.3	–	42.3	Vanderslice et al. (1990)
Cabbage (boiled)	24.4	–	24.4	Vanderslice et al. (1990)
Cauliflower (fresh)	54.0	8.7	62.7	Vanderslice et al. (1990)
Collards (fresh)	92.7	–	92.7	Vanderslice et al. (1990)
Collards (boiled)	40.7	–	40.7	Vanderslice et al. (1990)
Mustard greens (fresh)	36.2	–	36.2	Vanderslice et al. (1990)
Mustard greens (boiled)	4.8	–	4.8	Vanderslice et al. (1990)
Peppers (red)	151.0	4.0	155.0	Vanderslice et al. (1990)
Peppers (green)	129.0	5.0	134.0	Vanderslice et al. (1990)
Potatoes (fresh)	8.0	3.0	11.0	Vanderslice et al. (1990)
Potatoes (boiled)	7.0	1.3	8.3	Vanderslice et al. (1990)
Spinach (fresh)	62.0	13.0	75.0	Gil et al. (1999)
Spinach (boiled)	12.0	18.0	30.0	Gil et al. (1999)
Swiss chard (fresh)	–	45.0	45.0	Gil et al. (1998)
Swiss chard (boiled)	–	9.0	9.0	Gil et al. (1998)
Tomatoes (fresh)	10.6	3.0	13.6	Vanderslice et al. (1990)
Watermelon (fresh)	8.0	1.7	9.7	Vanderslice et al. (1990)

Table 3
Effect of nitrogen fertilization on AA (mg/100g DW) content in three potato cultivars (Augustin, 1975)

N (kg ha^{-1})	A63126-2	Russet Burbank	Norgold
45	98.8	130.7	126.1
135	91.8	120.9	120.6
225	96.7	111.7	119.1

1991). In cruciferous vegetables reduced glutathione would reduce DHA to AA. It is interesting to note that only DHA was detected in Swiss chard. When the sample was spiked with AA it was completely and immediately transformed to DHA, which was the only vitamin C form detected. This result could be associated with a high oxidase activity in the Swiss chard extracts (Gil et al., 1998).

Vitamin C contents of fruits and vegetables are also variable among cultivars and tissues. Nelson et al. (1972) found a range from 19.3 to 71.5 mg/100g AA in six strawberry cultivars from four locations. Lee et al. (1995) reported a range from 64 to 168 mg/100g AA in five fresh pepper cultivars. In citrus fruit, flavedo tissues contained four times higher AA content than the juice (Nagy, 1980). Usually skin tissues have more AA content to protect the fruit from outside stress caused by light and oxidation.

3. Preharvest factors

3.1. Climatic conditions

Climatic conditions including light and average temperature have a strong influence on the chemical composition of horticultural crops (Klein and Perry, 1982). Although light is not essential for the synthesis of AA in plants, the amount and intensity of light during the growing season have a definite influence on the amount of AA formed. AA is synthesized from sugars supplied through photosynthesis in plants. Outside fruit exposed to maximum sunlight contain higher amount of vitamin C than inside and shaded fruit on the same plant. In general, the lower the light intensity during growth, the lower the AA content of plant tissues (Harris, 1975).

Temperature also influences the composition of plant tissues during growth and development. Total available heat and the extent of low and high temperatures are the most important factors in determining growth rate and chemical composition of horticultural crops. Reuther and Nauer (unpublished report, 1972) showed that ‘Frost Satsuma’ mandarins contained more vitamin C when grown under cool temperatures (20–22°C day, 11–13°C night) than hot temperatures (30–35°C day, 20–25°C night). Grapefruits grown in coastal areas of California generally contain more vitamin C than fruit grown in desert areas of California and Arizona.

3.2. Cultural practices

Augustin (1975) reported a decrease in AA content of some cultivars of potatoes with increasing amounts of nitrogen fertilizer used (Table 3). Lisiewska and Kmiecik (1996) reported that increasing the amount of nitrogen fertilizer from 80 to 120 kg ha^{-1} decreased the vitamin C content by 7% in cauliflower. Reduced levels of vitamin C in juices of oranges, lemons, grapefruits, and mandarins resulted from the application of high levels of nitrogen fertilizer to those crops, while increased potassium fertilization increased AA content (Nagy, 1980).

Based on these reports, nitrogen fertilizers, especially at high rates, seem to decrease the concentration of vitamin C in many fruits and vegetables. Plant growth is generally enhanced by the nitrogen fertilization so that a relative dilution effect may occur in the plant tissues. Nitrogen fertilizers are also known to increase plant foliage and thus may reduce the light intensity and accumulation of AA in shaded parts. Since excess use of nitrogen fertilizers increases the concentration of NO_3 and simultaneously decreases that of AA, it may have a double negative effect on the quality of plant foods (Mozafar, 1993).

Although vitamin C concentration has been found to be positively correlated with the nitrogen supply in butterhead lettuce (Muller and Hippe, 1987), it is inversely correlated with the nitrogen supply in white cabbage (Sorensen, 1984; Freyman et al., 1991) and crisphead lettuce (Sorensen et al., 1994). This discrepancy between different vegetable crops may be due to differences in growth habit and growing conditions.

Leeks grown with less frequent irrigation showed increased concentrations of dietary fiber, vitamin C, protein, calcium, magnesium, and manganese (Sorensen et al., 1995). Vitamin C content of broccoli varied inversely with the average precipitation during head development and increased with moderate water deficits (Toivonen et al., 1994). High vitamin C content may serve as a protective strategy against drought injury. Therefore, from a nutritional point of view, horticultural crops grown under low nitrogen supply, and irrigated less frequently, may be preferred due to the high concentrations of vitamin C and low concentrations of nitrate.

Cultural practices such as pruning and thinning determine the crop load and fruit size, which can influence the nutritional composition of fruits. The use of agricultural chemicals, such as pesticides and growth regulators, may indirectly affect the nutritional quality of fruits and vegetables. Application of gibberellins was beneficial to green tea quality, increasing vitamin C content by 18% (Liang et al., 1996).

4. Harvesting factors

4.1. Maturity at harvest

Maturity is one of the major factors that determines the compositional quality of fruits and vegetables. Total vitamin C of red pepper was about 30% higher than that of green pepper (Howard et al., 1994). Tomato fruit harvested green and ripened at 20°C to table-ripeness contained less AA than those harvested at the table-ripe stage (Kader et al., 1977). Betancourt et al. (1977) also reported that tomato fruit analyzed at the ‘breaker’ stage contained only 69% of their potential AA concentration if ripened on the vine to table-ripe. Fruit accumulated AA during ripening on or off the plant, but the increase was much greater for those fruit left on the plant. AA content increased with ripening on the plant in apricots, peaches, and papayas, but decreased in apples and mangoes (Table 4). Lee et al. (1982) reported that large and more mature peas contained less ascorbic acid than smaller and immature peas.

Table 4
Effect of maturity stage on AA content (mg /100g FW) of some fruits (Zubeckis, 1962; Wenkam, 1979)

Fruit (Cultivar)	Green	Half-ripe	Ripe
Apricot (Tilton)	11.7	12.9	14.3
Peach (Elberta)	7.8	10.2	12.2
Papaya (Solo)	72.0	95.0	102.2
Apple (Baldwin)	18.7	18.5	12.4
Mango (Pirie)	60.0	50.0	14.0

Nagy (1980) reported that immature citrus fruits contained the highest concentration of vitamin C, whereas ripe fruits contained the least. Although vitamin C concentration decreased during maturation of citrus fruits, the total vitamin C content per fruit tended to increase because the total volume of juice and fruit size increased with advancing maturity.

4.2. Harvesting method

The method of harvest can determine the extent of variability in maturity and physical injuries, and consequently influence nutritional composition of fruits and vegetables. Mechanical injuries such as bruising, surface abrasions, and cuts can result in accelerated loss of vitamin C. The incidence and severity of such injuries are influenced by the method of harvest and handling operations. Proper management to minimize physical damage to the commodity is a must whether harvesting is done by hand or by machine. Strawberries and other berries lost vitamin C quickly if bruised during harvesting (Ezell et al., 1947). Mondy and Leja (1986) found a very large decrease in AA content of the bruised tissue of potato tubers, while the unbruised halves appeared to show an increase in their AA content.

Table 5
Effect of temperature and wilting on vitamin C loss in kale (Ezell and Wilcox, 1959)

Rate of wilting	Average loss (%) after 2 days at different temperatures		
	0°C	10°C	20°C
Slow	2.4	15.3	60.9
Moderate	3.8	15.8	69.6
Rapid	5.3	33.1	88.8

5. Postharvest factors

Fresh fruits and vegetables as living tissues are subject to continual changes after harvest. Such changes cannot be stopped but can be controlled within certain limits by using various postharvest procedures. In general, freshly harvested fruits and vegetables contain more vitamin C than those held in storage.

5.1. Temperature and relative humidity management

Temperature management is the most important tool to extend shelf-life and maintain quality of fresh fruits and vegetables. Delays between harvesting and cooling or processing can result in direct losses due to water loss and decay and indirect losses such as those in flavor and nutritional quality. Kader and Morris (1978) found that delays of 24 h at 30 and 40°C between harvest and processing of tomatoes result in about a 5 and 12% loss in AA, respectively.

Zepplin and Elvehjein (1944) found that leafy vegetables held at 6°C lost 10% of their AA content in 6 days while those held at room temperature lost 20% in only 2 days. Losses in vitamin C in kale were accelerated at higher temperatures (Table 5). Similar results were obtained with spinach, cabbage, and snap beans (Ezell and Wilcox, 1959). All citrus fruits lost vitamin C if stored at high temperatures. The range of temperatures and the extent of vitamin C loss depended on the type of citrus fruit. In general the extent of loss in AA content in response to elevated temperatures was greater in vegetables than in acidic fruits, such as citrus, because AA is more stable under acidic condition (Nagy, 1980). Albrecht el al. (1990) reported that retention of AA ranged from 56 to 98% for six broccoli cultivars stored at 2°C for 3 weeks. Wu et al. (1992) found that AA decreased rapidly in green beans kept at 5°C after 3 days, but remained stable in broccoli. Esteve et al. (1995) showed that AA concentration in fresh green asparagus stored at 4°C increased 2 days after harvest.

Some horticultural crops such as sweet potatoes, bananas, and pineapples can suffer from chilling injury at low temperatures. Chilling injury causes accelerated losses in AA content of chilling sensitive crops. Destruction of AA can occur before any visible symptoms of chilling (Miller and Heilman, 1952).

Conditions favorable to wilting resulted in a more rapid loss of vitamin C in kale (Table 5). Wrapping, which prevented water loss, reduced AA loss in strawberry (Nunes et al., 1998). The effect was not due to modification of O_2 and CO_2 levels in wrapped treatments, which was minimal. The total AA content of wrapped strawberries changed little during storage for 8 days at 1 or 10°C. Losses in total AA content of unwrapped strawberries at 1°C ranged from 20 to 30% over 8 days.

5.2. Bruising, trimming, and cutting

Bruising significantly affected the chemical composition of pericarp and locular tissues of tomato fruit. Vitamin C content was about 15% lower in bruised locular tissue than unbruised fruit (Moretti et al., 1998). AA retention in shredded iceberg lettuce is affected by the nature of the slicing method used. Higher levels of AA were retained in samples that had been prepared by manually tearing the lettuce into strips. Lettuce shredded using a sharp knife retained initially 18% less AA than the torn samples. The retention of AA in the products sliced by machine was 25–63% lower than lettuce shredded by manual tearing. Using a blunt machine blade resulted in 10% lower AA levels than when a sharp blade was used (Barry-Ryan and O'Beirne, 1999). Excessive

Table 6
Effect of ethylene treatment on AA content (mg/100g FW) of tomato (Kader et al., 1978)

Treatment	When ripe
Picked table-ripe	19.2 a
Picked mature-green ripened at 20°C	12.3 b
Picked mature-green ripened with ethylene at 20°C	15.5 c

trimming of leafy vegetables results in loss of outer green leaves which contain more vitamins than inner leaves. Trimming of outer leaves and of the core and associated inner leaves of Chinese cabbage had a greater effect on reduction of vitamin C content than storage at 4°C for 11 days (Klieber and Franklin, 2000). Losses in vitamin C occur when vegetables are severely cut or shredded, as in the case of cabbage, lettuce, carrots, and other vegetables sold as salad mixes (Mozafar, 1994). Green peas and green lima beans retain their nutrients better if left in the pods than if shelled.

5.3. Chemical treatments

Calcium dips may be used to reduce physiological disorders and maintain firmness in apples and cherries. Bangerth (1976) observed an increase in vitamin C content of apples and tomatoes treated with calcium chloride. Dehydrated pineapples and guava pretreated with cysteine hydrochloride had increased AA retention and reduced color change during storage (Mohamed et al., 1993).

Watada et al. (1976) reported that AA content was slightly higher in mature-green tomatoes treated with ethylene than in those ripened without added ethylene. Kader et al. (1978) found a significant difference in ethylene-treated versus control mature-green tomato fruit (Table 6).

Kiwifruit slices stored in ethylene-free air contained 3-fold more AA than controls. When dipped in 1% $CaCl_2$ after cutting and kept in an ethylene-free atmosphere, slices had a slightly higher AA content than those treated with 1% $CaCl_2$ only (Agar et al., 1999).

5.4. Irradiation

Ionizing radiation may be used for sprout inhibition, insect control, or delay of ripening of certain fruits and vegetables. Mitchell et al. (1992) studied the irradiation effect on horticultural crops at relatively low doses and found that irradiation at 300 Gy had no significant effects on AA and DHA. Irradiation at 75–100 Gy irreversibly inhibited sprouting of potatoes regardless of storage temperature. Losses in vitamin C were lower in potato irradiated for sprout control and subsequently stored at 15°C than in non-irradiated tubers stored at 2–4°C (Joshi et al., 1990). 'Galia' muskmelons were irradiated at doses up to 1 kGy as a quarantine treatment, and the treatment had no effect on vitamin C content (Lalaguna, 1998).

In general doses of 2–3 kGy combined with refrigeration were useful for extending the shelf-life of strawberries (Graham and Stevenson, 1997). During storage AA levels significantly in-

Table 7
Effect of irradiation dose and storage on the total AA (TAA), reduced AA (RAA), and DHA concentrations (mg/100g FW) of strawberry (Graham and Stevenson, 1997)

Storage (days)	Irradiation dose (kGy)											
	0			1			2			3		
	TAA	RAA	DHA	TAA	RAA	DHA	TAA	RAA	DHA	TAA	RAA	DHA
0	68.7	67.3	1.4	60.9	57.1	3.9	57.2	48.0	9.2	59.9	47.7	12.2
5	70.9	68.2	2.7	63.3	60.6	2.7	67.4	62.6	4.7	60.9	53.1	7.9
10	78.9	72.6	6.3	77.1	69.2	7.9	77.4	74.5	2.8	61.0	58.1	2.9

Table 8
AA content (mg/100g FW) of apples (Zubeckis, 1962)

Cultivar	At harvest	Stored at 0°C for 6 months
Delicious	10.2	4.2
McIntosh	5.0	Traces

Table 9
Changes in the reduced AA, DHA, and total AA content (mg/100g FW) of fresh-cut kiwifruit slices as related to storage conditions (Agar et al., 1999)

	AA	DHA	Total
Initial	59.6	5.3	64.9
After 6 days at			
0°C	51.6	8.1	59.7
5°C	46.8	9.8	56.6
10°C	39.4	12.1	51.5
LSD at 5% level	2.9	1.2	1.6

Table 10
Effect of low oxygen on AA content (mg/100g FW) of apples at 15°C (Delaporte, 1971)

Storage time (days)	Control	3% O_2
10	18.1	24.1
35	8.9	18.4
66	5.5	15.9
85	3.3	14.9

creased while DHA content decreased in irradiated strawberries (Table 7).

5.5. Storage

Generally, fruits and vegetables show a gradual decrease in AA content as the storage temperature or duration increases (Adisa, 1986). Pantos and Markakis (1973) recorded a decline in AA content of artificially-ripened tomato fruit during storage. Zubeckis (1962) showed that the AA content of apples could drop down to less than 50% of the original amount during cold storage after 6 months (Table 8).

Kiwifruit slices stored at 5 and 10°C exhibited a gradual decrease in AA and an increase in DHA content (Table 9). The total vitamin C was 8, 13, or 21% lower than initial values in slices kept for 6 days at 0, 5, or 10°C, respectively (Agar et al., 1999).

Izumi et al. (1984) studied the effect of chilling temperatures on changes of AA content of some chilling-sensitive crops. Contents of AA in cucumber decreased continuously at 5°C, but no decrease was observed at 20°C. AA content in winter squash started to decrease only after the occurrence of chilling injury during storage at 1°C. In the case of sweet potato AA content decreased in the browned part due to chilling injury, but not in the healthy part during storage at 5°C.

Minimum loss of AA during storage has been reported in cruciferous vegetables, whereas, in other vegetables large losses occurred during storage. Vegetables with high AA retention were those high in total sulfur and glutathione. Glutathione may be involved in the mechanism responsible for reduction of DHA to AA in crucifers (Albrecht et al., 1990). According to the degree of AA retention, vegetables were classified as high retention (greater than 95% for broccoli, Brussels sprouts); medium retention (65–70% for green pea, spinach, turnip); and low retention (5–30% for asparagus and green beans).

5.6. Controlled/modified atmosphere

In general atmospheric modification reduces physiological and chemical changes of fruits and vegetables during storage. Loss of AA can be reduced by storing apples in a reduced oxygen atmosphere (Table 10).

Vitamin C content of fresh-cut kiwifruit slices kept in 0.5, 2, or 4 kPa O_2 at 0°C decreased by 7, 12, or 18%, respectively, after 12 days storage. Vitamin C content in slices kept in air + 5, 10, or 20 kPa CO_2 decreased by 14, 22 or 34%, respectively, of their initial vitamin C contents (Table 11). Generally, high CO_2 concentration in the storage atmosphere caused degradation of vitamin C in fresh-cut kiwifruit slices. Enhanced losses of vitamin C in response to air + 10 and 20 kPa CO_2 may be due to their stimulating effects on oxidation of AA and/or inhibition of DHA reduction to AA (Agar et al., 1999).

Bangerth (1977) found accelerated AA losses in apples and red currants stored in elevated CO_2 atmospheres. Storage in 2 kPa O_2 + 10 kPa CO_2 resulted in 60% loss in AA content of Conference pears (Veltman et al., 1999). Storage for 6 days in CO_2-enriched atmospheres resulted in a reduction in AA content of sweet pepper kept at 13°C (Wang, 1977) but an increase in its content in broccoli kept at 5°C (Wang, 1979). Vitamin C content was reduced by high CO_2 (10–30%), particularly in strawberries. Reducing the O_2 concentration in the storage atmosphere in the presence of high CO_2 had little effect on the vitamin C content. AA was more diminished at high CO_2 than DHA. (Agar et al., 1997). High CO_2 may stimulate the oxidation of AA, probably by ascorbate peroxidase. Mehlhorn (1990) demonstrated an increase in ascorbate peroxidase activity in response to ethylene. High CO_2 at injurious concentrations for the commodity may reduce AA by increasing ethylene production and, thus, the activity of ascorbate peroxidase.

Wright and Kader (1997) studied the fresh-cut products of strawberries and persimmons for 8 days CA (2 kPa O_2, air + 12 kPa CO_2, or 2 kPa O_2 + 12 kPa CO_2) at 0°C and found that the post-cutting life based on visual quality ended before significant losses of vitamin C occurred. Nutritional quality of broccoli florets were evaluated during storage at 4°C in air or CA of 2 kPa O_2 + 6 kPa CO_2. Retention of vitamin C was slightly greater in CA than in air. Returning the samples to ambient conditions for 24 h after storage in either condition resulted in chlorophyll and vitamin C losses (Paradis et al., 1996).

Wang (1983) noted that 1 kPa O_2 retarded AA degradation in Chinese cabbage stored for 3 months at 0°C. In contrast, treatment with 10 or 20 kPa CO_2 for 5 or 10 days was without any effect, and 30 or 40 kPa CO_2 increased AA decomposition. The effect of elevated CO_2 on AA content varied among commodities and was dependent on CO_2 level and storage temperature and duration (Weichmann, 1986).

Modified atmosphere packaging (MAP) of broccoli resulted in better maintenance of AA, chlorophyll and moisture retention compared to broccoli stored in air (Barth et al., 1993a,b). There was no significant difference in activity of AA oxidase in response to package conditions. Greater humidity inside the packages possibly served to better preserve vitamin C content in packaged broccoli spears. Retention of vitamin C in jalapeno pepper rings after 12 days storage at 4.4°C, and an additional 3 days at 13°C was 83% in MAP and 56% in air. MAP retarded the conversion of AA to DHA that occurred in air-stored peppers. Other quality attributes of peppers were maintained better in MAP than in air (Howard et al., 1994; Howard and Hernandez-Brenes, 1998).

Table 11
Changes in reduced AA, DHA, and total AA contents (mg/100g FW) of fresh-cut kiwifruit slices as related to O_2 and CO_2 concentrations at 0°C (Agar et al., 1999)

Treatment	After 6 days			After 12 Days		
	AA	DHA	Total	AA	DHA	Total
Initial	55.0	6.8	61.8	55.0	6.8	61.8
Air	44.6	8.7	53.3	36.2	14.1	50.3
0.5 kPa O_2	50.7	7.8	58.5	49.7	7.8	57.6
2 kPa O_2	47.7	12.9	60.6	44.2	10.3	54.5
4 kPa O_2	51.6	9.8	61.4	39.9	11.2	51.1
Air + 5 kPa CO_2	46.4	11.1	57.5	40.7	12.4	53.1
Air + 10 kPa CO_2	41.1	10.5	51.6	36.9	11.4	48.3
Air + 20 kPa CO_2	36.0	10.2	46.4	33.7	7.6	41.3
LSD at 5% level	3.2	1.2	2.5	3.2	1.2	2.5

Table 12
Effect of blanching method on vitamin C content of frozen spinach. (Ponne et al., 1994)

Blanching treatment	AA (mg/100g FW)
Not blanched	14.4 a
Microwave	9.2 c
Microwave steam	10.6 bc
Infrared	6.5 d
Radio frequency	5.7 d
Steam	12.3 ab
Water	5.1 d

Initially, fresh-cut spinach contained AA as a predominant form of vitamin C. However, a decrease in AA and an accumulation of DHA were observed during storage. The increase in DHA was more prominent in MAP and resulted in a higher vitamin C value of spinach in MAP than air. An increase in the pH of spinach stored in MAP was also observed (Gil et al., 1999). In contrast, fresh-cut products of Swiss chard contained only DHA, and vitamin C was better preserved in air than MAP (Gil et al., 1998).

5.7. Processing methods

AA is very susceptible to chemical and enzymatic oxidation during the processing, cooking and storage of produce. Blanching and pasteurization prevent the action of AA oxidase. Other plant enzymes, including phenolase, cytochrome oxidase and peroxidase, are indirectly responsible for AA loss. Electromagnetic energy presents advantages over conventional blanching by reduction of processing times, energy and water usage, and improvement of product quality. Vitamin C retention in frozen spinach was highest after steam blanching, microwave steam blanching, and microwave blanching (Table 12). The highest vitamin C losses occurred in the water-blanched samples. Loss of vitamin C is caused by leaching in surrounding water and thermal breakdown. Although infrared blanching and radio frequency blanching are processing steps without water, vitamin C retention was low (Ponne et al., 1994).

Cooking is often responsible for the greatest loss of vitamin C, and the extent of the loss depends upon variations in cooking methods and periods. Cooking decreased the vitamin C content of potatoes by about 30% and keeping potatoes hot for 1 h after cooking decreased vitamin C content by a further 10% (Hagg et al., 1998). Vegetables prepared by microwave-steaming and stir-frying with oil had significantly higher (1.3–1.8-fold) vitamin C retention values than those that were boiled (Masrizal et al., 1997). Vegetables reheated after 1 day of chilled storage had greater losses of vitamin C compared to those held at 72°C for 30 min, but better vitamin C retention than vegetables held hot for 2 h. If warm-holding is restricted to less than 90 min vitamin retention in vegetables is likely to be higher in a cook/hot-hold foodservice than with a cook/chill system (Williams et al., 1995). Howard et al. (1999) reported that steam blanching of broccoli, carrot, and green beans resulted in slight losses in carrot and green beans but up to 30% loss of total AA in broccoli; microwave cooking had minimal effects on AA content.

Unblanched beans and peppers lost more than 97% of their vitamin C within 1 month of freezing at −22°C, whether or not they were contained in bags sealed under vacuum. Blanching reduced the vitamin C content by 28% due to dissolution and oxidation of the vitamin during blanching, but limited further decreases to between 3% (vacuum sealed) and 10% (no vacuum) in 12 months (Oruna-Concha et al., 1998). In contrast, the losses in vitamin C content during blanching averaged 40% in broccoli and 30% in cauliflower. Freezing resulted in little change of the vitamin C content, which was reduced by 15–18% in broccoli and by 6–13% in cauliflower after 12 months of frozen-storage at −30°C (Lisiewska and Kmiecik, 1996). Baked frozen sweet potatoes were stable during 6 months frozen-storage, with the exception of vitamin C, which decreased by about 50% during the first month (Wu et al., 1991).

Citrus juices in unopened bottles and cans contain high AA content and a low level of DHA, whereas those juices exposed to air and stored at warm temperatures contain higher levels of DHA and diketogulonic acid. The higher level of fructose in an orange juice product, the greater the loss of vitamin C. A reaction between the carbonyl groups of fructose and vitamin C was responsible for the reduction in vitamin C in orange juice products (Nagy, 1980). The hydroxyl acids, citric and malic, stabilize vitamin C by chelating prooxidant metals and increasing juice acidity (Nagy, 1980). Phenolics were reported to protect vitamin C against oxidative decomposition in fruit juices (Miller and Rice-Evans, 1997).

6. Conclusions

Selection of the genotype with the highest vitamin C content for a given commodity is a much more important factor than climatic conditions and cultural practices in producing high amounts of vitamin C at harvest. Among preharvest factors light intensity and temperature are the most important in determining the final vitamin C content of the commodity. Pruning and thinning of fruit trees determine their crop load, which affects fruit size and composition, including vitamins. Other preharvest factors have a relatively minor direct effect on the vitamin C content of fruits and vegetables.

Many harvesting and postharvest handling procedures influence the nutritional quality of fruits and vegetables. Much of the available information is about AA, which appears to be the most sensitive to postharvest losses. Oxidation can occur in the presence of catalysts, oxidase enzymes, or as a result of heat during processing. Therefore, vitamin C losses continue through postharvest handling, processing, cooking, and storage of fruits and vegetables. Additional research is needed to investigate the effects of postharvest handling procedures on nutrients in fresh fruits and vegetables. Also, the possible effects on nutritional quality of those procedures that have not been evaluated need to be elucidated. Any new harvesting or postharvest handling method should be evaluated as to its potential impact on nutritional quality before being recommended for use.

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