Ascorbic Acid in Processed Plant-Based Foods

Sze Ying Leong, Tingting Liu, Indrawati Oey, and David J. Burritt

Abstract Vitamin C (ascorbic acid or L-ascorbic acid) is an essential vitamin for humans and is vital for maintaining good health. As humans are unable to synthesise ascorbic acid, they are dependent upon its presence in their diet to meet their daily ascorbic acid needs. Plants are a good source of ascorbic acid and so it is not difficult for humans to obtain an adequate daily supply of ascorbic acid from a wide range of plant-based foods. However, the ascorbic acid content in plant tissues is variable and levels in fresh product can be affected from the time of harvest until ingestion. In addition, the increasing consumption of processed plant-based foods, rather than fresh product, has led to a considerable amount of research into the most appropriate processing methods to convert raw plant materials into plant-based foods while retaining high levels of ascorbic acid in the final food product. In this chapter, we discuss the impacts of conventional food processing techniques, such as blanching, frying, and freezing on ascorbic acid levels and how novel processing techniques, such as pulsed electric field and high hydrostatic pressure, could be used to improve the retention of ascorbic acid in plant-based foods. The importance of selecting appropriate food processing techniques to maintain both the levels and bioactivity of vitamin C in a range of different plant-based foods is critically evaluated.

Keywords Ascorbic acid · Plants · Food · Processing · Stability · Bioactivity

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1 Introduction to Ascorbic Acid in Plants and its Importance for Human Health

Vitamin C (ascorbic acid or L-ascorbic acid) is an important multifunctional molecule in plants, with a diverse array of functions including regulating gene expression, acting as a cofactor for key enzymes and as a substrate for oxalate and tartrate biosynthesis, modulating plant growth via interactions with plant hormones, and can also act as an antioxidant and a regulator of intracellular redox state (Gest et al. 2013). Ascorbic acid also has a multifunctional role in animals where it is important as an antioxidant and regulator of intracellular redox state, promotes iron absorption, helps to promote immune responses, strengthens blood vessels, and reduces cholesterol concentrations (Figueroa-Méndez and Rivas-Arancibia 2015). Ascorbic acid also promotes collagen formation and cartilage development and helps to facilitate wound healing (Figueroa-Méndez and Rivas-Arancibia 2015). Because of these properties, ascorbic acid has also been shown to help prevent diseases such as arteriosclerosis-related cardiovascular diseases (e.g. hypertension) and cancer (Figueroa-Méndez and Rivas-Arancibia 2015).

Humans, unlike most animals, cannot synthesise ascorbic acid and so must obtain their daily requirement from dietary sources. Ascorbic acid deficiency can result in the development of several diseases including scurvy, a disease associated with the breakdown of the connective tissues. While it is widely acknowledged that the best source of ascorbic acid for humans is fresh fruit and vegetables, increasingly humans are relying on processed foods to meet their daily nutritional needs, including plant-based products (Weaver et al. 2014).

It is well known that the ascorbic acid contents of plant tissues are highly variable, with levels in fresh produce being sensitive to change from the time of harvest until consumption. Numerous studies have shown that the choice of processing method can greatly influence ascorbic acid stability and hence its levels in processed plant-based foods. In addition, how ascorbate/vitamin C levels are reported in the published literature also varies. Some studies report both the levels of ascorbic acid and ascorbic acid + dehydroascorbic acid (total vitamin C), while others only report ascorbic acid or total vitamin C levels. For the remainder of this chapter, we will use the terms ascorbic acid and total vitamin C as defined above.

In the following sections, we provide an overview of conventional food processing techniques, including those most commonly used to stabilise/protect ascorbic acid from enzyme-catalysed oxidation e.g. blanching, and combined blanching and freezing, and discuss how novel processing techniques could be used to improve the retention of biologically active ascorbic acid in processed plant-based foods. The importance of selecting appropriate food processing techniques to maintain both the levels and bioactivity of ascorbic acid, in a range of different plant-based foods, is critically evaluated.

2 An Overview of Food Processing Techniques for Fruit and Vegetables

Most fruit and vegetables are perishable after harvest and undergo a progressive loss of quality-related characteristics including reduced nutritional value and changes in organoleptic properties, e.g. colour, taste, appearance, flavour, texture, and palatability. This often results in the post-harvest loss of produce and hence food wastage. The application of food processing technologies to fruit and vegetables is becoming increasingly important as processing can reduce waste and produce plant-based foods of consistent quality. Processing fruit and vegetables can retard the activity of microorganisms that cause spoilage of fresh produce, help to inhibit biochemical reactions that are associated with reduced quality in fresh produce, create product variation in order to improve customer satisfaction, make nutritious plant-based foods that are more convenient for consumers, and enable consumers to access seasonal commodities all-year round.

With respect to processing, fruit and vegetables can be washed, cut, sliced, shredded, juiced or pureed, and then further processed to produce canned, frozen, dried, or preserved products. Depending on the physical characteristics of the fruit or vegetables, the extent of the quality-related changes caused by processing is variable, with some fruit and vegetables being suitable for most food processing techniques, while for others suitable processing techniques are more limited. For example, apples can be processed to produce fresh-cut or dried slices, juice, puree, cider, jam, chutney, marmalade, chips, and canned or frozen products. In contrast, bananas are best when eaten fresh, in a pureed form or as a dried chip, but are not suitable for juicing, canning, or freezing. The high water contents of leafy vegetables e.g. spinach, lettuce, and cucumber mean that they are not suitable for freezing due to the loss of cell turgor and the resultant textural changes that occur upon thawing.

Traditionally, thermal processing techniques such as blanching, canning, and pasteurisation are used by food industries to inactivate enzymes that can cause undesirable quality-related changes and to eliminate microbes that could compromise the safety of processed food products. However, thermal processing may have negative effects on plant-based foods including unwanted changes in colour, softening, loss of flavour, and degradation of heat-sensitive compounds, including ascorbic acid. Since blanching at high temperatures for short times is very effective for enzyme inactivation, fruit and vegetables are often blanched before they are processed into dried or frozen products, which have longer shelf lives. As most fresh fruits and vegetables have high water contents, that can limit their storage life, freeze-drying can also be used to remove water from the plant tissues with minimal degradation of heat-sensitive components. However, frozen food products can experience degradation of some nutrients and texture loss upon thawing.

To better preserve some of the inherent characteristics of fruit and vegetables, novel processing technologies such as pulsed electric fields (PEF) and high hydrostatic pressure processing (HPP) have been developed. These technologies involve non-thermal processing, as they most often involve processing at ambient

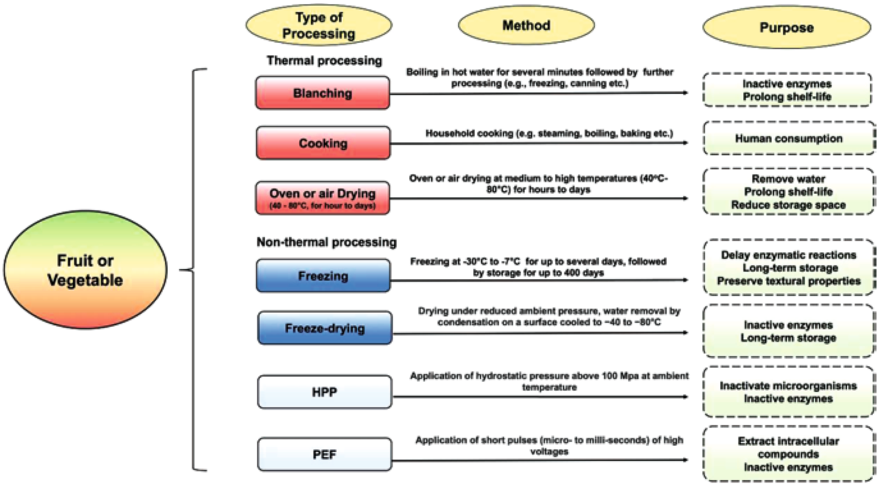

Fig. 1 Summary diagram of the most commonly used processing technologies

temperatures, and have the potential to minimise quality-associated degradation of plant-based foods while still inactivating microorganisms.

In the context of the ascorbic acid content of plant-based foods, it can be expected that each processing step involved in the production of the final product can have consequences on the ascorbic acid content. A processing technique that may appear to be suitable for maintaining the levels of ascorbic acid in a specific fruit or vegetable could exert a negative impact on the ascorbic acid content of a different fruit or vegetable. Therefore, ongoing evaluation of the effects of conventional and novel food processing technologies on the ascorbic acid contents of a wide range of plant-based foods is important. Figure 1 provides a summary of the main processing technologies used in the food industry.

3 The Impact of Conventional Processing on the Levels of Ascorbic Acid in Plant-Based Foods

Ascorbic acid is a labile molecule and the concentration of ascorbic acid often decreases in fruit and vegetables during conventional processing. Tables 1 and 2 summarise the ascorbic acid and total vitamin C contents of selected fresh and processed fruits and vegetables. Food processing techniques are often harsh and the first step in processing usually requires a reduction in size or damage to the fruit or vegetable, e.g. peeling, cutting, or other size-reduction operations. As a result, enzymes are released from their cellular compartments and come into contact with their substrates. This kind of enzyme–substrate interaction can bring about ascorbic acid oxidation and degradation.

Table 1 Ascorbic acid and total vitamin C (mg/kg fresh weight) contents of selected fresh and processed fruits

Fruit	Fresh or processed	Processing parameters	Country	Ascorbic acid (retention %)[a]	Total vitamin C (retention %)	With (+) or without (−) skin and or/ seeds	References
				mg/kg fresh weight unless specified			
Apple	Fresh		China	<50	60	+/+	Szeto et al. (2002)
			China	–	45–48	+/−	Zhang and Zhang (2014)
			UK	–	60	+/+	Proteggente et al. (2002)
			Nigeria	218	–	−/+	Achinewhu (1983)
			Germany	–	108	Unknown	Taiwo et al. (2001)
			Canada	–	1124.3[b]	+/−	Joshi et al. (2011)
	Juice	Wash, slice, and then press	Korea	67	–	–	Kim et al. (2012)
	Juiced + heated	Fresh pressed juice heat at 85 °C for 1 min	Korea	6 (9%)	–	–	Kim et al. (2012)
	Blanched	60 °C for 5 min	Germany	–	ND	+/−	Taiwo et al. (2001)
	Dried	Air dried at 47 °C for 7 h	Canada	–	555.3[b] (50%)[a]	+/−	Joshi et al. (2011)
		Oven dried at 70 °C for 10 h		–	781.4[b] (70%)	+/−	
		Vacuum dried at 20 °C for 24 h		–	1109.1[b] (99%)	+/−	
	Microwave treated	90 W for 25 s	China	–	43–45 (95–97%)	+/−	Zhang and Zhang (2014)

(continued)

Table 1 (continued)

Fruit	Fresh or processed	Processing parameters	Country	Ascorbic acid (retention %) [a]	Total vitamin C (retention %)	With (+) or without (−) skin and or/ seeds	References
				mg/kg fresh weight unless specified			
Apple	Frozen	−28 °C, overnight	Germany	–	41 (38%)	+/−	Taiwo et al. (2001)
	HPP	400 MPa for 10 min at 25 °C	Germany	–	103 (95%)	+/−	Taiwo et al. (2001)
	Juice + HPP	Fresh pressed juice treated at 500 MPa, 25 °C for 3 min	Korea	64 (96%)	–	–	Kim et al. (2012)
	PEF	1.4 kV/cm, specific energy 154 J/kg	Germany	–	74 (69%)	+/−	Taiwo et al. (2001)
Avocado	Fresh		Nigeria	260	–	−/−	Achinewhu (1983)
	Roasted	5 min	Nigeria	146 (56%)	–	−/−	
	Boiled	5 min	Nigeria	109 (42%)	–	−/−	
Apricot	Fresh		New Zealand	10^b	40^b	−/−	Leong and Oey (2012b)
	Heated	98 °C, 1:5 food/water, for 10 min	New Zealand	0^b (0%)	60^b (150%)	−/−	
	Frozen	Frozen in liquid nitrogen, then frozen at −20 °C	New Zealand	10^b (100%)	90^b (225%)	−/−	
	Freeze-dried	Frozen in liquid nitrogen, then freeze-drying for 48 h	New Zealand	10^b (100%)	20^b (50%)	−/−	

Banana (ripe)	Fresh		UK	–	100	–/–	Proteggente et al. (2002)
			USA	153	190	–/–	Vanderslice et al. (1990)
			China	–	110	–/–	Szeto et al. (2002)
			Malawi	–	130	–/–	Masamba et al. (2013)
	Dried	40–45 °C, humidity (25–45%), 10–16 h	Malawi		37.4 (29%)	–/–	Masamba et al. (2013)
		60 °C for 10 min	Nigeria	100.5 (NA)	–	–/–	Taiwo and Adeyemi (2009)
	Blanched + dried	60 °C blanching + 60 °C drying	Nigeria	99.2 (NA)	–	–/–	Taiwo and Adeyemi (2009)
Banana (unripe)	Fresh		Unknown	17–23	–	–/–	Belayneh et al. (2014)
	Fried	170 °C for 4 min	Unknown	11–17 (65–74%)	–	–/–	
Cherry	Fresh		New Zealand	50^b	90^b	–/–	Leong and Oey (2012b)
	Heated	98 °C, 1:5 food/water, for 10 min	New Zealand	10^b (20%)	120^b (133%)	+/–	
	Frozen	Frozen in liquid nitrogen, then frozen at −20 °C	New Zealand	10^b(20%)	210^b (233%)	+/–	
	Freeze-dried	Frozen in liquid nitrogen, then freeze-drying for 48 h	New Zealand	0^b (0%)	60^b (67%)	+/–	

(continued)

Table 1 (continued)

Fruit	Fresh or processed	Processing parameters	Country	Ascorbic acid (retention %) [a]	Total vitamin C (retention %)	With (+) or without (−) skin and or/ seeds	References
				mg/kg fresh weight unless specified			
Lemon	Fresh		China	420	580	−/−	Szeto et al. (2002)
			Romania	–	410–470	−/−	Simion et al. (2008)
	Oven dried	30 °C for 5 h	Romania	–	420 (95%)	−/−	Simion et al. (2008)
		80 °C for 5 h		–	74 (17%)	−/−	
	Frozen + thawed	−6 °C for 2 days	Romania	–	432 (98%)	−/−	Simion et al. (2008)
	Freeze-dried	Unknown	Romania	–	411 (93%)	−/−	Simion et al. (2008)
Blue Berry	Fresh		Unknown	–	7650[b]	+/+	Arancibia-Avila et al. (2012)
			Chile	210[b]	–	+/+	López et al. (2010)
	Oven heated	100 °C for 60 min	Poland	–	4330[b] (57%)	+/+	Arancibia-Avila et al. (2012)

Blue Berry	Dried	80 °C until constant weight achieved	Chile	17^b (8%)	–	+/+	López et al. (2010)
	Juice	Washed, pressed, centrifuged at 4000 × *g* for 15 min, fresh	Germany	163	–	–	Barba et al. (2012)
		Washed, pressed, centrifuged at 4000 × *g* for 15 min, stored at 4 °C for 56 days	Germany	81 (50%)	–	–	
	Juice + HPP	HPP: (600 MPa, for 5 min, from 25 to 45 °C	Germany	155 (95%)	–	–	Barba et al. (2012)
		HPP: (600 MPa, for 5 min, from 25 to 45 °C); stored at 4 °C for 56 days	Germany	112 (69%)	–	–	
	Juice + PEF	PEF: (36 kV/cm, 100 µs, pulse width 3 µs)	Germany	158 (97%)	–	–	Barba et al. (2012)
		PEF: (36 kV/cm, 100 µs, pulse width 3 µs) stored at 4 °C for 56 days	Germany	82 (50%)	–	–	
Kiwi fruit	Fresh		China	520	590	–/+	Szeto et al. (2002)
			Italy	–	300–500	–/+	Tavarini et al. (2008)
			Turkey	–	2321.8	–/+	Kayaa et al. (2010)
	Dried	35 °C, humidity 85%	Turkey	–	1176.5 (51%)	–/+	Kayaa et al. (2010)
		65 °C, humidity 40%		–	274.47 (12%)	–/+	

(continued)

Table 1 (continued)

Fruit	Fresh or processed	Processing parameters	Country	Ascorbic acid (retention %) [a]	Total vitamin C (retention %)	With (+) or without (−) skin and or/ seeds	References
				mg/kg fresh weight unless specified			
Strawberry	Fresh		China	540	770	+/+	Szeto et al. (2002)
			UK	–	610	+/+	Proteggente et al. (2002)
			Ireland	6331^b	–	+/+	Patras et al. (2009a, b)
	Air-dried	48.9 °C for 88 h	USA	36–53 (NA)	–	+/+	Asami et al. (2003)
	Blanched	70–80 °C	Ireland	4691^b (74%)	–	+/+	Patras et al. (2009a, b)
	Frozen	−25 °F for 10 min	USA	271–326 (unknown %)	–	+/+	Asami et al. (2003)
	Freeze-dried	−45 °C, 20–22 h	USA	98–144 (unknown %)	–	+/+	Asami et al. (2003)
	HPP	600 MPa	Ireland	5991^b (95%)	–	+/+	Patras et al. (2009a, b)
Mango	Fresh		China	210	370	−/−	Szeto et al. (2002)
			Nigeria	980	–	−/−	Achinewhu (1983)
			Malawi	–	260	−/−	Masamba et al. (2013)
	Dried	40–45 °C, humidity (25–45%), 10–16 h	Malawi	–	50.8 (20%)	−/−	Masamba et al. (2013)

Pineapple	Fresh		China	100	325	–/–	Szeto et al. (2002)
			Nigeria	335	–	–/–	Achinewhu (1983)
			Malawi	–	325	–/–	Masamba et al. (2013)
	Dried	40–45°C, humidity (25–45%), 10–16 h	Malawi	–	65.2 (20%)	–/–	Masamba et al. (2013)
Green Grape	Fresh		China	20	30	+/–	Szeto et al. (2002)
			UK		20	+/+	Proteggente et al. (2002)
Red Grape	Fresh		China	<10		+/–	Szeto et al. (2002)

(continued)

Table 1 (continued)

Fruit	Fresh or processed	Processing parameters	Country	Ascorbic acid (retention %)[a]	Total vitamin C (retention %)	With (+) or without (−) skin and or/ seeds	References
				mg/kg fresh weight unless specified			
Orange	Fresh		China	330	540	−/−	Szeto et al. (2002)
			UK	–	460	−/+	Proteggente et al. (2002)
			Nigerian	483	–	−/−	Achinewhu (1983)
			USA	547–750	630–830	−/−	Vanderslice et al. (1990)
			Nigeria	–	611.8	−/−	Bello and Fowoyo (2014)
	Juice	Fresh pressed	Spain	–	563	–	Elez-Martínez and Martín-Belloso (2007)
		Fresh pressed	Spain	409	444	–	Sánchez-Moreno et al. (2005)
	Juice + PEF	15 kV/cm, 200 Hz, 4 μs length	Spain	–	(98.2%)	–	Elez-Martínez and Martín-Belloso (2007)
		35 kV/cm, for 750 μs	Spain	378 (92%)	413 (93%)	–	Sánchez-Moreno et al. (2005)
	Juice + HPP	400 MPa, 40 °C, 1 min	Spain	36.9 (90%)	42.8 (96%)		Sánchez-Moreno et al. (2005)
Guava (white)	Fresh		Nigeria	675	–	+/+	Achinewhu (1983)

Guava (white)	Puree	Fresh pressed	China	1800	–	–	Yen and Lin (1996)
	Puree + heated	Heat: 88–90 °C for 24 s	China	1800 (100%)	–	–	Yen and Lin (1996)
	Puree + HPP	HPP: 600 MPa, 25 °C, for 15 min	China	1800 (100%)	–	–	Yen and Lin (1996)
Pear	Fresh		China	<10	60	+/–	Szeto et al. (2002)
			UK		30	+/+	Proteggente et al. (2002)
Peach	Fresh		UK	–	60	+/+	Proteggente et al. (2002)
Papaya	Fresh		Nigeria	518	–	+/+	Achinewhu (1983)
Chinese pear	Fresh		China	<10	–	+/–	Szeto et al. (2002)
Raspberry	Fresh		UK	–	260	+/+	Proteggente et al. (2002)
			Spain	–	311	+/+	de Ancos et al. (2000)
Raspberry	Frozen	−80 °C for 15 min	Spain	–	320 (103%)	+/+	de Ancos et al. (2000)
		−80 °C for 15 min; then −20 °C for 90 days		–	243 (76%)	Unknown	
		−80 °C for 15 min; then −20 °C for 180 days		–	192 (60%)	Unknown	

(continued)

Table 1 (continued)

Fruit	Fresh or processed	Processing parameters	Country	Ascorbic acid (retention %) [a]	Total vitamin C (retention %)	With (+) or without (−) skin and or/ seeds	References
				mg/kg fresh weight unless specified			
Grapefruit	Fresh		UK	–	520	−/+	Proteggente et al. (2002)
			China	390	360	−/−	Szeto et al. (2002)
			USA	213	240	−/−	Vanderslice et al. (1990)
Persimmon	Fresh		China	–	80	+/−	Szeto et al. (2002)
Mandarin	Fresh		China	–	240	−/−	Szeto et al. (2002)
Cantaloupe	Fresh		USA	313	340	−/−	Vanderslice et al. (1990)
Watermelon	Fresh		USA	80	100	−/−	Vanderslice et al. (1990)
	Juice	Chopped and filtered using a steel sieve with an approximate mesh of 2 mm	Spain	26	–	−/−	Oms-Oliu et al. (2009)
Watermelon	Juice + PEF	Chopped and filtered using a steel sieve with an approximate mesh of 2 mm; juice treated at 35 kV/cm, 7 μs pulse length, 200 Hz	Spain	19 (72%)	–	−/−	Oms-Oliu et al. (2009)

Peppers, green	Fresh		USA	1290	1340	+/–	Vanderslice et al. (1990)
			NA	885.0	–		Castro et al. (2008)
			Japan	767	708	+/–	Chuah et al. (2008)
	Blanched	98 °C, 2.5 min	NA	440–460 (50–52%)	–	+/–	Castro et al. (2008)
	Boiled	30 min	Japan	~400 (52%)	–	+/–	Chuah et al. (2008)
	Stir-fried	5 min	Japan	~550 (72%)	–	+/–	Chuah et al. (2008)
	Microwave	30 min	Japan	~640 (83%)	–	+/–	Chuah et al. (2008)
	HPP	200 MPa, 20 min	NA	720–750 (81–84%)	–	+/–	Castro et al. (2008)

(continued)

Table 1 (continued)

Fruit	Fresh or processed	Processing parameters	Country	Ascorbic acid (retention %)[a]	Total vitamin C (retention %)	With (+) or without (−) skin and or/ seeds	References
				mg/kg fresh weight unless specified			
Peppers, red	Fresh		USA	1510	1550	+/−	Vanderslice et al. (1990)
			NA	1074	–	+/−	Castro et al. (2008)
			Japan	1446	–	+/−	Chuah et al. (2008)
	Blanched	98 °C, 2.5 min	NA	620–650 (58–61%)	–	+/−	Castro et al. (2008)
	Boiled	30 min	Japan	~850 (59 %)	–	+/−	Chuah et al. (2008)
	Stir-fried	5 min	Japan	~1240 (86%)	–	+/−	Chuah et al. (2008)
	Microwave	30 min	Japan	~1250 (86%)	–	+/−	Chuah et al. (2008)
	HPP	200 MPa, 20 min	NA	1230–1250 (115–116%)	–	+/−	Castro et al. (2008)

Tomato	Fresh		UK	–	180	+/+	Proteggente et al. (2002)
			Israel	120–160	–	+/+	Stevens et al. (2008)
			USA	–	133	+/+	Dewanto et al. (2002)
			USA	106	140	+/+	Vanderslice et al. (1990)
			USA	4339^b	–	+/+	Horuz et al. (2017)
			Italy	185^b	–	+/+	Zanoni et al. (1998)
			China	~700^b		+/+	Chang et al. (2006)
	Heated	80 °C, 30 min	USA	–	95(71%)	+/+	Dewanto et al. (2002)
	Microwave	120 W, until constant weight	Turkey	1209.7^b (28%)	–	+/+	Horuz et al. (2017)
	Dried	80 °C, air flow 1.5 m/s, 190 min	Italy	106^b (57%)		+/+	Zanoni et al. (1998)
		110 °C, air flow 1.5 m/s, 190 min		Not detected (0%)		+/+	
	Freeze-dried	−50 °C, 5 Pa, 24 h	China	~630^b (90%)		+/+	Chang et al. (2006)

(continued)

Table 1 (continued)

Fruit	Fresh or processed	Processing parameters	Country	Ascorbic acid (retention %)[a]	Total vitamin C (retention %)	With (+) or without (−) skin and or/ seeds	References
				mg/kg fresh weight unless specified			
Tomato	Puree	Vacuum mixed at 500 rpm, 1 °C	Ireland	2048	–	+/+	Patras et al. (2009a, b)
	Puree + thermal	Vacuum mixed at 500 rpm, 1 °C; then heat at 70 °C for 2 min	Ireland	1250 (61%)	–	+/+	Patras et al. (2009a, b)
	Puree + HPP	Vacuum mixed at 500 rpm, 1°C; then treat at 600 MPa at 20 °C for 15 min	Ireland	1921 (94%)	–	+/+	Patras et al. (2009a, b)
	Juice	Blending at high speed 10 s	China	186	210	+/+	Hsu et al. (2008)
		Chopped and then filtered through steel sieves 2 mm in diameter	Spain	152	–	+/+	Odriozola-Serrano et al. (2007)
	Juice + thermal	Fresh prepared juice treated at 92 °C for 2 min, then 98 °C for 15 min, cooled at 0 °C for 2 min, stored at 4 °C for 0 h	China	70 (38%)	88 (42%)	+/+	Hsu et al. (2008)
		Fresh prepared juice treated at 92°C for 2min, then 98°C for 15 min, cooled at 0 °C for 2 min, stored at 4°C for 28 days		55 (30%)	70 (33%)	+/+	
	Juice + HPP	Fresh prepared juice treated at 500 MPa, 25 °C for 10 min, stored at 4 °C for 0 days	China	142 (76%)	151 (72%)	+/+	Hsu et al. (2008)
		Fresh prepared juice treated at 500 MPa, 25 °C for 10 min, stored at 4 °C for 28 days		137 (74%)	147 (70%)	+/+	

Tomato	Juice + PEF	Fresh pressed juice treated at 35 kV/cm, 1 μs pulse duration, 250 HZ	Spain	137 (90%)	–	+/+	Odriozola-Serrano et al. (2007)

HPP high pressure processed, *PEF* pulsed electric field processed

[a] Data in bracket represent the value of the retention of ascorbic acid/total vitamin C after processing

[b] Data were presented as mg of ascorbic acid/vitamin C per kg of dried samples

Table 2 Ascorbic acid and total vitamin C (mg/kg fresh weight) contents of selected fresh and processed vegetables

Vegetables	Fresh/processing	Processing parameter	Country of the study conducted	Ascorbic acid (retention %)^a	Total vitamin C (retention %)	Reference
				mg/kg fresh weight unless specified		
Broccoli	Fresh		USA	890	970	Vanderslice et al. (1990)
			Poland	1160	–	Lisiewska and Kmiecik (1996)
			Spain	–	1120	Murcia et al. (2000)
			UK	–	450	Proteggente et al. (2002)
			Turkey	–	681.8	Tosun and Yücecan (2008)
			Romania	–	344.5	Balan et al. (2016)
			Italy	1500^b	–	Severini et al. (2016)
			Italy	8020^b	–	Pellegrini et al. (2010)
	Blanched	96 °C for 170 s	Turkey	–	551.6 (78%)	Tosun and Yücecan (2008)
		92–96 °C for 150 s	Spain	–	550 (49%)	Murcia et al. (2000)
		100 °C for 30 s	Italy	1250^b (83%)	–	Severini et al. (2016)
		100 °C for 60 s		850^b (57%)	–	
		100 °C for 180 s		620^b (41%)	–	
	Blanched + frozen	Blanching at 98 °C for 3 min, frozen at 30 °C for 12 months	Poland	569 (49%)	–	Lisiewska and Kmiecik (1996)

Broccoli	Steamed	Unknown	Italy	5755^b (68%)	–	Miglio et al. (2007)
		100 °C for 30 s	Italy	1150^b (77%)	–	Severini et al. (2016)
		100 °C for 60 s		980^b (65%)	–	
		100 °C for 180 s		700^b (47%)	–	
		Oven steaming, 13 min	Italy	6435^b (80%)	–	Pellegrini et al. (2010)
	Boiled	5 min	USA	370 (42%)	400 (41%)	Vanderslice et al. (1990)
		10 min	Romania	–	161.8 (49%)	Balan et al. (2016)
		Unknown	Italy	4376^b (52%)	–	Miglio et al. (2007)
		1:5, food/water; 8 min	Italy	6450^b (80%)	–	Pellegrini et al. (2010)
	Canned	121 °C for 30 min	Spain	–	180 (16%)	Murcia et al. (2000)
	Microwave	2450 MHz, 900 W for 40 s	Italy	1760^b (117%)	–	Severini et al. (2016)
		2450 MHz, 900 W for 60 s		1400^b (93%)	–	
		2450 MHz, 900 W for 80 s		1600^b (107%)	–	
		2450 Hz, 300 W for 17 min	Italy	133 (2%)		Pellegrini et al. (2010)
		High heat, 6 min	USA	1110 (124%)	1160 (119%)	Vanderslice et al. (1990)

(continued)

Table 2 (continued)

Vegetables	Fresh/processing	Processing parameter	Country of the study conducted	Ascorbic acid (retention %)^{a}	Total vitamin C (retention %)	Reference
				mg/kg fresh weight unless specified		
Broccoli	Fried	Frying at 170 °C	Italy	1133^{b} (13%)	–	Miglio et al. (2007)
	Frozen + boiled	Boiling for 5 min	USA	210 (23%)	230 (23%)	Vanderslice et al. (1990)
	Frozen	6 months	Turkey	–	532.6 (78.1%)	Tosun and Yücecan (2008)
		Unknown	USA	537 (60%)	560 (58%)	Vanderslice et al. (1990)
Brussels sprouts	Fresh		Italy	10969^{b}	–	Pellegrini et al. (2010)
			Argentina	964	–	Vina et al. (2007)
	Blanched	100 °C, for 1 min	Argentina	964 (100%)	–	Vina et al. (2007)
		100 °C, for 4 min		732 (76%)	–	
		50 °C, for 5 min		780 (89%)	–	
	Boiled	1:5, food/water; 10 min	Italy	6077^{b} (55%)	–	Pellegrini et al. (2010)
	Steamed	Oven steaming, 17 min	Italy	8370^{b} (76%)	–	Pellegrini et al. (2010)
	Microwave	2450 Hz, 300 W for 18 min	Italy	3851^{b}(35%)	–	Pellegrini et al. (2010)
		700 W for 5 min	Argentina	1156 (120%)		Vina et al. (2007)
Cucumber	Fresh		USA	103	140	Vanderslice et al. (1990)
			Japan	–	98	Matsufuji et al. (2009)

Cabbage	Fresh		USA	423	420	Vanderslice et al. (1990)
			Poland	725	–	Podsędek et al. (2008)
	Boiled	15 min	USA	244 (58%)	240 (58%)	Vanderslice et al. (1990)
		1:2 food to water ratio, for 20 min	Poland	237.4 (33%)	–	Podsędek et al. (2008)
		1:1 food to water ratio, for 20 min		336.1 (46%)	–	
	Steamed	100 °C, for 5 min	Poland	615 (85%)	–	Podsędek et al. (2008)
		100 °C, for 20 min		563 (78%)	–	
Carrots	Fresh		USA	47	70	Vanderslice et al. (1990)
			Japan	–	22	Matsufuji et al. (2009)
	Boiled	Unknown	Italy	281^b (91%)	–	Miglio et al. (2007)
	Steamed	Unknown	Italy	192^b (62%)	–	Miglio et al. (2007)
	Fried	Frying at 170 °C	Italy	Not detected	–	Miglio et al. (2007)
Celery	Fresh		Japan	–	59	Matsufuji et al. (2009)

(continued)

Table 2 (continued)

Vegetables	Fresh/processing	Processing parameter	Country of the study conducted	Ascorbic acid (retention %)^a	Total vitamin C (retention %)	Reference
				mg/kg fresh weight unless specified		
Cauliflower	Fresh		UK	–	150	Proteggente et al. (2002)
			USA	540	630	Vanderslice et al. (1990)
			Poland	647	–	Lisiewska and Kmiecik (1996)
			Italy	11945^b	–	Pellegrini et al. (2010)
	Boiled	1:5, food/water; 10 min	Italy	6919^b (58%)	–	Pellegrini et al. (2010)
	Steamed	Oven steaming, 17 min	Italy	5865^b (49%)	–	Pellegrini et al. (2010)
	Microwave	2450 Hz, 300 W for 30 min	Italy	629^b(5%)	–	Pellegrini et al. (2010)
	Blanched + frozen	Blanching at 98 °C for 3 min; frozen at 30 °C for 12 months	Poland	440 (68%)	–	Lisiewska and Kmiecik (1996)
Corn	Frozen	−26 °F	USA	21–35 (AN)	–	Asami et al. (2003)
	Freeze-dried	−45 °F for 20–24 h	USA	ND	–	
	Air-dried	48.9 °C for 20–25 h	USA	ND	–	
Beans	Fresh		USA	100	120	Vanderslice et al. (1990)
	Boiled	Boiled for10 min	USA	67 (67%)	80 (67%)	
	Frozen	Unknown	USA	190 (NA)	220 (NA)	
	Frozen + boiled	Boiled for 10 min	USA	93 (93%)	120 (100%)	

Fennel	Thermal + extracted Juice	90 °C, for 80 min	France	~135		El-Belghiti et al. (2008)
	PEF + extracted Juice	0.4 kV/cm, 450 pulses	France	~335		
Green beans	Fresh		Turkey	–	115	Tosun and Yücecan (2008)
			Romania	–	152.0	Balan et al. (2016)
	Blanched	94–96 °C for 2.5 min	Turkey	–	84.1 (73%)	Tosun and Yücecan (2008)
	Boiled	10 min	Romania	–	84.5 (56%)	Balan et al. (2016)
Leek	Fresh		UK	–	160	Proteggente et al. (2002)
Lettuce	Fresh		UK	–	<20	Proteggente et al. (2002)
			USA	33	60	Vanderslice et al. (1990)
			Japan	–	44	Matsufuji et al. (2009)
Mustard green	Fresh		USA	362	360	Vanderslice et al. (1990)
	Boiled	100 °C for 1 h	US	48 (13%)	50 (14%)	
Onion	Fresh		UK	–	60	Proteggente et al. (2002)
			Japan	–	36	Matsufuji et al. (2009)

(continued)

Table 2 (continued)

Vegetables	Fresh/processing	Processing parameter	Country of the study conducted	Ascorbic acid (retention %)[a]	Total vitamin C (retention %)	Reference
				mg/kg fresh weight unless specified		
Peas	Fresh		UK	–	220	Proteggente et al. (2002)
			Turkey	–	286.3	Tosun and Yücecan (2008)
			Romania	–	212.0	Balan et al. (2016)
	Boiled	10 min	Romania	–	107.6 (51%)	Balan et al. (2016)
	Blanched	94–96 °C for 2.5 min	Turkey	–	208 (73%)	Tosun and Yücecan (2008)
	Frozen	Unknown	Turkey	–	203.1 (71%)	Tosun and Yücecan (2008)
Potato	Fresh		USA	77	130	Vanderslice et al. (1990)
			Turkey	–	224.9	Tosun and Yücecan (2008)
	Peeled		Turkey	–	199.9 (89%)	Tosun and Yücecan (2008)
	Washed		Turkey	–	168.8 (75%)	Tosun and Yücecan (2008)
	Blanched	94–96 °C for 2.5 min	Turkey	–	132.9 (59%)	Tosun and Yücecan (2008)
	Boiled	25 min	USA	83 (107%)	100 (76%)	Vanderslice et al. (1990)
	Baked	240 °C for 1 h	USA	97 (126%)	240 (185%)	Vanderslice et al. (1990)

Spinach	Fresh		UK	–	70	Proteggente et al. (2002)
			USA	520	520	Vanderslice et al. (1990)
			Turkey	–	1108.7	Tosun and Yücecan (2008)
			Romania	–	353.7	Balan et al. (2016)
	Washed		Turkey	–	936.1 (85%)	Tosun and Yücecan (2008)
	Blanched	95 °C for 140 s	Turkey	–	766.8 (69%)	Tosun and Yücecan (2008)
	Boiled	1 min	US	196 (38%)	200 (38%)	Vanderslice et al. (1990)
		5 min	Romania		206.9 (58%)	Balan et al. (2016)
	Microwave	3–5 min	USA	483 (93%)	540 (104%)	Vanderslice et al. (1990)
	Frozen	Unknown	USA	220 (42%)	250 (48%)	Vanderslice et al. (1990)
		−18 °C for 3–6 months	Turkey	–	705.3 (64%)	Tosun and Yücecan (2008)
Indian Spinach	Fresh		Nigeria	–	224	Babalola et al. (2010)
	Sun dried	Drying under the sun until crispy texture achieved	Nigeria	–	208 (93%)	
Water leaf	Fresh		Nigeria	5470[b]	–	Adefegha and Oboh (2011)
	Steamed	10 min	Nigeria	1982[b] (36%)	–	
Wild basil	Fresh		Nigeria	8420[b]	–	Adefegha and Oboh (2011)
	Steamed	10 min	Nigeria	6384[b] (76%)	–	

(continued)

Table 2 (continued)

Vegetables	Fresh/processing	Processing parameter	Country of the study conducted	Ascorbic acid (retention %)[a]	Total vitamin C (retention %)	Reference
				mg/kg fresh weight unless specified		
Ewuro-odo	Fresh		Nigeria	–	522	Oboh (2005)
	Boiled	1:1 food/water for 5 min	Nigeria	–	169 (32%)	
Efinrin	Fresh		Nigeria	–	520	Oboh (2005)
	Boiled	1:1 food/water for 5 min	Nigeria	–	273 (52%)	
Water cress	Fresh		Portugal	367	–	Gonçalves et al. (2009)
	Blanched	95 °C, for 20 s	Portugal	406	–	
	Frozen	Frozen at −40 °C until the food reach −25 °C, then stored at −7 °C for 400 days	Portugal	20 (5%)	–	
		Frozen at −40 °C until the food reach −25 °C, then stored at −15 °C for 400 days		28 (7%)	–	
		Frozen at −40 °C until the food reach −25 °C, then stored at −30 °C for 400 days		97 (24%)	–	

HPP high pressure processed, *PEF* pulsed electric field treated

[a] Data in bracket represent the value of the retention of ascorbic acid/total vitamin C after processing

[b] Data were presented as mg of ascorbic acid/vitamin C per kg of dried samples

During processing, the oxidation of biological-active L-ascorbic acid (L-AA) can be enhanced by enzyme catalysis, with ascorbic acid oxidase (AAO, EC 1.10.3.3) and ascorbic acid peroxidase (APX, EC 1.11.1.11) being the main families of enzymes involved in L-AA oxidation (Hancock and Viola 2005). AAO catalyses the oxidation of L-AA in the presence of oxygen (De Tullio et al. 2007), while APX catalyses the reduction of hydrogen peroxide with L-AA functioning as a cofactor (Noctor and Foyer 1998). Both enzymatic reactions result in the transfer of an electron from L-AA, leading in the formation of the partially oxidised monodehydro-L-ascorbic acid (MDHA) radical. MDHA then disproportionates spontaneously to form the fully oxidised molecular species dehydro-L-ascorbic acid (DHA). DHA is relatively unstable and can rapidly undergo irreversible hydrolysis to form 2,3-diketo-L-gulonic acid (2,3-DKG), with a consequent loss of potential biological activity. Therefore, it is important to minimise and prevent the oxidation of L-AA to DHA during food processing through efficient inactivation of both AAO and APX.

3.1 Heat Treatment

Heat treatment is the most widely applied food processing technology. Heat treatment helps to ensure long-term storage and stabilises some of the quality attributes of fresh fruit and vegetable products, by killing microorganisms and through the inactivation of endogenous enzymes. Since ascorbic acid is known to be the most labile and temperature-sensitive vitamin (Lee and Kader 2000), it is necessary to optimise any heat treatment conditions to sufficiently inactivate ascorbic acid degrading enzymes while ensuring optimum L-AA retention in plant-based foods. Conventional heat treatments are used for a wide range of fruit and vegetables and include domestic cooking, blanching, and drying.

3.1.1 Cooking

Domestic cooking can result in the loss of ascorbic acid, the extent of which depends upon the cooking method used. A study on the effect of three common cooking methods (boiling, steaming, and frying) on carrots and broccoli showed that frying caused the greatest loss of ascorbic acid (>80%), while boiling and steaming resulted in losses of up to 10% and 40% ascorbic acid, respectively (Miglio et al. 2007). With respect to boiling, reducing the volume of cooking water by half can minimise the amount of ascorbic acid leaching out of the plant produce (Podsędek et al. 2008), and reducing the cooking time results in better preservation of ascorbic acid (Castro et al. 2008; Severini et al. 2016). Steaming has been recognised as the gentlest cooking method and leads to minimal ascorbic acid loss in most vegetables, e.g. broccoli (Severini et al. 2016), cabbage (Podsędek et al. 2008), and tropical green leafy vegetables (Adefegha and Oboh 2011).

Microwave ovens have gained popularity for domestic cooking as they provide convenience, with more homogeneous heating (a greater penetration depth) and shorter cooking times than conventional ovens (Chandrasekaran et al. 2013). However, the impact of microwave cooking on plant produce has been shown to be variable. Microwaved peppers and apples retain more ascorbic acid than stir-fried or boiled peppers (Chuah et al. 2008; Zhang and Zhang 2014), while in contrast microwave cooking resulted in less ascorbic acid retention than conventional cooking for broccoli, cauliflower, and Brussels sprouts with the loss of 98% of the ascorbic acid found in raw produce (Pellegrini et al. 2010). This effect was attributed to water loss during microwave heating that resulted in the concurrent loss of water-soluble nutrients, including ascorbic acid (Pellegrini et al. 2010).

3.1.2 Blanching

Blanching, exposure to boiling hot water for a short time, is a relatively mild heat treatment often used during the processing of fruits and vegetables. Blanching is highly effective at inactivating enzymes and is commonly used as a step in the processing line for the production of frozen, and canned fruit and vegetable products. Blanching can greatly reduce (by at least 50%) the ascorbic acid content of various fruits and vegetables (Tables 1 and 2), including strawberries (Patras et al. 2009a), broccoli (Severini et al. 2016), and several green leafy vegetables (Oboh 2005). The lower levels of ascorbic acid and total vitamin C in fruits and vegetables after blanching is predominantly due to thermal degradation of temperature-sensitive ascorbic acid, but can also be due to leaching of ascorbic acid from the plant tissues into the blanching medium. Ascorbic acid losses can be minimised by blanching with steam instead of immersion in hot water (Severini et al. 2016), or by microwave blanching (Vadivambal and Jayas 2007).

By carefully optimising both temperature and blanching time, it is possible to better preserve the ascorbic acid contents of a wide range of fruit and vegetables, e.g. optimal conditions for maximal retention of ascorbic acid in red peppers are 70 °C for 1 min (Castro et al. 2008), carrots are 95 °C for 5 min (Shivhare et al. 2009), and Brussels sprouts are 100 °C for 1 min (Vina et al. 2007). Blanching fruits and vegetables at optimised temperature and time combinations is very effective at inactivating L-AA oxidising enzymes, e.g. AAO, and minimises the thermal degradation of ascorbic acid and total vitamin C (Munyaka et al. 2010; Wawire et al. 2011; Leong and Oey 2012a). In addition, optimised blanching treatments can be used to inactivate other enzymes, such as peroxidases and catalases, which can negatively influence product quality (Shivhare et al. 2009).

3.1.3 Drying

Dehydrated fruits and vegetables can be produced by drying fresh produce under the sun or by using a hot air dryer, or conventional or microwave oven (Santos and Silva 2008). As fruit and vegetables have high water contents (80% or more) and when fully hydrated are metabolically active, removal of most of this water stops metabolic activity, extends shelf life, and can reduce storage space and packaging costs. Drying can also be used to produce products with a crispy texture. However, many nutrients are sensitive to heat, light, and oxygen, and experience oxidative degradation and heat damage during the dehydration process. Drying at high temperatures, for a long time, with constant exposure to oxygen causes degradation of ascorbic acid in fruit and vegetables (Sablani 2006). However, degradation can be reduced by optimising the drying temperature, duration of drying and airflow (Santos and Silva 2008).

For blueberries (López et al. 2010), tomatoes (Zanoni et al. 1998), and red bell peppers (Di Scala and Crapiste 2008), slow drying results in more ascorbic acid degradation than rapid drying. Ascorbic acid oxidation during drying can also be minimised by pre-soaking fruit or vegetables in a concentrated sugar or salt solution. This drying method is known as osmotic dehydration and has been widely used for processing fruit, as it helps to prevent oxygen penetrating into the tissues during drying (Torreggiani and Bertolo 2001). Vacuum drying is a method that can be used to reduce oxidation of nutrients as drying is conducted in a reduced oxygen environment. Vacuum drying has been shown to prevent ascorbic acid loss in apple slices dried for 24 h at 20 °C (Joshi et al. 2011). Pre-drying treatments, such as blanching or freezing, of fresh produce prior to drying can be used to inactivate oxidative enzymes and can also help to minimise ascorbic acid losses during drying (Lewicki 1998).

3.2 Freezing

Freezing can delay the enzymatic reactions that affect the stability of nutrients and is well suited for the long-term storage of many fruits and vegetables. In general, the freezing process has only a slight effect on total vitamin C levels in fruit and vegetables, with losses dependent upon the freezing rate. Most total vitamin C losses in frozen fruit and vegetables occur during prolonged storage and during thawing, due to oxidative breakdown. Factors that influence breakdown include storage duration, temperature fluctuations during storage, thawing rate, and thawing method. For example, frozen raspberry fruits stored for 180 days at −20 °C retain only 40% of initial ascorbic acid levels (de Ancos et al. 2000). The rate of ascorbic acid and total vitamin C loss is often dependent upon the fruit or vegetable, e.g. leafy vegetables such as spinach that have large surface areas and lose more ascorbic acid than frozen green peas and okra that have lower surface area to volume ratios (Giannakourou and Taoukis 2003). To improve ascorbic acid retention in frozen products, destined for long-term storage, a pre-blanching step is often used prior to freezing to inactivate oxidative enzymes and ensure better preservation of nutrients. Blanching watercress for 20 s at 95 °C prior to freezing and storage (400 days, at temperatures of −7, −15, and −30 °C) has been reported to stabilise ascorbic acid levels (Gonçalves et al. 2009).

3.2.1 Freeze-Drying

Dehydration by freeze-drying is widely used for fruit and in contrast to drying at elevated temperatures is based upon the direct phase transition of ice to water vapour (sublimation), without an intermediate liquid phase. Due to the lack of a liquid phase and the low temperatures required for the drying process, undesirable enzymatic reactions can be avoided and hence the ascorbic acid contents of freeze-dried fruit are generally higher than in heat dried fruit. Previous studies have shown that freeze-dried tomatoes (Chang et al. 2006) and summer fruits (Leong and Oey 2012b) have ascorbic acid levels similar to those found in fresh fruit.

4 The Potential for Novel Processing Techniques to Maintain Ascorbic Acid Levels in Plant-Based Foods

Recently interest in adopting novel food processing technologies for the preservation of fruit and vegetables has increased due to high consumer demand for healthy, safe foods, without preservatives and additives, and with properties more similar to those of fresh produce. The wider use of non-thermal food processing techniques could enable increased production of healthy and safe plant-based foods high in nutrients. Non-thermal processing technologies such as PEF and HPP have been used on various fruit and vegetables, and have been shown to improve the retention of nutrients, including biologically active ascorbic acid.

4.1 Pulsed Electric Fields Processing

PEF processing involves the application of short electric pulses, typically in the range of micro- to milli-seconds, of high voltage across a food product (preferably in semi-solid or liquid form) placed between two conducting electrodes. This process induces cell electroporation and the formation of permanent holes in cell membranes, thus increasing cell permeability and allowing the leakage of the cell contents to take place (Knorr et al. 1994). This can improve the release of intracellular compounds, especially in plant-based foods.

With respect to ascorbic acid, it has been shown that PEF (electric field strength of 0.4 kV/cm for 450 rectangular pulses) facilitated aqueous extraction of fennel bulbs produced extracts containing more ascorbic acid than extracts obtained by thermal extraction at 90 °C (El-Belghiti et al. 2008). In addition to improving extraction, PEF can also be used as an alternative to conventional pre-treatment for the production of plant-based foods high in ascorbic acid. PEF pre-treatment (electric field strength of 2 kV/cm and 400 μs pulse width) of red bell peppers was found to be an effective replacement for a freezing pre-treatment step, enhancing the efficiency of the subsequent osmotic dehydration process and promoting a faster rate of water loss from the peppers during convective air drying (Ade-Omowaye et al.

2003). PEF pre-treated peppers showed a 11–24% loss in ascorbic acid after convective drying while a freezing pre-treatment resulted in a 24% loss in ascorbic acid, compared to fresh samples.

Other important feature of PEF, when applied at high electric field strengths (E = 25–40 kV/cm), is the ability to inactivate microbes and also to achieve at least an 80–90% inactivation of undesirable oxidative enzymes. For these reasons, the use of PEF as a potential preservation technology to replace conventional thermal treatments for the production of fruit and vegetable juices has been investigated. Studies on oranges (Elez-Martínez and Martín-Belloso 2007; Sánchez-Moreno et al. 2005), tomatoes (Odriozola-Serrano et al. 2007), and watermelon (Oms-Oliu et al. 2009) have shown that PEF can minimise the degradation of ascorbic acid and maintain up to 98% of the total vitamin C content of fresh juice. In addition, the PEF-treated juices have shelf lives of between 30 and 70 days at 4 °C without substantial depletion of ascorbic acid.

One plausible explanation for the better retention of ascorbic acid in PEF-treated produce is the inactivation of ascorbic acid degrading enzymes. Recent work on carrots showed that carrot AAO was susceptible to PEF treatment (Leong et al. 2015). In this respect, future research should consider optimising appropriate combinations of PEF processing parameters (electric field strength and specific energy input) for a wide range of plant produce in order to reduce the adverse effect of AAO, while maintaining the stability and improving the retention of ascorbic acid. Overall, there is strong evidence to indicate that PEF has the potential to help maintain high ascorbic acid levels in plant-based foods/juices and has numerous potential applications for plant-based food products.

4.2 High Hydrostatic Pressure Processing

HPP involves the application of hydrostatic pressures above 100 MPa at ambient temperatures to inactivate microbes and inhibit the activities of oxidative enzymes, while retaining the inherent quality attributes of the food material (Oey et al. 2008). Food products, in the form of liquids or semi-solids, are pre-packed and loaded into a HPP chamber vessel and the vessel is then closed and filled with a pressure-transmitting medium such as water or food-grade solutions (e.g. castor oil, silicone oil, sodium benzoate, ethanol, and glycol). The food products are then held inside the vessel under pressure for a predefined duration, then the system is depressurised, the vessel is opened, and the food products are unloaded (Tao et al. 2014).

HPP has considerable potential for the preservation of high quality plant-based foods, either in the form of pulps, purees, or juices, and could replace conventional thermal treatments (e.g. blanching or pasteurisation). Previous studies have demonstrated that HPP (applied between 400 and 600 MPa for 5–10 min) can improve the retention of ascorbic acid in apple juice (Kim et al. 2012), guava puree (Yen and Lin 1996), strawberry and blackberry purees (Patras et al. 2009a, b), and tomato puree (Patras et al. 2009b), compared to thermally processed products. In general, HPP-processed food products have similar ascorbic acid contents to that of their fresh or untreated counterparts, which is thought to be mostly due to the fact that HPP food products are not exposed to high temperatures during HPP processing. HPP-processed food products have also demonstrated better ascorbic acid stability during refrigerated storage, particularly at lower storage temperatures (Tewari et al. 2017). The shelf life of refrigerated (4 °C) HPP-treated juice can be extended up to 28 days for tomato juice (Hsu et al. 2008), up to 35 days for pomegranate juice (Varela-Santos et al. 2012), up to 56 days for blueberry juice (Barba et al. 2012), and up to 60 days for grape juice (Daoudi et al. 2002), without substantial loss of ascorbic acid. It is, however, important to note that some HPP plant materials may show a slight enhancement of ascorbic acid degradation, under both aerobic and anaerobic conditions (Tewari et al. 2017). This is possibly caused by the presence of endogenous pro-oxidants, such as metal ions and ascorbic acid degrading enzymes, in the food matrix.

During HPP, the pressure applied to foods is usually instantaneously and uniformly distributed, and so the size and shape of food products are not greatly affected, unless the product has a very porous structure (Oey et al. 2008). HPP also increases cell permeability and hence the movement of molecules, including water, out of plant cells. HPP can therefore improve the process of osmotic dehydration by increasing the rate of cellular water loss and sugar uptake in HPP-treated plant materials, compared to other pre-treatments. Freezing or blanching is often used in the food industry to produce dehydrated frozen food products including apple slices. However, apple slices pre-treated with HPP (400 MPa for 10 min) had a higher ascorbic acid content, firmer texture, and brighter colour than slices produced using freezing or blanching pre-treatments (Taiwo et al. 2001).

It is clear that HPP can be a suitable alternative to thermal processing to prolong the shelf life while improving the retention of ascorbic acid in plant-based foods and has now been adopted as a cold-pasteurisation technique by several food companies in Europe and the USA to preserve fruit juices.

5 Conclusions and Future Perspectives

We live in a world where an increasing global population is set against a background of climate change, and where difficulties associated with sustainable food production and distribution mean that eliminating food waste is becoming increasingly important. Efficient, low energy food processing technologies that can be used to preserve fruit and vegetables and produce plant-based foods of consistent quality, while maintaining their nutritional value, are becoming increasingly important. An adequate daily intake of ascorbic acid is a requirement for a healthy diet and while a diet high in fresh fruit and vegetables is ideal, increasingly humans are relying on processed plant products in their daily diets to supply their nutritional needs. Greater use of novel, energy efficient non-thermal processing technologies, such as PEF and HPP, has the potential to aid in the preservation of biologically active ascorbic acid in plant-based foods. However, as fresh plant produce is highly variable and hence the raw materials used to produce processed plant-based foods are also highly variable, much more work is required to understand how non-thermal processing technologies change the raw plant material used to produce plant-based foods, and how any changes might affect the nutritional and storage attributes of the final product. The development and optimisation of low cost and energy efficient processing methods that retain high levels of key nutrients, such as ascorbic acid, and can be used for a wide range of plant-based food products are critical areas for future research in order to help ensure global food security in the future.

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