Received: 9 August 2011 Revised: 7 October 2011 Accepted: 9 October 2011 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/jsfa.4718

Advanced preservation methods and nutrient retention in fruits and vegetables

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Abstract

Despite the recommendations of international health organizations and scientific research carried out around the world, consumers do not take in sufficient quantities of healthy fruit and vegetable products. The use of new, 'advanced' preservation methods creates a unique opportunity for food manufacturers to retain nutrient content similar to that found in fresh fruits and vegetables. This review presents a summary of the published literature regarding the potential of high-pressure and microwave preservation, the most studied of the 'advanced' processes, to retain the natural vitamin A, B, C, phenolic, mineral and fiber content in fruits and vegetables at the time of harvest. Comparisons are made with more traditional preservation methods that utilize thermal processing. Case studies on specific commodities which have received the most attention are highlighted; these include apples, carrots, oranges, tomatoes and spinach. In addition to summarizing the literature, the review includes a discussion of postharvest losses in general and factors affecting nutrient losses in fruits and vegetables. Recommendations are made for future research required to evaluate these advanced process methods.

Keywords: nutrients; fruit; vegetable; preservation; processing; high pressure; microwave

INTRODUCTION

Epidemiological studies suggest that the consumption of fruit and vegetables may play an important role in the protection of many chronic diseases, including cardiovascular disease,[1] type II diabetes,[2] dementia,[3] macular degeneration[4] and some cancers.[5,6] These observations have led to recommendations by the World Health Organization[7] to consume 400 g of fruit and vegetables per day and the instigation of many individual campaigns by government agencies in countries throughout the world. For example, the Dietary Guidelines for Americans[8] recommends that you make half your plate fruit and vegetables, which equates to seven to ten portions per day, depending on a person's age and sex. In addition to the well-established benefits of the essential vitamins and minerals found in high quantities in a wide range of fruit and vegetables, they also provide a good source of fiber to the diet and a diverse array of nonessential nutrients. These are known as phytochemicals, and have been reported to have extensive health benefits including antioxidant, anti-inflammatory, lipid-lowering and beneficial effects on blood pressure and endothelial function.[9–11]

Despite widespread investigation as to what constituents of fruit and vegetables are responsible for these health-promoting effects, it is still somewhat unclear and it is likely that maximum beneficial effects occur through synergies between individual phytochemicals, along with macronutrients and fiber contained within fruit and vegetables.[12] With this in mind, it is of paramount importance that retention of these essential nutrients and phytochemicals is maintained to the highest possible levels from farm to fork, so that maximum health benefits can be conferred to the consumer. The main focus of this review will be on some of the key advanced food preservation technologies that are now available and their effects on the beneficial components of fruits and vegetables. In addition, we will also provide an overview of traditional methods of food preservation. First, however, we will summarize other factors which influence the content of nutrients and phytochemicals within fruit and vegetables and why preservation technologies are of such importance in meeting the global targets of fruit and vegetable consumption.

POSTHARVEST LOSSES IN FRUITS AND VEGETABLES

In addition to the effects of preservation techniques which will be discussed later, there are many other factors that affect the nutritional quality of fruits and vegetables. Most consumers do not have home gardens capable of providing the recommended 5–13 daily servings year round. In the USA, fruits and vegetables grown in North America may spend up to 5 days in transit postharvest, before arriving at a distribution center. For produce grown in the Southern Hemisphere for winter and spring consumption in the USA, transit may be a matter of days if transported by air freight, to several weeks if fruits and vegetables are sent by refrigerated ship.[13] Once arriving at the retail store, fruits and vegetables may spend 1–3 days on display prior to being purchased and brought to the consumer's home, where they may be stored up to 7 days at room or refrigerated temperatures prior to consumption.

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During this postharvest period, significant changes in moisture and nutrient content will occur.

In addition to the effects of transport and storage on fruit and vegetables, the variety and stage of ripeness all have an impact on the levels of vitamins, minerals and phytochemicals within fruit and vegetables.[14] Most varieties of fruits and vegetables found in the supermarkets are not chosen for their nutritional content and instead varieties are chosen for their appearance, yield and their ability to withstand long-distance transport.[15] The stage of ripeness may also have a significant impact on the nutritional quality of fruit and vegetables.[16] For example, many fruits and vegetables are harvested before they reach full maturity in order to extend their shelf life. Fruits such as tomatoes, apples, melons and peaches, which are known as climacteric, will continue to ripen and reach their peak color after being detached from the mother plant. There are considerable losses of vitamin C compared to that found if the product had been freshly picked at its peak of maturity (http://chge.med.harvard.edu/programs/food/local.html).[13–16]

WHY PRESERVE FRUITS AND VEGETABLES?

While fruits and vegetables are desirable components of a healthy diet, they are 'perishable' commodities that may only have a shelf life of days or hours. Some fruits and vegetables are only grown in particular regions of the world, often for very short seasons, and transportation of the fresh commodity to distant markets may result in tremendous postharvest losses.[13,17,18] For centuries, storage and preservation technologies have been utilized to transform these perishable fruits and vegetables into safe, delicious and stable products.

The food industry uses a variety of preservation, or processing, methods to extend the shelf life of fruits and vegetables such that they can be consumed year round, and transported safely to consumers all over the world – not only those located near the growing region. Food preservation aims primarily to create a microbiologically safe product, but processors also strive to produce the highest-quality food. Depending on how processing is carried out, processing may result in a change in color, texture, flavor and nutritional quality, the last of which is the subject of the following literature review.

FACTORS AFFECTING FRUIT AND VEGETABLE PRESERVATION METHOD

Microorganisms may be controlled through the use of heat, cold, dehydration, acid, sugar, salt, smoke, atmospheric composition and radiation.[19] Mild heat treatments in the range of 82–93 °C are commonly used to kill bacteria in low-acid foods (pH $\geq$ 4.6), but to ensure spore destruction temperatures of 121 °C wet heat for 15 min or longer are required. High-acid foods (pH $<$ 4.6) require less heat, and often a treatment of 93 °C for 15 min will ensure commercial sterility. Water activity (a_w) of a food of 0.85 or below requires no thermal process, regardless of the pH. Most fruits are high acid, with the exception of low-acid fruit such as bananas, figs, mangoes, and some mature stone fruit. Vegetables, on the other hand, are primarily low acid or alkaline in pH, with the exception of some 'fruit vegetables' such as tomatoes, which for the most part have pH values $<$ 4.6. Another main consideration in choosing the most appropriate method of food preservation is the intended shelf life required of the product. This will dictate to a large extent the method of preservation selected. If the product is meant for consumption within a week or two, fresh-cut or minimal processing may be sufficient, but refrigeration and other means of preventing microbial growth will be required. If, on the other hand, the product is to be stored for a year or more, a process that ensures commercial sterility and long-term acceptability, such as canning or freezing, is desirable. An overview of these traditional and novel or 'advanced' methods of food preservation will be described briefly below.

Traditional preservation methods

Preservation methods such as dehydration and fermentation have been utilized for centuries, whereas thermal processing and freezing technologies have developed more recently in the 20th century. It is these later traditional technologies that will be referred to as standard 'traditional' methods, to which 'advanced' methods, which are the focus of this review, will be compared.

Thermal processing is one of the most common current forms of food preservation because it efficiently reduces microbial population, destroys natural enzymes and renders horticultural products more palatable. Most canned and bottled fruits and vegetables are produced under conditions of commercial sterility, and have a shelf life of 2 years or longer. Thermal processing essentially involves either heating unsterile foods in their final containers (canning), or heating foods prior to packaging and then packaging under sterile conditions (aseptic processing).

In contrast, freezing serves as a method of preservation because water activity can be lowered to a level which prevents microbial activity and reduces the rates of chemical reactions. There are three basic freezing methods used commercially: freezing in air, freezing by indirect contact with the refrigerant, and freezing by direct immersion in a refrigerating medium. Prior to freezing, most vegetables are exposed to a short blanching treatment with either steam or hot water to inactivate enzymes. While the thermal exposure in frozen vegetables and fruits is relatively low, the freezing and thawing process itself results in significant tissue structure damage, depending on the rate and temperature at which each is applied. This degradation of plant tissue may allow loss of cellular integrity and interaction of enzymes and nutrient substrates, resulting in nutrient loss in addition to deterioration of texture, color and flavor.

In 2007, Rickman *et al*. published a two-part literature review on the nutritional quality of canned and frozen fruits and vegetables, as compared to their fresh counterparts.[17,18] A review of the recent and classical literature revealed that loss of nutrients in fresh products prior to consumption may be more substantial than commonly perceived. Storage and cooking can lead to overall losses of up to half of the original nutrient content.

These authors found that, depending on the commodity, freezing and canning processes may preserve nutrient value. While the initial thermal treatment of canned products can result in loss, nutrients are relatively stable during subsequent storage due to the lack of oxygen. Frozen products lose fewer nutrients initially because of the short heating time in blanching, but they lose more nutrients during storage due to oxidation.

One major finding was that changes in moisture content during storage, cooking and processing can misrepresent actual nutrient content. In many cases, scientists had not determined nutrients on a dry weight basis, but on an ever-changing fresh weight basis, which severely limited the usefulness of the data. If researchers want to follow changes in fresh weight nutrient content through a process step, they must measure the weight before and after to adjust values for moisture loss. The authors concluded that nutritional comparison would be facilitated if future research would express nutrient data on a dry weight basis to account for changes in moisture.

Advanced preservation methods

Overview

Under the heading of 'advanced processing' might be included relatively newer technologies which may or may not be in commercial practice. These include high-pressure processing and use of various electric methods such as microwave, pulsed electric fields and between electric fields, ohmic processing. One tremendous advantage of these advanced methods is the uniform application of pressure or electric fields to the product as a whole, rather than needing to rely on heat or freezing temperature penetration from the external surface to the inside of the container. During pressurization there is some heating of the material, but this is generally less than if temperature was the only means of preservation. Electric field processing generates heat locally, which also minimizes the amount of heat required. Advanced processes therefore minimize the temperature (and hence the quality) gradient in the product and shorten the process time required.

High-pressure preservation

High-pressure processing is effective against microorganisms because it results in the rupture of microbial membranes. A number of commercial products preserved using high-pressure pasteurization followed by refrigeration of the processed product exist today in the US, Japanese and European markets. Recent studies on high-pressure sterilization, achieved through the use of high initial temperatures, have further advanced this technology. Microwaves, pulsed electric fields and irradiation utilize radiant energy, which changes foods as it is absorbed, while ohmic processing raises the temperature of food itself by passing an electrical current through it. Microwave energy occurs as alternating electric current at frequencies of either 915 or 2450 MHz, which means the electric field reverses 915 or 2450 million times per second. Water and other molecules in food are dipolar, e.g. they have distinct positive and negative ends which oscillate to align themselves with alternating microwave current. These high-speed oscillations cause friction, which heats the food.

Four recent reviews related to the effects of high-pressure processing (and some other advanced technologies) were found during this literature review. Two were fairly comprehensive and relevant to this topic. The first is by Sanchez-Moreno and co-workers,[20] from the Instituto de Frio in Madrid, which discusses the importance of numerous vitamins and phytonutrients. While quite comprehensive, the primary nutrients reviewed in actual fruits and vegetables were vitamin C, carotenoids, vitamin A, flavonoids and glucosinolates. There were no studies discussed which focused on the various B vitamins, fiber or minerals.

The Hendrickx in Leuven, Belgium, has worked for many years on the effects of high pressure on endogenous enzymes and texture. Their 2008 review by Oey *et al*. in *Trends in Food Science and Technology*[21] is also quite good. They describe their own work and that of others on vitamin C, B_1, B_2, B_6, carotenoids and vitamins A and E. These authors described effects of high pressure primarily in fruits and vegetables; however, the folate (B_9) studies were carried out in model solutions.

The third and fourth reviews are less comprehensive and fairly limited. One published in 2009 by Tiwari and co-workers[22] only covers anthocyanins in berry and grape juices. A fourth by San Martin and co-workers,[23] working at Washington State University, published in 2003 in *Critical Reviews in Food Science and Nutrition*, is fairly general and has little information on nutrients.

Microwave, ohmic and pulsed electric field preservation

Heating through the use of electric fields and/or high pressure differs from conventional thermal processing because it is able to uniformly penetrate several centimeters into the food. Heat is generated quickly and evenly throughout the mass, and steam generated heats adjacent areas by conduction. Microwave heating applications to fruit and vegetable products include the following: concentrating heat-sensitive solutions at low temperatures through the use of vacuum; cooking large pieces without high temperature gradients; uniform dehydration; rapid enzyme inactivation; combination with freeze drying to accelerate final moisture removal; heating temperature-sensitive products; and controlled thawing of frozen products.[19]

Ohmic processing is a continuous process applied to particulates in a conducting solution by passing them through a series of low-frequency alternating electric currents of 50 or 60 Hz. Both particulate and carrier liquid heat quickly, then are cooled using similar technology and are packaged aseptically. Pulsed electric field processing, which is currently applied to juices, involves application of short pulses of a strong electric field on a flowing fluid in order to kill the vegetative cells of microorganisms. In both ohmic and pulsed electric field processing, the electric current is uniformly applied to the entire food product, which creates local heating and also causes rupture of microbial and plant cells.

There were no review articles found on microwave or microwave vacuum processing; therefore the summary of findings below is derived from individual articles, which commonly compared microwaving to more traditional thermal processing methods, often on just one or a few commodities.

METHODOLOGY FOR REVIEW OF THE CURRENT LITERATURE

Three primary databases were searched, in the following order: Agricola, CAB and FSTA. Duplicates already retrieved from an earlier database were eliminated. The references targeted were those related to the advanced processing of fruits and vegetables, highlighting nutrient retention. Search terms used were the following: (process* or preserv*) AND (high pressure or microwave* or electric field*) AND (nutriti* or antioxidant or phytochem* or vitamin* or mineral or ascorbic acid or lycopene or beta carotene or carotene* or phenolic or fiber) AND (fruit* or vegetable*) AND LIMIT 1997-current.

In total there were 734 references identified from the three databases. Abstracts from all were reviewed for relevancy, and only the most pertinent to the topic of effects of advanced processing on fruit and vegetable nutrients were obtained. The largest percentage of these manuscripts (35%) related to high-pressure processing, followed by microwave and microwave vacuum processing (31%). Pulsed electric field processing was the focus of 25% of the manuscripts, while less than 3% of the manuscripts obtained dealt with manothermosonication, radiofrequency, ohmic processing or ultrasonics. Because high-pressure and microwave processing of fruits and vegetables were the most studied, this literature review focused on these two technologies. When manuscripts addressing these technologies were carefully read, the number of relevant publications on high-pressure processing and on microwave processing was reduced to 29 related to high pressure, 15 for microwave and 11 for microwave vacuum preservation. Relevance of a particular manuscript was determined by its focus on nutrient content, fruits and vegetables, high-pressure and/or microwave processing, and adequate description of methods used. A careful review of the work described in these manuscripts is the focus of this manuscript.

HIGH-PRESSURE PRESERVATION: EFFECTS ON FRUIT AND VEGETABLE NUTRIENTS

Prior to reviewing the results of studies on high-pressure processing (HPP) effects on nutrients, a number of general comments must be made. Many publications reported nutrient content on a wet weight basis; in fact, only a few of the 29 publications evaluated gave results on a dry weight basis (Table 1). Because the moisture content of fruits and vegetables typically declines throughout its postharvest life, wet basis reporting is invalid. Many of the studies focused on juices, with less than half evaluating fruit and vegetable pieces or slices. There were few studies on the B vitamins whatsoever and a number of these were carried out on model solutions rather than fruit and vegetable materials. There were no manuscripts found on high-pressure preservation effects on lipids or minerals. Only a few investigators compared HPP to a comparative technology, such as thermal, and regrettably most studies did not state a common target, e.g. microbial reduction, enzyme activity or nutrient content. Of the few that did, the primary target was microbial.

Vitamin A and total carotenoids

Most manuscripts reported vitamin A in relation to total or specific carotenoid content. Total carotenoids found in fruits and vegetables are relatively stable to preservation by HPP and conventional thermal processing (Table 1). Most authors found that the total carotenoid content of fruits and vegetables was either unaffected or increased by preservation using high pressure.[21,22] A determination of increased content of a particular nutrient may result from either moisture loss and thereby a 'concentration' of the nutrient, or the process itself may free the nutrient from the cellular matrix such that the analytical determination is higher.

The vitamin A content of persimmon purée increased 45% as a result of application of a high-pressure process.[24] Patras *et al.*[46] found that the total carotenoid content was significantly higher in all carrot purées treated with high pressure. Following the 600 MPa/20 °C/15 min treatment, total carotenoids increased 58% as compared to raw carrots. Butz *et al.*[49] studied the effects of both high pressure (600 MPa/25 °C) or thermal processing (118 °C/20 min) and found that neither preservation method resulted in a significant change in total carotenoids in fruit and vegetable juices, or pieces of apple, peach and tomato.

Specific carotenoids

HPP effects on specific carotenoids differed somewhat, depending on the fruit or vegetable product form (e.g. pieces, purée or juice) and the specific carotenoids studied. For example, McInerney *et al.*[47] found that in carrot, green bean and broccoli pieces there was no effect of HPP at 400 or 600 MPa on the content of α- or β-carotene, or lutein in any vegetables. Lutein bioavailability in green beans was increased by pressure at 600 MPa, while broccoli β-carotene availability was reduced by pressure processing at both 400 and 600 MPa.[47]

In tomato quarters treated at a low pressure of 133 MPa/34 °C, there was no significant change in the dry weight of total lycopene determined, nor did isomerization from the *trans* to the *cis* form occur.[30] However, three other studies of wet weight changes in tomato purée found that specific carotenoids increased, decreased or did not change after high-pressure treatment. Sanchez-Moreno *et al.*[45] reported that tomato purée samples treated at 400 Mpa/25 °C/15 min had the highest content of all carotenoids – β-carotene, γ-carotene, lycopene and lutein. In contrast, tomato purée processed at HPP 500 and 600 MPa for 12 min was determined to cause 21% and 56% loss of total lycopene, respectively, probably due to isomerization of *trans* to *cis* forms.[31] These authors found that lower pressure levels (100–400 MPa) had no effect on lycopene content, and storage of processed (HPP 100–300 MPa) tomato purée at 24 °C for 16 days resulted in only 8–9% loss. Finally, Krebbers *et al.*[51] found that lycopene content was unaffected by any HPP or thermal treatment.

In a study evaluating HPP effects on persimmon purée made from two different cultivars, de Ancos and collaborators[24] found that total carotenoids increased 19% and 16% following 50 and 400 MPa treatments, respectively, in the Sharon cultivar (Table 1). This correlated with improved extraction of violaxanthin, lutein, antheroxanthin, β-cryptoxanthin and β-carotene. However, in the Rojo Billante cultivar, HPP treatments did not cause a significant modification to carotenoids.

HPP treatments (300–500 MPa) alone resulted in better retention of carotenoids in carrot juice, as compared to mild thermal treatments at 50–70 °C.[48] The highest content was determined following 400 MPa/70 °C/10 min, where 75% of α- and 76% of the initial β-carotene were retained. The authors correlated retention of these specific carotenoids with the reduction in lipoxygenase activity, which catalyzes oxidation of carotenoids. The combination of high pressure and relatively moderate heat (70 °C) resulted in the best carotenoid retention.

Vitamin B

There are relatively few studies published on the effects of HPP on B vitamins, and many of those are carried out in model solutions rather than in fruit or vegetable pieces, purées or juices. Most researchers have found that the B vitamins are stable to HPP at room temperature. Findings specific to vitamins B_1, B_2, B_6 and B_9 are summarized below.

Vitamin B_1 (thiamin), B_2 (riboflavin) and B_6 (pyridoxal)

These particular B vitamins are quite stable to high-pressure preservation (Table 1). In the few recent manuscripts evaluating high-pressure effects on vitamin B_1, it was generally determined that there was no significant loss of vitamin content due to high pressure. Sancho *et al.*[25] found that in strawberry 'coulis' the vitamin B_1 and B_2 retention was not significantly affected by HPP, and retention was higher than that following thermal processing. These authors determined that vitamins B_1, B_2, B_6 and C (ascorbate) were also better retained in high-pressure-treated (400–600 MPa/25 °C/30 min) model solutions than in those treated using thermal processing. Likewise, Donsi *et al.*[26] and Gabrovska *et al.*[27] both determined that there were no significant losses in these B vitamins following HPP treatments on red orange juice or sprouted alfalfa seeds.

Table 1. High-pressure preservation effects on fruit and vegetable nutrients

Vitamin	Commodity and product	Wet vs. dry basis	High-pressure conditions	% loss	% gain	Range % loss or (gain)	Source	Ref.
Vitamin A	Persimmon purée	Wet	350 MPa/5 min		45	(+45)	de Ancos *et al*. 2000	24
Vitamin B_1 (thiamin)	Model solution	Wet	400–600 MPa/25 °C/30 min	0–1		0	Sancho *et al*. 1999	25
	Red orange juice	Wet	200–500 MPa/30 °C/1 min	0			Donsi *et al*. 1996	26
	Strawberry sauce 'coulis'	Wet	200–600 MPa/30 min	0			Sancho *et al*. 1999	25
Vitamin B_2 (riboflavin)	Model solution	Wet	400–600 MPa/25 °C/30 min	0–1		0	Sancho *et al*. 1999	25
	Red orange juice	Wet	200–500 MPa/30 °C/1 min	0			Donsi *et al*. 1996	26
	Sprouted alfalfa seed	Wet	500 MPa/25 °C/10 min	0			Gabrovska *et al*. 2005	27
	Strawberry sauce 'coulis'	Wet	200–600 MPa/30 min	0			Sancho *et al*. 1999	25
Vitamin B_3 (niacin)	Red orange juice	Wet	200–500 MPa/30 °C/1 min	0		0	Donsi *et al*. 1996	26
	Sprouted alfalfa seed	Wet	500 MPa/25 °C/10 min	0			Gabrovska *et al*. 2005	27
Vitamin B_5 (pantothenic acid)	Sprouted alfalfa seed	Wet	500 MPa/25 °C/10 min	0		0	Gabrovska *et al*. 2005	27
Vitamin B_6 (pyridoxal)	Model solution	Wet	400–600 MPa/25 °C/30 min	0		0	Sancho *et al*. 1999	25
	Red orange juice	Wet	200–500 MPa/30 °C/1 min	0			Donsi *et al*. 1996	26
Vitamin B_9 (folic acid)	Model solution	Wet	400–600 MPa/25 °C/30 min	0		0–90	Sancho *et al*. 1999	25
5-CH_3-H_4-folate	Asparagus juice	Wet	500 MPa/60 °C/40 min	90			Indrawati *et al*. 2004	28
	Carrot juice	Wet	500 MPa/60 °C/40 min	33			Indrawati *et al*. 2004	28
	Kiwi purée	Wet	500 MPa/60 °C/40 min	0			Indrawati *et al*. 2004	28
	Orange juice	Wet	500 MPa/60 °C/40 min	0			Indrawati *et al*. 2004	28
Total folate	Broccoli	Wet	600 MPa/20 °C/15 min	48–78			Verlinde *et al*. 2008	29
	Leek	Dry	200 MPa/5 min	81			Melse-Boonstra *et al*. 2002	30
	Cauliflower	Dry	200 MPa/5 min	43			Melse-Boonstra *et al*. 2002	30
	Green beans	Dry	200 MPa/5 min	47			Melse-Boonstra *et al*. 2002	30
Vitamin C	Buffer solution	Wet	850/60 °C/1 h	0		0–100	Oey *et al*. 2008	21
	Buffer solution	Wet	850/60 °C/6 h	100			Oey *et al*. 2008	21
	Apple–broccoli juice	Wet	500 MPa/5 min	3			Houska *et al*. 2005	31
	Apple–broccoli juice	Wet	500 MPa/20 min	28			Houska *et al*. 2005	31
	Cowpea sprout seeds	Wet	500 MPa/25 °C/15 min	41			Doblado *et al*. 2007	32
	Green beans (whole)	Wet	500 MPa/25 °C/1 min	8			Krebbers *et al*. 2002	33
	Green peas (whole)	Wet	900 MPa/20 °C/5–10 min	12			Quaglia *et al*. 1996	34
	Green peppers	Wet	100–200 MPa/10–20 min	10 to 15			Castro *et al*. 2008	35
	Guava puree		400 and 600 MPa/15 min	0			Yen and Lin 1996	36
	Kiwi–strawberry jam	Wet	400–600 MPa/10–30 min	0–5			Kimura *et al*. 1994	37
	Melon pieces	Wet	600 MPa/10 min	50–90			Wolbang *et al*. 2008	38
	Muscadine grape juice	Wet	400–550 MPa	84, 18			Del Pozo-Insfran 2007	39
	Orange juice	Wet	500 and 800 MPa/25 °C/5 min	2			Fernandez-Garcia *et al*. 2001	40
	Orange juice	Wet	100 MPa/60°/5 min	10			Sanchez-Moreno *et al*. 2003	41
	Orange juice	Wet	400 MPa/40 °C/1 min	5 to 8			Sanchez-Moreno *et al*. 2003	41
	Orange juice	Wet	350 MPa/30 °C/2.5 min	0			Sanchez-Moreno *et al*. 2003	41
	Orange juice	Wet	14 kbar	0			Butz *et al*. 2003	42
	Orange–lemon–carrot juice	Wet	14 kbar	0			Butz *et al*. 2003	42
	Orange–lemon–carrot juice	Wet	500 and 800 MPa/25 °C/5 min	4			Fernandez-Garcia *et al*. 2001	40
	Papaya slices	Wet	400 MPa/25 °C/1 min	7			de Ancos *et al*. 2007	43

Table 1. *(Continued)*

Vitamin	Commodity and product	Wet vs. dry basis	High-pressure conditions	% loss	% gain	Range % loss or (gain)	Source	Ref.
	Red peppers	Wet	100–200 MPa/10–20 min		10 to 15		Castro *et al*. 2008	35
	Strawberry sauce 'coulis'	Wet	200–600 MPa/30 min	11			Sancho *et al*. 1999	25
	Strawberry puree	Wet	600 MPa/30 °C/15 min	6			Patras *et al*. 2009a	44
	Tomato purée	Wet	400 MPa/40 °C/15 min	29			Sanchez-Moreno *et al*. 2006	45
	Tomato purée	Wet	600 MPa/20 °C/15 min	6			Patras *et al*. 2009b	46
			Carotenoids					
α- Carotene	Carrot (whole)	Wet	600 MPa/25 °C/2 min	0		0–72 (+34)	McInerney *et al*. 2007	47
	Carrot juice	Wet	500 MPa/25 °C/10 min	50			Kim *et al*. 2001	48
	Carrot juice	Wet	500 MPa/25 °C/60 min	72			Kim *et al*. 2001	48
	Orange juice	Wet	400 MPa/40 °C/1 min		34		Sanchez-Moreno *et al*. 2009	20
	Orange–lemon–carrot juice	Wet	500 and 800 MPa/25 °C/5 min	0			Fernandez-Garcia *et al*. 2001	40
	Orange–lemon–carrot juice	Wet	14 kbar	0			Butz *et al*. 2003	42
β- Carotene	Broccoli (whole)	Wet	600 MPa/25 °C/2 min	17		0–60 (+1–30)	McInerney *et al*. 2007	47
	Carrot (whole)	Wet	600 Mpa/25 °C/2 min	0			McInerney *et al*. 2007	47
	Carrot juice	Wet	500 MPa/25 °C/10 min	40			Kim *et al*. 2001	48
	Carrot juice	Wet	500 MPa/25 °C/60 min	60			Kim *et al*. 2001	48
	Melon pieces	Wet	600 MPa/10 min		1 to 10		Wolbang *et al*. 2008	38
	Orange juice	Wet	400 MPa/40 °C/1 min		30		Sanchez-Moreno *et al*. 2003	41
	Orange–lemon–carrot juice	Wet	500 and 800 MPa/25 °C/5 min	0			Fernandez-Garcia *et al*. 2001	40
	Tomato purée	Wet	600 MPa/25 °C/60 min	0			Butz *et al*. 2002	49
	Tomato purée	Wet	14 kbar	0			Butz *et al*. 2002	49
	Tomato purée	Wet	400 MPa/25 °C/15 min	0			Sanchez-Moreno *et al*. 2006	45
β-Cryptoxanthan	Orange juice	Wet	400 MPa/40 °C/1 min		43	(+43)	Sanchez-Moreno *et al*. 2003	41
Lutein	Broccoli (whole)	Wet	600 MPa/25 °C/2 min	10		0–10 (+75)	McInerney *et al*. 2007	47
	Green beans	Wet	600 MPa/25 °C/2 min	0			McInerney *et al*. 2007	47
	Orange juice	Wet	400 MPa/40 °C/1 min		75		Sanchez-Moreno *et al*. 2003	41
Lycopene	Tomato purée	Wet	600 MPa/25 °C/60 min	0			Butz *et al*. 2002	49
	Tomato purée	Wet	500 MPa/25 °C/12 min		21		Qiu *et al*. 2006	50
	Tomato purée	Wet	500 MPa/20 °C/2 min		60		Krebbers *et al*. 2003	51
	Tomato purée	Wet	400 MPa/25 °C/15 min		49		Sanchez-Moreno *et al*. 2006	45
Zeaxanthan	Orange juice	Wet	400 MPa/40 °C/1 min		45	(+45)	Sanchez-Moreno *et al*. 2003	41
Total carotenoids	Carrot puree	Wet	600 MPa/20 °C/15 min		58	19 (+8–58)	Patras *et al*. 2009a	46
	Papaya slices	Wet	400 MPa/25 °C/1 min	19			de Ancos *et al*. 2007	43
	Persimmon purée	Wet	400 MPa/25 °C/15 min		16		de Ancos *et al*. 2000	24
	Vegetable soup	Wet	400 MPa/60 °C/15 min		8		Plaza *et al*. 2006	52
			Phenolics					
Catechins	Apple juice		400 MPa/10 min		290	(+290)	Baron *et al*. 2006	53
Dihydrochalcones	Apple juice	Wet	400 MPa/10 min	0		0	Baron *et al*. 2006	53
	Apple juice	Wet	400 MPa/10 min		31	(+31)	Baron *et al*. 2006	53
Procyanidins	Apple juice	Wet	400 MPa/10 min		170	(+170)	Baron *et al*. 2006	53
Cyanidin-3-glucoside	Model solution	Wet	600 MPa/20 °C/30 min	0		0	Corrales *et al*. 2008	54
	Blackberry purée	Wet	600 MPa/30 °C/15 min	0			Patras *et al*. 2009a	44
	Raspberry purée	Wet	200–800 MPa/18–22 °C/15 min	0			Suthanthangjai *et al.* 2005	55
Cyanidin-3-sophoroside	Raspberry purée	Wet	200–800 MPa/18–2 °C/15 min	0		0	Suthanthangjai *et al.* 2005	55
Delphinidin-3-rutinoside	Blackcurrant purée	Wet	200–800 MPa/18–22 °C/15 min	0		0	Kouniaki *et al*. 2004	56

Table 1. (*Continued*)

Vitamin	Commodity and product	Wet vs. dry basis	High-pressure conditions	% loss	% gain	Range % loss or (gain)	Source	Ref.
Cyanidin-3-rutinoside	Blackcurrant purée	Wet	200–800 MPa/18–22 °C/15 min	0		0	Kouniaki *et al*. 2004	56
Pelargonidin-3-glucoside	Model solution	Wet	200–800 MPa/18–22 °C/15 min	0		0	Zabetakis *et al*. 2000	57
	Strawberry purée	Wet	600 MPa/30 °C/15 min	0			Patras *et al*. 2009a	44
Quercitin-4′-glucoside	Onion	Dry	400 MPa/5 °C/5 min		33	(+33)	Roldan-Marin *et al*. 2009	58
Quercitin-3,4′-diglucoside	Onion	Dry	100–400 MPa/5 °C/5 min		17	(+17)	Roldan-Marin *et al*. 2009	58
Total quercetin	Onion	Dry	100–400 MPa/5 °C/5 min		26	(+26)	Roldan-Marin *et al*. 2009	58
Total anthocyanins	Muscadine grape juice	Wet	400–550 MPa	70, 46		46–70	Del Pozo Insfran 2007	39
Total phenolics	Blackberry purée	Wet	600 MPa/30 °C/15 min		10	(+10–100)	Patras *et al*. 2009a	44
	Longan powder	Dry	500 MPa/30 °C		100		Prasad *et al*. 2009	59
	Onion	Dry	100–400 MPa/5–50 °C/5 min		12		Roldan-Marin *et al*. 2009	58
	Strawberry purée	Wet	600 MPa/30 °C/15 min		10		Patras *et al*. 2009a	44
	Tomato purée	Wet	600 MPa/20 °C/15 min	0			Patras *et al*. 2009b	46
			Dietary fiber					
Total dietary fiber	Cabbage	Wet	400–500 MPa/20, 50, 80 °C/10 min	0			Wennberg and Nyman 2004	60
Soluble fiber	Cabbage	Wet	400–500 MPa/20, 50, 80 °C/10 min	40			Wennberg and Nyman 2004	60

Vitamin B_9 (folic acid)

Recent information indicating that limited fruit and vegetable consumption has led to folic acid deficiencies in many developing countries has catalyzed research regarding this nutrient. In 2002, Melse-Boonstra *et al*.[30] carried out an extensive study of various processing methods and their effects on dry weight content of total, monoglutamate and polyglutamate folate forms. High-pressure treatments were applied with the goal of allowing glutamyl hydrolase activity to hydrolyze polyglutamates to monoglutamate in vegetable pieces, increasing absorbable folate content. These researchers found that while HPP increased monoglutamate content, losses of total folate were observed of the order of >55%. It was determined that much of the folate was leached into cooking water.

Researchers who followed up on this work took note of the water solubility of folates (and B vitamins in general) and designed their studies in such a way that HPP was applied directly to vegetable pieces, excluding a liquid solution. Verlinde *et al*.[29] found that high-pressure treatment (0.1–600 MPa/20 °C/15 min) of broccoli pieces resulted in 48–78% total folate loss, whereas folates were stable to thermal treatments up to 90 °C. These authors stated that there was no non-enzymatic hydrolysis of folates occurring in either thermal or HPP trials, but there was deglutamylation, with resulting accumulation of mono- and diglutamate folates following HPP treatment. In a separate study, the same research group[21] suggested that folate degradation during HPP was primarily a result of oxidation and cleavage of covalent bonds. Non-oxidative conversions occurred readily at high temperatures, and enzyme-catalyzed hydrolysis was also induced during HPP.

In a recent study by Wang *et al*.,[61] these authors determined that steaming vegetables was required to rapidly inactivate the enzyme γ-glutamyl hydrolase, and correctly quantify the polyglutamyl folate forms present. In the Verlinde *et al*. study,[29] boiling extraction buffer was added to a frozen sample, which was blended, and during this preparative step there is likelihood that the enzyme is still active.

Vitamin C (ascorbic acid)

Most studies have found that vitamin C is relatively unaffected by HPP; however, there are exceptions (Table 1). Sanchez-Moreno *et al*.[20] summarized a number of recent manuscripts on a variety of fruit and vegetable pieces, purées and juices in which vitamin C retention after HPP processing was generally above 80%. Much of the literature on vitamin C stability is contradictory because oxidation is an important pathway for degradation of vitamin C, and most studies do not control for this. In addition, oxidative enzymes (polyphenol oxidase and peroxidase) may affect vitamin C content, and these are often not evaluated. Oey *et al*.[21] found that vitamin C was unstable at high pressure levels combined with temperatures above 65 °C, but concluded that the major degradation was due to oxidation, especially during adiabatic heating.

Fruit and vegetable pieces

Red and green pepper pieces blanched using either pressure or heat had varying results in terms of vitamin C retention.[35] Relatively low-pressure treatments (100–200 MPa for 10–20 min) on green peppers caused a decrease of 15–20% of the initial vitamin C, while in red peppers these treatments resulted in a 10–20% increase in vitamin C. In comparing the HPP and heat (70, 80 and 98 °C for 1 and 2.5 min), these authors found that pressure-treated green peppers had similar to higher levels of vitamin C, when compared to 80 and 98 °C thermal treatments. HPP-blanched red peppers likewise had 50–100% higher vitamin C content when compared to 80 and 98 °C thermal treatments. Wolbang *et al*.[38] determined that HPP treatment at 600 MPa for 10 min prior to refrigerated storage resulted in 50–90% loss in vitamin C, depending on the melon cultivar.

Fruit and vegetable purée

Vitamin C content in purées of peas, guava, kiwi and strawberry were found to be fairly stable following HPP alone or HPP plus mild heat treatments, but not in HPP plus high heat application. In strawberry sauce or 'coulis', Sancho *et al*.[25] found that vitamin C retention was not significantly different between high-pressure thermal pasteurized products (91% and 89% retention, respectively), but was significantly lower (67%) after sterilization. Patras *et al*.[44] found that dry weight content of vitamin C in strawberry and blackberry purées was significantly higher in HPP-treated samples. Small reductions in vitamin C occurred following 400 and 500 MPa treatments, but 94% was retained after the 600 MPa process. This was compared to a thermal treatment which resulted in only 67% retention.

In a study focusing on tomato purée, Patras *et al*.[46] determined that there were significant reductions in vitamin C in all processed products, whether HPP or thermal. However, thermally processed samples retained only 54% of the original vitamin C content, while HPP processing at 600 MPa resulted in 94% of the original content. The same authors also determined that vitamin C was not detectable in any processed carrot purée samples. Sanchez-Moreno *et al*.[45] found that tomato purées processed using either HPP or thermal treatments caused about 29% loss in vitamin C.

Fruit and vegetable juices

A number of researchers have found vitamin C to be relatively impervious to high-pressure preservation.[20,42] In one study[21] focusing on orange, tomato, carrot and apple–broccoli juices, it was determined that high pressure level (250–500 MPa) did not have a major impact on vitamin C; rather, the major effect was matrix (e.g. commodity) and holding time as well as storage conditions.

In another study on heat- and HPP-pasteurized tomato and carrot juices, the vitamin C content in HPP-treated and stored juices (4 °C) was over 70%.[31] Carrot juice maintained a slightly greater concentration of vitamin C than tomato juice preserved under the same conditions, and longer holding times resulted in less vitamin C retention. While vitamin C content of orange juice generally decreases during storage time, HPP-treated juice declined less than thermally pasteurized orange juice, at all storage temperatures studied.[62] Losses were reduced in both preservation methods and shelf life was extended when juices were stored at lower temperatures (0 and 5 °C). Fernandez-Garcia *et al*.[40] likewise found that in stored orange and orange–lemon–carrot juice the vitamin C was the same or only slightly reduced in juices processed at 800 or 500 MPa. However, vitamin C in HPP-treated broccoli–apple juice was found to be lower than that in frozen broccoli.[31] Polyphenol oxidase activity in blackcurrant juice was thought to result in greater vitamin C losses in HPP *versus* thermally treated juices.[56]

Phenolics

Total phenolics

Studies on high-pressure preservation effects on total phenolics determined that these compounds were either unaffected or actually increased in concentration and/or extractability following treatment with high pressure. Prasad *et al*.[59] found that extraction of total phenolics from dried longan powder was improved with any HPP treatment (~200% with HPP at 200 MPa). The highest total phenolics concentrations were achieved after processing at 500 MPa.

Total phenolics in strawberry and blackberry purée were also found to be resistant to processing.[44] High pressure preservation at 600 MPa resulted in a ~10% increase compared to untreated. Likewise, total phenolics in tomato purée were largely unaffected by HPP or thermal processing.[46] Onion pieces had a 12% increase in total phenolics when treatments included 100 and 400 MPa combined with high (50 °C) and low (5 °C) temperatures.[58]

Specific phenolics

In a very extensive study, Baron *et al*.[53] found that after a 10 min hold at 400 MPa, the catechins, hydroxycinnamic acids and procyanidins were significantly higher than in control juice (Table 1). These authors stated that polyphenol oxidase was activated in the range of 200–300 MPa, and this increased catechin oxidation. Treatment of onions at 100 MPa and 50 °C resulted in 12% higher total phenolics as well as increased levels of quercitin-4′-glucoside and quercitin-3,4-diglucoside.[58]

A number of studies on strawberry, blackberry and raspberry purées determined that the anthocyanins are also relatively stable to high-pressure preservation (Table 1). HPP treatments resulted in no losses of pelargonidin-3-glucoside, the major anthocyanin in strawberry, or in cyanindin-3-glycoside, the major anthocyanin in blackberries. Corrales *et al*.[54] reported that there was an insignificant reduction in cyanidin-3-glucoside in model solutions preserved at 600 MPa and 20 °C, but there were reductions when the temperature were increased to 70 °C. Other authors found that pelargonidin-3-glucoside and -3-rutinoside in raspberry and strawberry juices and delphinidin-3-rutinoside and cyanidin-3-rutinoside in blackcurrant juice were all stable to high-pressure processing treatments.[56,57]

Dietary fiber

High-pressure preservation did not have much effect on total dietary fiber in one manuscript on cabbage, but the distribution changed.[60] Soluble fiber decreased while insoluble fiber increased after HPP treatments at 400 MPa, 20 °C. This decrease in soluble fiber was greater if the 400 MPa high-pressure treatments were conducted at 50 or 80 °C.

Case studies on specific commodities

It appears that some commodities have received more attention than others; therefore some general tendencies may be drawn from these studies. Our review identified 38 manuscripts on high-pressure preservation of fruits and vegetables as follows: oranges (5), apples (6), tomatoes (12), carrots (12) and spinach (3), and the highlights of these will be summarized.

Oranges

HPP (up to 850 MPa) of orange juice has only minimal effect on vitamin C, with losses of 10% or less if temperatures are kept below 50 °C.[20,30,42] However, if temperatures above 50 °C are used in combination with HPP treatments, vitamin C losses increase.[20] During storage of orange juice, vitamin C losses were lower in HPP treated *versus* thermally pasteurized juice. Comparing 500 and 800 MPa treatments and storage of orange juice, vitamin C losses were slightly higher in 800 MPa treatments.[30] 'Mild' HPP treatments (350–500 MPa) at 25–30 °C resulted in 20–45% greater extraction of carotenoids in orange juice.[21] If HPP treatment was applied at 40 °C, one report indicated a 75% increase in extraction of carotenoids.[20] Flavonoid content in HPP-treated orange juice was not significantly different from fresh, but was higher in stored juice.[20,62] Vitamins A and E were stable, or increased after HPP treatment. Folate (vitamin B_9) content was stable to HPP treatments of up to 500 MPa at 60 °C.[21]

Apples

High-pressure treatments from 250 to 500 MPa were not generally found to have an effect on vitamin C content. Fruit juices and pieces (including apple) processed at 600–800 MPa for a short 6 min did not have losses in vitamin C.[20] However, one study found that HPP treatments at levels of 500 MPa and above resulted in loss of vitamin C in broccoli–apple juice.[31] Phenolics were affected by HPP. HPP at 200–300 MPa activated polyphenol oxidase and therefore increased oxidation of catechins, which were inhibitors of pectin methylesterase (PME) (therefore less cloud).[53] After a 10 min hold at 400 MPa (20 °C), hydroxycinnamic acids and procyanidins were significantly higher than control juice. Dihydrochalcones were not modified by HPP but effect on catechins varied.[53]

Tomatoes

HPP of tomato juice at levels from 250 to 500 MPa, under relatively low temperatures (20 °C), resulted in little to moderate reductions in vitamin C content.[20,46] In one study, after 600 MPa treatment of tomato purée (20 °C) for 15 min, 94% retention of vitamin C was obtained, while thermal treatment resulted in only 54% retention.[46] A second study, however, found that 400 MPa treatment for 15 min (20 °C) resulted in only 71% retention of vitamin C.[20] At levels of 850 MPa, especially if temperature were not controlled, more significant losses occurred in tomato purées. One study indicated that in tomato pieces HPP treatments of up to 600–800 MPa (20 °C) did not result in a change in vitamin C.[21] In stored tomato juice, vitamin C losses occurred over time, with only 70% retention after 30 days at 4 °C. The lycopene and β-carotene content of tomato juice were unaffected by HPP treatments at 600–700 MPa and temperatures as high as 90 °C.[20]

The phenolics and carotenoids were largely unaffected by HPP treatments of up to 600 MPa; in fact, at this level (and higher) there was often a significant increase in extractability of these compounds from tomato purée.[20,46] A number of additional studies indicated that lycopene and other carotenoids were stable in tomato purée and pieces up to 700–800 MPa.[30,42] One study found that isomerization of lycopene from *trans* to *cis* occurred after 500–600 MPa treatments, with 89% and 44% retention of the *trans* form, respectively.[50] This same study found that storage at 24 °C for 16 days resulted in greater retention (92%) in HPP-treated tomato purée than in thermally treated purée (85% retention).[50]

Carrots

Most studies found that low levels (250–500 MPa) of HPP did not result in a loss in vitamin C in carrot juice.[20] One study of HPP at 250 MPa at a higher temperature (35 °C for 15 min) even found over 70% retention after 30 days of storage at 4 °C.[20] When the storage temperature was increased to 25 °C, vitamin C retention was 45% in carrot juice, compared to juice that was pasteurized at 80 °C for 1 min, which had no vitamin C left after storage at 4 °C for 16 days. However, one study on carrot pieces found that 400–600 MPa applications did result in total loss of vitamin C; however, these samples were frozen and then thawed overnight prior to HPP application, and this period may have allowed for enzymatic oxidation of vitamin C by ascorbic acid oxidase.[20,47]

Treatment of carrot pieces at 600–800 MPa (25 °C, 1–2 min) resulted in retention of over 80% of the initial carotenoid content, with no effect on the content of α- or β-carotene, or lutein.[47] Another study found that 400–600 applications (20 °C, 15 min) to carrot purée resulted in total retention of phenolics, and very little change, at times an increase, in carotenoids.[46] Heat treatment at 105 °C for 30 s caused 83% loss of α-carotene and 69% loss of β-carotene, whereas HPP (300–500 MPa, 50–70 °C for 10 min) resulted in better retention, highest at 300 Mpa for 10 min, where 75% of α- and 76% of β-carotene were retained. Lipoxygenase activity was lowest at 300 MPa, and higher levels activated it, resulting in oxidation of carotenoids.[34] Folate was unstable to fairly severe HPP treatments (500 MPa, 60 °C, 40 min), but if ascorbic acid were added this decreased what may have been enzymatic degradation.[28]

MICROWAVE PRESERVATION: EFFECTS ON FRUIT AND VEGETABLE NUTRIENTS

Table 2 summarizes losses in nutrients in produce preserved using microwaves, while Table 3 includes nutrient losses in fruits and vegetables preserved using microwave vacuum preservation. There were no reviews related to effects of microwave processing on fruit and vegetable nutrients. As with the high-pressure manuscripts, very few reported changes in nutrients on a dry weight basis.

Vitamin A and total carotenoids

Most authors reported that application of microwave preservation treatments resulted in loss of vitamin A and/or carotenoids. In a study evaluating vitamins A, C and E content in microwave-dried apricots, Karatas and Kamsl[63] reported increases in these nutrients of 250–350%, but again this was due to moisture removal and concentration of nutrients. These authors failed to report results on a dry weight basis. Total carotenoid content of papaya purée was determined after application of various levels of microwave power (285–850 W), and losses were reported to be as high as 57%.[73] A limited number of reports on specific carotenoids, such as β-carotene and lycopene, generally reported losses following microwave treatments (Table 2).

Specific carotenoids

Microwave treatments resulted in significant reduction in chlorophylls in kiwi purée.[73] The authors stated that oxidative enzyme activity may degrade chlorophylls. Two studies on carrots found either no degradation of β-carotene, or 30% loss. Heredia *et al.*[74] recently reported that lycopene degradation in cherry tomatoes could be significant, and in addition to oxidative losses isomerization from *trans* to *cis* forms was noted.

Vitamins B_1, B_2 and B_3

Vitamins B_1 (thiamin) and B_2 (riboflavin) content in Swiss chard and green beans were determined by Orzaez Villanueva *et al.*,[64] in a comparison of boiling, frying and microwaving cooking practices. However, these authors did not provide adequate information regarding the process time and temperature for any of the methods evaluated; therefore it is impossible to derive specific

Table 2. Microwave preservation effects on fruit and vegetable nutrients

Vitamin	Commodity and product	Wet vs. dry basis	Microwave conditions	% loss	% gain	Range % loss or (gain)	Source	Ref.
Vitamin A	Apricots	Wet	50–60 Hz, 50–160 °C		∼250	(+260)	Karatas and Kamsl 2007	63
Vitamin B_1 (thiamin)	Swiss chard	Wet	No information	60		32–60	Orzaez Villanueva *et al.* 2000	64
	Green beans	Wet	No information	32			Orzaez Villanueva *et al.* 2000	64
Vitamin B_2 (riboflavin)	Swiss chard	Wet	No information	9		9–47	Orzaez Villanueva *et al.* 2000	64
	Green beans	Wet	No information	47			Orzaez Villanueva *et al.* 2000	64
Vitamin C	Apple purée	Wet	2450 MHz, 652 W, 15–60 °C, 35 s	57		0–57 (+10–260)	Picouet *et al.* 2009	65
	Apricots	Wet	50–60 Hz, 50–160 °C		∼260		Karatas and Kamsl 2007	63
	Broccoli	Wet	700 W, 9 min	0			Howard *et al.* 1999	66
	Brussels sprouts	Wet	700 W, 5 min, 74 °C		10–15		Vina *et al.* 2007	67
	Carrots	Wet	700 W, 9 min		120–130		Howard *et al.* 1999	66
	Carrots	Wet	2450 MHz, 4 kW, 50 °C	35			Yan *et al.* 2010	68
	Green beans	Wet	700 W, 9 min		117		Howard *et al.* 1999	66
	Orange juice	Wet	245–455 W, 0.5–15 min, 100–125 °C	30–50			Vikram *et al.* 2005	69
	Peas	Wet	750 W, 2 min	13			Hunter and Fletcher 2002	70
	Spinach	Wet	750 W, 2 min		106		Hunter and Fletcher 2002	70
	Tomatoes	Wet	700 W, 4 min	10			Begum and Brewer 2001	71
Vitamin E	Apricots	Wet	50–60 Hz, 50–160 °C		∼350		Karatas and Kamsl 2007	63
			Carotenoids					
β-Carotene	Carrots	Wet	1000 W, 60 °C/90 min or 90 °C/4 min	0		0–75	Lemmens *et al.* 2009	72
	Carrots	Wet	2450 MHz, 4 kW, 50 °C	30			Yan *et al.* 2010	68
	Kiwi purée	Wet	2450 MHz, 285, 570 and 850 W, 15–60 s	75			de Ancos *et al.* 1999	73
Chlorophyll	Brussels sprouts	Wet	700 W, 5 min, 74 °C	8		8–75	Vina *et al.* 2007	67
	Kiwi purée	Wet	2450 MHz, 285, 570 and 850 W, 15–60 s	25–75			de Ancos *et al.* 1999	73
Lycopene	Cherry tomatoes	Wet	1–33 W g^{-1}, 40–80 °C	86		86	Heredia *et al.* 2010	74
Total carotenoids	Papaya purée	Wet	2450 MHz, 285, 570 and 850 W, 15–60 s	0–57		0–57	de Ancos *et al.* 1999	73
			Phenolics					
Rutin	Asparagus	Wet	915 MHz, 121 °C, 3 min	0		0	Sun *et al.* 2007	75
Protocatechuic acid	Unpeeled potato	Wet	2450 MHz, 150–1000 W, 95–420 min	14–26		14–84	Barba *et al.* 2008	76
	Peeled potato	Wet	2450 MHz, 150–1000 W, 95–420 min	50–84			Barba *et al.* 2008	76
Caffeoylquinic acid	Unpeeled potato	Wet	2450 MHz, 150–1000 W, 95–420 min	6–60		6–65	Barba *et al.* 2008	76
	Peeled potato	Wet	2450 MHz, 150–1000 W, 95–420 min	23–65			Barba *et al.* 2008	76
Pelargonidin-3-glucosides	Strawberry puree	Wet	2450 MHz, 285, 570 and 850 W, 15–60 s	0		0	de Ancos *et al.* 1999	73
Total anthocyanins	Kiwi purée	Wet	2450 MHz, 285, 570 and 850 W, 15–60 s				de Ancos *et al.* 1999	73
	Strawberry purée	Wet	2450 MHz, 285, 570 and 850 W, 15–60 s	0			de Ancos *et al.* 1999	73
	Sweet potato	Wet	915 kW, 5 kW and 60 kW	15			Steed *et al.* 2008	77
Total flavonoids	Brussels sprouts	Wet	700 W, 5 min, 74 °C	15		15	Vina *et al.* 2007	67
Total phenolics	Apple purée	Wet	2450 MHz, 652 W, 75 °C, 35 s	57		0–57 (+104–125)	Picouet *et al.* 2009	65

Table 2. (*Continued*)

Vitamin	Commodity and product	Wet vs. dry basis	Microwave conditions	% loss	% gain	Range % loss or (gain)	Source	Ref.
	Carrots	Dry	800 W, 6 min		125		Natella *et al*. 2008	78
	Cauliflower	Dry	800 W, 8 min		114		Natella *et al*. 2008	78
	Peas	Dry	800 W, 5.5 min	39			Natella *et al*. 2008	78
	Potato	Dry	800 W, 6.5 min		107		Natella *et al*. 2008	78
	Potato	Wet	2450 MHz, 150–1000 W, 95–420 min	4–32			Barba *et al*. 2008	76
	Spinach	Dry	800 W, 6.5 min	42			Natella *et al*. 2008	78
	Sweet potato	Wet	915 kW, 5 kW and 60 kW		105–108		Steed *et al*. 2008	77
	Swiss chard	Dry	800 W, 6.5 min	86			Natella *et al*. 2008	78
	Tomato	Dry	800 W, 3 min	91			Natella *et al*. 2008	78
			Fiber					
Neutral detergent fiber	10 vegetables	Dry	115 550 cooking power, 10 min	28.5		28.5	Zia-ur-Rehman *et al*. 2003	79
Acid detergent fiber	10 vegetables	Dry	115 550 cooking power, 10 min	27.6		27.6	Zia-ur-Rehman *et al*. 2003	79

results from their study. They did report losses of between 9% and 60% of the initial vitamin B_1 and B_2 content, but results were on a wet weight basis.

Vitamin C

Fruit and vegetable pieces or purée

Vitamin C content in fruits and vegetables varied from losses as high as 57% to increases of 10–260% as a result of microwaving (Table 2). Picouet *et al.*[65] found that total vitamin C content in apple purée was similar before and after the microwave process; however, ascorbic acid content decreased (43% retention) and dehydroascorbic acid increased (57%). As mentioned above, vitamin C content in microwaved apricots was reported to increase 260%.[63]

In a comparison of vitamin C content in tomatoes, Begum and Brewer[71] found that the content of this vitamin decreased after boiling-water blanching (65% retention), but there was only 10% loss after the microwave blanching method. Howard *et al.*[66] evaluated vitamin C changes in broccoli, carrots and green beans in a 2-year study. Results differed by vegetable, with no losses in broccoli and significant increases in vitamin C reported for carrots and green beans (Table 2). Vina *et al.*[67] evaluated effects of microwaving on Brussels sprouts and also reported increases following microwave preservation.

Fruit and vegetable juices

In contrast to the relatively high retention of vitamin C found in fruit and vegetable pieces and purées, Vikram *et al.*[69] reported that microwaving caused the greatest degradation in vitamin C in orange juice, compared to ohmic, IR and conventional heating. These authors specified each process endpoint as a particular target temperature; therefore results were appropriate to compare.

Vitamin C is sensitive to heat, light, oxygen and pH. Most storage studies found significant losses during storage. Microwave processing was generally less damaging to vitamin C, and fruits/vegetables had greater retention after microwaving than after a comparable thermal process. One notable exception was the orange juice study, where microwave-processed juice had the lowest vitamin C content.

Phenolics

Total phenolics

Total phenolics contents either declined (4–91%) or increased (104–125%) as a result of microwave treatments (Table 2), depending on the study and particular commodity. Picouet *et al.*[65] found that the total phenolics content in apple purée was similar before and after microwaving. Carrot, cauliflower, pea, potato, spinach, Swiss chard and tomato were studied by Natella *et al.*[78] and results were reported on a dry weight basis. Total phenolics were retained at 104–125% in all of the microwaved vegetables except peas (39% loss) and spinach (42% loss).

Barba *et al.*[76] found that the microwave process retained more total phenolics than boiling, in particular in unpeeled potatoes. In general, 750 W processing led to greatest loss in unpeeled potatoes, and cutting potatoes into smaller pieces and applying a shorter heating time resulted in overall higher levels of retention. Steed *et al.*[77] also found higher levels of total phenolics in microwaved sweet potatoes.

Specific phenolics

With the exception of rutin in asparagus, and pelargonidin-3-glucoside in strawberry purée, many of the specific phenolic compounds decreased in concentration as an effect of microwaving (Table 2). The Barba *et al.*[76] group measured individual phenolics in addition to total phenolics, and found that in unpeeled potatoes lowest protocatechuic acid loss (14%) occurred after the 500 W treatment, while the highest loss (26%) occurred following the 750 W process. In peeled potatoes, the lowest loss (50%) was found after the 300 W, and the greatest loss (84%) after 750 W. In unpeeled potatoes, the lowest caffeoylquinc loss (6%) was reported in the 1000 W treatment, while the greatest loss (60%) occurred after the 750 W application. In peeled potatoes, the lowest loss (23%) occurred after 500 W treatment, and the greatest (65%) after the 750 W application.

Fiber

The fiber content in home-cooked cabbage, carrots, cauliflower, eggplant, onions, peas, potatoes, radish, spinach and turnips was studied in one report by Zia-ur-Rehman *et al.*[79] These authors found that the neutral detergent fiber was significantly reduced with cooking. Microwave cooking resulted in approximately 4–29% loss, depending on the vegetable studied, compared to only 8–22% loss with traditional boiling methods. The acid detergent fiber content was also reduced between 12% and 28% with microwave cooking.

MICROWAVE VACUUM PRESERVATION: EFFECTS ON FRUIT AND VEGETABLE NUTRIENTS

Vitamins A, B and carotenoids

Clary *et al.*[80] studied the effects of microwave vacuum drying on whole grapes, and compared Vitamins A, B and C content to that in fresh and sun-dried grapes (Table 3). In all cases, the removal of water resulted in a concentration of the initial nutrient content, ranging from 50% to over 700% higher values in the microwave-dried product. However, these authors neglected to report nutrient content on a dry weight comparison, which would have been of greater merit. The microwave vacuum-dried grapes had a moisture content of 2.8%, while the fresh grape moisture content was 73.3%, representing over a 30-fold difference.

Vitamin B content in Swiss chard and green beans was also studied by Orzaez Villanueva *et al.*,[64] but these authors gave little to no information on the preservation methodology; therefore their reported losses are difficult to evaluate.

Relatively few studies reported changes in carotenoids as an effect of microwave vacuum preservation. Those evaluated in this review noted losses of up to 30% in carrot β-carotene but only 3–4% loss in total carotenoids in either carrots or chive leaves.[68,84]

Vitamin C

In most cases, vitamin C content was reduced by microwave vacuum preservation. Wojdylo *et al.*[82] studied the effect of microwave vacuum drying on strawberries, in a very thorough manuscript which reported results on a dry weight basis. Microwave energy levels of 240, 360 and 480 W were utilized, and vitamin C losses were only 13–40%, with the highest losses occurring under the 480 W conditions. In another study also carried out on strawberries, Bohm *et al.*[83] found losses of 54–56% in vitamin C as a result of microwave vacuum drying. However, the microwave energy level (4 kW) was much lower than that used in the previous study. These losses were higher than those observed by these authors in convective or freeze drying of strawberries.

Total and specific phenolics

Total phenolics were retained at higher levels in microwaved vacuum-dried fruits and vegetables than in those that were air dried; however, at high levels of microwave power (>500 W) this difference was not as great.[82,83,85,86] When compared to air drying and freeze drying, microwave vacuum drying of fruit had intermediate levels of total phenolics retention.

Wojdylo *et al.*[82] also determined total and individual phenolics and anthocyanins in microwave vacuum-dried strawberries. Microwave vacuum drying typically resulted in a loss of these compounds, but quercetin 3-*O*-glycoside and catechin content actually increased as a result of the drying procedure.

Blueberries preserved using microwave vacuum methods showed a loss in total phenols, but a concentration-related gain in total anthocyanins.[85] Saskatoon berries dried using microwave vacuum also showed a 50% decrease in total anthocyanins.[86] These authors determined that microwave preservation was better than air drying, but not as beneficial to nutrient content as freeze drying.

Minerals and crude fiber

There was only one study – that of Clary *et al.*[80] – on microwave vacuum-dried grapes, that measured mineral and fiber content. In all cases, microwave vacuum-preserved grapes had higher levels of minerals and crude fiber, most likely due to concentration in the dried product.

Case studies by specific commodities

As with the studies on high-pressure processing, some commodities have received more attention than others and general conclusions may be drawn. Our review identified 16 manuscripts on microwave or microwave drying effects on fruit and vegetable nutrients, as follows: oranges (1), apples (2), tomatoes (3), carrots (7) and spinach (3).

Oranges

Microwaving orange juice resulted in the greatest loss of vitamin C, as compared to ohmic and thermal pasteurization treatments.[69]

Apples

Microwave processing apple purée at 652 W (75 °C) for 35 s resulted in a loss in the reduced form of vitamin C (43% retention) and an increase in the oxidized form (57% increase).[65] Vitamin C loss occurred during storage as well, with only 7% retention after 5 days at 5 °C. Microwave vacuum dehydration of apple slices resulted in retention of only 60% of the initial vitamin C content.[81]

Tomatoes

Microwave blanching of tomato pieces (700 W for 4 min in either glass or plastic bags) did not result in a significant reduction (88–91% retention) in vitamin C, while boiling-water blanching only retained 65%.[71] Microwave cooking at 800 W for 3–8 min did not result in a loss of total phenolics (100% or higher retention), whereas boiling resulted in significant losses.[78] Hot-air and/or microwave vacuum drying of cherry tomato halves resulted in both isomerization of *trans* to *cis* lycopene and oxidation of total lycopene, but these changes were reduced at lower temperature and microwave power levels.[74] Highest retention of *trans*-lycopene occurred when drying occurred at 1 W g^{-1} and 40 °C.

Carrots

Various effects on vitamin C retention as a result of microwave cooking of carrot pieces have been reported.[66,80,81] A number of studies reported that microwave processing in the range of 300–800 W for up to 10 min retained all of the total phenolics and most of the carotenoids in carrot pieces.[68,80] Freezing carrots following microwave cooking did not affect carotenoid content.[68] Pretreating carrots with calcium chloride prior to microwaving or heating resulted in higher β-carotene content.[68] Authors state that this is due to precipitates forming. One study focused on fiber content in carrots and other vegetables, but the microwave power units are unconventional and the methods in general were not well described.[79] They reported that neutral detergent fiber was best retained (78–92%) in ordinary cooking, while microwave cooking retained only 71–86%. The acid detergent fiber was also degraded with any kind of cooking, due primarily to hemicellulose degradation but also to breakdown in cellulose. Lignin content remained unchanged by any cooking method.[79]

In one study, microwave freeze drying was compared to microwave alone and microwave vacuum drying of carrot pieces,

Table 3. Microwave vacuum preservation effects on fruit and vegetable nutrients

Vitamin	Commodity and product	Wet vs. dry basis	Microwave vacuum conditions	% loss	% gain	Range % loss (gain)	Source	Ref.
Vitamin A	Grapes	Wet	2450 MHz, 3 kW, 71 °C		219	(+219)	Clary *et al*. 2007	80
Vitamin B_1 (thiamin)	Grapes	Wet	2450 MHz, 3 kW, 71 °C		725	(+725)	Clary *et al*. 2007	80
Vitamin B_2 (riboflavin)	Grapes	Wet	2450 MHz, 3 kW, 71 °C		52	9–47 (+52)	Clary *et al*. 2007	80
	Swiss chard	Wet	No information	9			Orzaez Villanueva *et al*. 2000	64
	Green beans	Wet	No information	47			Orzaez Villanueva *et al*. 2000	64
Vitamin B_3 (niacin)	Grapes	Wet	2450 MHz, 3 kW, 71 °C		108	(+108)	Clary *et al*. 2007	80
Vitamin C	Apple slices	Wet	390 W for 30 min + 195 W for 39 min	40		13–56 (+500)	Mindak and Dolan 1999	81
	Carrots	Wet	4 kW, 50 °C	35			Yan *et al*. 2010	68
	Grapes	Wet	2450 MHz, 3 kW, 71 °C		500		Clary *et al*. 2007	80
	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	13–40			Wojdylo *et al*. 2009	82
	Strawberries	Wet	4 kW, 4 kPa, 45–52 °C, 8 min	54–56			Bohm *et al*. 2006	83
	Strawberries	Wet	390 W for 37 min + 195 W for 15 min	40			Mindak and Dolan 1999	81
			Carotenoids					
β-Carotene	Carrots	Wet	4 kW, 50 °C	30		3–30	Yan *et al*. 2010	68
Total carotenoids	Carrots	Dry	400 W, 25 mbar, 100%/15 min, 50%/30 min, 20%/30 min	4			Cui *et al*. 2004	84
	Chive leaves	Dry	400 W, 25 mbar, 100%/15 min, 50%/40 min, 20%/30 min.	3			Cui *et al*. 2004	84
			Phenolics					
p-Coumaroyl glycoside	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	12–24		12–24	Wojdylo *et al*. 2009	82
Ellagic acid glycoside	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	6–45		6–45	Wojdylo *et al*. 2009	82
Quercetin 3-*O*-glycoside	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min		5–83	(+5–83)	Wojdylo *et al*. 2009	82
Kaempferol 3-*O*-glycoside	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	0–5		0–5	Wojdylo *et al*. 2009	82
Catechin	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	15	2–4	15 (+2–4)	Wojdylo *et al*. 2009	82
Procyanidin B_3	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	25–34		25–34	Wojdylo *et al*. 2009	82
Procyanidin polymers	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	5–10		5–10	Wojdylo *et al*. 2009	82
Total phenols	Blueberries	Wet	3000 W, 2.6 kPa	72		5–77	Mejia-Meza *et al*. 2008	85
	Saskatoon berries	Wet	1.77 kW, 20–25 min	51			Kwok *et al*. 2004	86
	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	11–13			Wojdylo *et al*. 2009	82
	Strawberries	Wet	4 kW, 4 kPa, 45–52 °C, 8 min	54–56			Bohm *et al*. 2006	83
Cyanidin 3-*O*-glycoside	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	5–20			Wojdylo *et al*. 2009	82
Pelargonidin 3-*O*-glucoside	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	23–30			Wojdylo *et al*. 2009	82
Pelargonidin 3-*O*-rutinoside	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	39–50			Wojdylo *et al*. 2009	82
Pelargonidin 3-*O*-malonyl-glucoside	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	21–77			Wojdylo *et al*. 2009	82
Total anthocyanins	Blueberries	Wet	3000 W, 2.6 kPa		252	22–50 (+252)	Mejia-Meza *et al*. 2008	85
	Saskatoon berries	Wet	1.77 kW, 20–25 min	50			Kwok *et al*. 2004	86
	Strawberries	Dry	240, 360, 480 W, 4–6 kPa, 16–33 min	22–28			Wojdylo *et al*. 2009	82
Iron	Grapes	Wet	2450 MHz, 3 kW, 71 °C		135	(+135)	Clary *et al*. 2007	80
Potassium	Grapes	Wet	2450 MHz, 3 kW, 71 °C		450	(+450)	Clary *et al*. 2007	80
Crude fiber	Grapes	Wet	2450 MHz, 3 kW, 71 °C		184	(+180)	Clary *et al*. 2007	80

and vitamin C retention was 100%, 65% and 65%, respectively.[68] Similarly, the β-carotene content was highest in microwave freeze drying (100%) compared to microwave alone and/or with vacuum, which both resulted in 70% retention.[68] In another study, however, microwave vacuum drying of carrot slices resulted in better carotenoid retention than hot air drying, and retention was comparable to freeze drying.[84] Carotenoid retention after microwave alone, microwave + hot air and microwave vacuum + vacuum drying in this second study was 96%, 95% and 98%, respectively. Retention of carotenoids after freeze drying was 95% but after hot-air drying alone was only 70%. Authors stated that residual lipoxygenase (LOX) activity resulted in carotenoid degradation.[84]

Spinach

Total phenolics were retained at only 58% in spinach microwaved at 800 W.[78] Total phenolics content was generally more degraded after boiling than microwaving. Microwaving resulted in higher levels of minerals in spinach as compared to cooking in boiling water for the following: ash, P, K, Ca, Mg, Na, Fe, Zn, Mn, Cu (all but C and Ni, which were same as boiling).[78] In New Zealand spinach the following were higher: ash, P, K, Ca, Mg, Na, Fe, Mn, Cu, Cr and Ni (all but Zn, which was same as boiling).[78]

SUMMARY AND FUTURE RESEARCH NEEDS

Adequate reviews of the literature only exist on effects of high pressure on nutrients, where there were two fairly good reviews. There were no reviews focused on microwave processing and nutrients. Very few studies specified a common process target, e.g. reduction of a number of logs of a specific microorganism, or inactivation of a particular enzyme, for the processes under evaluation. In fact, it was typically difficult to determine how and why the authors chose a particular combination of process conditions.

Most authors reported results on a wet weight rather than a dry weight basis. In the best of all worlds, it is beneficial to have both. It is important to report results on a wet weight basis, because this is relevant to the portion sizes one consumes. However, in order to do so properly it is imperative to record weights before and after application of a process, because changes in moisture content may significantly affect concentration of the nutrient(s) under investigation. It is also desirable to report results on a dry weight basis, so that it is possible to evaluate degradation during processing. Some authors who find increases in nutrient content following a process have suggested that the process increases 'extractability', which may rather be a result of moisture loss and therefore concentration of nutrients.

Few of the microwave studies used the same power level of microwave, or the same power application to the fruit or vegetable; therefore these studies were difficult to compare. There were no studies quantifying effects of the microwave process on tissue structure and subsequent retention or loss of nutrients.

Most studies targeted vitamin C, total phenolics and total carotenoids. Vitamin C studies require more control, due to its sensitivity to oxygen. Because processing often results in conversion of L-ascorbic acid (reduced form) to dehydroascorbic acid, it is important to determine both. There was very little information on the B vitamins, lipids, minerals and fiber. In terms of carotenoid analysis, use of a C30 column allows researchers to determine both *cis* and *trans* isomers. This is important to quantify in processed products in particular as the process may cause transformation. There were very few studies that looked at a large number of 'advanced' processes, as well as thermal, on the same commodity. Only one paper[69] reports on a study comparing orange juice processed using four technologies, e.g. conventional heat, microwave, ohmic and IR.

Therefore, there is a tremendous need for future research which approaches the use of thermal and 'advanced' preservation technologies, using equivalent processes (e.g. to a target endpoint) on a wide range of nutrients, reporting results both on wet and dry weight basis. Only with this type of quantitative information can decisions regarding the best preservation method for nutrient retention be made. In addition, future work must incorporate control of the raw material, from the time it is planted and harvested, including postharvest handling prior to the application of a preservation method. Lack of control of the raw material leaves scientists unable to separate variability in the raw material (due to differences in cultivar/variety, maturity at harvest, growing conditions, agricultural inputs, etc.) from the effect of the preservation method itself. This involves an appreciation of the entire supply chain, from farm to fork, that affects the nutrient content of the fruits and vegetables at consumption.

CONCLUSIONS

Depending on the fruit or vegetable of interest, and the preservation conditions and specific nutrient(s), 'advanced' technologies may have a positive, neutral or negative effect on nutrient retention. To properly address the impact of these technologies, future studies need to include the entire farm-to-fork supply chain. This is a topic of great interest to consumers, and food industry support of well-designed research studies which control the raw material, analyze key nutrients on both a wet and dry weight basis and compare technologies to traditional thermal preservation methods using a common target, are strongly encouraged. Without this type of data it is impossible to recommend new methods of preserving fruits and vegetables such that nutrient losses are minimized as compared to the fresh counterpart, and to offer consumers safely preserved, nutritious fruit and vegetable products that they can consume out of season at locations distant from production. Armed with consistent scientific data and superior preserved fruit and vegetable products, consumers are more likely to add these nutritious products to their plates.

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