Comprehensive REVIEWS in Food Science and Food Safety

Effects of Ultraviolet Light and High-Pressure Processing on Quality and Health-Related Constituents of Fresh Juice Products

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Abstract: Fresh juices are highly popular beverages in the global food market. They are perceived as wholesome, nutritious, all-day beverages. For a fast growing category of premium juice products such as cold-pressed juices, minimal-processing nonthermal techniques such as ultraviolet (UV) light and high-pressure processing (HPP) are expected to be used to extend shelf-life while retaining physicochemical, nutritional, and sensory characteristics with reduced microbial loads. Also, UV light and HPP are approved by regulatory agencies and recognized as one of the simplest and very environmentally friendly ways to destroy pathogenic organisms. One of the limitations to their more extensive commercial application lies in the lack of comparative effects on nutritional and quality-related compounds in juice products. This review provides a comparative analysis using 92 studies (UV light: 42, HPP: 50) mostly published between 2004 and 2015 to evaluate the effects of reported UV light and HPP processing conditions on the residual content or activity of bioactive compounds such as vitamins, polyphenols, antioxidants, and oxidative enzymes in 45 different fresh fruit and vegetable juices (low-acid, acid, and high-acid categories). Also, the effects of UV light and HPP on color and sensory characteristics of juices are summarized and discussed.

Keywords: color, enzyme, juice, nonthermal processing, nutritional quality

Introduction

Fresh juices are popular nonalcoholic (soft) drinks in the global beverage market. They are perceived as wholesome, nutritious, all-day beverages and as a simple way to get vitamins or calcium supplementation. However, because many popular juice brands are made from concentrates or purees as the major ingredient, juice products have recently come under fire regarding calorie and sugar concerns. Heat pasteurization has been used as an established standard method to extend juice shelf-life and provide safety of the finished products. Low-temperature long-time (LTLT) pasteurization and high-temperature short-time (HTST) pasteurization are used in large-scale continuous-mode juice production (Rupasinghe and Yu 2012). HTST has now replaced LTLT as the most commonly used pasteurization method for the treatment of juice products. However, juices that undergo thermal pasteurization tend to change color and lose some of their aroma and nutritional value during the process of heating.

In addition to the existing market of pasteurized juices and beverages, the premium segment of the juice industry, worth approximately $3.4 billion (USD), has shown exponential growth around the globe, while traditional beverages, for example, carbonated soft drinks, are on the decline (Blumenthal 2012). The growing consumption of premium and ultra-premium categories of juices has been attributed to the perceived health benefits of reduced calories, reduced sugar, and the "all natural" message based on high contents of enzymes, nutrients, and bioactive constituents. The addition of vegetable juices and fruit-vegetable blends also drives the low-calorie and health-beneficial messages. To achieve these attributes, the premium juice category is minimally processed using cold-pressing or other extraction methods to minimize treatment temperature and exposure to oxygen. Initially, small point-of-sale local processors who produce juice and sell it fresh or unpasteurized with a shelf-life of a few days dominated the cold-pressed premium juice sector. The growth of the cold-pressed juice industry into regional or national markets required higher juice yield after pressing and extension of product shelf-life to at least a few weeks. Additionally, given the number of foodborne illness outbreaks linked to fresh juices and beverages in high-acid and low-acid categories (Danyluk and others 2012), there is also a need to implement additional pathogen intervention processing steps, which have a dual purpose to ensure safety and to comply with the juice Hazard Analysis Critical Control Point (HACCP) requirements.

Given the expectations of fresh product quality for cold-pressed juices with respect to nutritive and health benefits, the use of nonthermal technologies is considered as more advanced, alternative processing options. To this end, high-pressure processing

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(HPP) or high-hydrostatic pressure (HHP) processing and ultraviolet (UV) light exposure currently represent attractive preservation strategies. The 2 treatments are contrasting with respect to the mode of operation, cost requirements, mode of microbial inactivation, and effect on product constituents. The application of HPP technology to fresh juices and other foods has experienced broad commercial success. Visiongain has predicted that the global HPP market will reach $9.8 billion (USD) and that the number of commercial HPP units will reach 350 in 2015 (Visiongain 2015). HPP currently serves as the primary processing technology in the cold-pressed juice market dominated by companies such as Suja Juice, BluePrint, and Evolution Fresh (Blumenthal 2012). The commercialization of UV light technology requires acceleration through existing regulatory approval in the U.S. and Canada, with emphasis on its validation at the commercial scale. A large knowledge gap remains with respect to the fate of juice quality and health-related constituents of fruits and vegetables including vitamins, antioxidants, enzymes, sensory compounds, and natural pigments. Therefore, the main motivation for juice processors is to select the most appropriate nonthermal technology along with validated processing conditions to retain nutritive constituents and color and flavor attributes. The overall objective of this review is to characterize and compare analyses of reported HPP and UV light processing conditions followed by an evaluation of their effects on quality and health-related bioactive compounds and sensory attributes over a broad range of fresh fruit and vegetable juices.

Search Approach for a Review of the Current Literature

The effect of UV light and HPP on quality attributes in 45 types of fresh juices in low-acid, acid, and high-acid categories is presented. This includes about 35 types of fruit juices (apple, orange, grape, mango, pineapple, and so on), 5 popular vegetable juices (carrot, cucumber, tomato, green asparagus, and green beans), 2 nut milk beverages (coconut and tiger nut) and their blends (garden juice, orange-carrot, citrus blend). The collected reports had been published mainly in the period from 2004 to 2015. For the analysis, the data from a total of 92 peer-reviewed research articles (UV light: 42, HPP: 50) and other research documents were analyzed. Scopus was the primary database used for collection of the articles. Only articles reporting solely the use of UV light or HPP on fresh fruit or vegetable juices were considered for this review. Other than the use of mild heat with HPP, combination treatments were omitted. Older studies (1990 to 2000) were only included if they added unique information to the review, such as juice type. Whenever possible, results with the highest reported UV dose or, in the case of HPP, pressure and exposure time, were used. Likewise, results with temperature values close to room temperature were favored. In the case of UV light, the applications of monochromatic light from low-pressure mercury (LPM) lamps and polychromatic light from medium-pressure mercury (MPM) lamps were both selected for this review. *Percent remaining content* (posttreatment concentration/original concentration) was used to report the effects of UV and HPP treatments on vitamins and total phenols; whereas *percent remaining activity* (posttreatment activity/original activity) was used for enzymes and antioxidants. In addition to summarizing the literature data, this review includes a discussion of factors affecting quality parameters in fresh juices, color, and sensory characteristics.

Part 1: Introduction to UV Processing of Juices

UV light covers only a part of the electromagnetic spectrum, which also includes radio waves, microwaves, infrared radiation, visible light, X-rays, and γ-radiation. UV light involves the use of radiation from 100 to 400 nm and is categorized as UV-A (320 to 400 nm), UV-B (280 to 320 nm), and UV-C (200 to 280 nm) (Koutchma and others 2009). UV-C light is considered to be germicidal against microorganisms such as bacteria, viruses, protozoa, yeasts, molds, and algae. The wavelength of 253.7 nm is used for the disinfection of surfaces, water, and various liquid food products including juices. UV-C treatment is performed at low temperatures and is classified as a nonthermal method. The other advantages associated with UV-C treatment are that no known toxic or significant nontoxic by-products are formed during the treatment, certain organic contaminants can be removed, no off-flavor or off-odor is formed when treating juice, and the treatment requires very little energy when compared to thermal pasteurization processes (Koutchma and others 2009).

Contrary to thermal processing, juices that are treated with UV radiation tend to maintain their aroma, taste, and color (Tran and Farid 2004). The U.S. FDA has approved UV-C radiation for the treatment of juice products to reduce human pathogens and other microorganisms (FDA, U.S. 2001). The U.S. Code of Federal Regulations (21 CFR 179.39) recognizes distinctions between flow patterns and stipulated turbulent flow through tubes with a minimum Reynolds (Re) number of 2200. The radiation source must consist of LPM lamps, which emit 90% of their UV light at a wavelength of 253.7 nm. This is known as a monochromatic light signal. LPM lamps operate at approximately 40 °C and at pressures of 10^2 to 10^3 Pa (Koutchma and others 2009). Later, Health Canada issued no objections in a novel foods decision on the use of the CiderSure 3500 UV (FPE Inc., Macedon, N.Y., U.S.A.) unit for apple juice/cider treatment to reduce the levels of microbial pathogens (Health Canada 2003). The regulatory review of the information presented in support of UV treatment concluded that there are no human food safety concerns associated with the sale of juice products that have been treated under the operating conditions within these constraints. Also, there is no objection to the application of this process as proposed. Moreover, data provided on the photochemistry of juice products indicated that the only degradation products that would occur from UV treatment of juice/cider products are those that occur naturally from sunlight.

Although not approved by U.S. FDA or Health Canada, MPM lamps are an alternative source of UV light, which is also presented in this review. MPM lamps emit more powerful polychromatic light between 250 and 600 nm with emission lines in the UV and visible light regions. These lamps are operated at higher temperatures (400 to 800 °C) and pressures (10^4 to 10^6 Pa) and are able to achieve a higher penetration depth (Koutchma and others 2009).

Regulatory approval of the UV process led to growing interest in accelerating technological commercialization and researching the quality and nutritional aspects of UV light technology on juices. The first part of this review is focused on the analysis of available research that investigated effects of UV treatment on quality and health-related constituents of fresh juice products. In total, 22 types of clear (apple, grape) and opaque (carrot, orange, pineapple, mango) juices were identified in the reported UV studies. A total of 17 juices were derived from fruit origin, 4 were derived from vegetables, and 1 juice was a blend of orange and carrot juices. The analyzed juices were primarily prepared by mechanical extraction from freshly purchased fruits or vegetables. The remaining authors either prepared the juices from concentrate or purchased freshly prepared juice from a local market.

UV light effects in juices have been analyzed based on:

1. Characterization of UV light equipment and processing conditions through UV dose, flow regimes and microbial inactivation
2. Characterization of the properties of tested fresh juices
3. Evaluation of the UV light sensitivity of health-related constituents such as vitamins, enzymes, and antioxidants
4. Effect of UV light on color and sensory other attributes
5. Establishing juice parameters (UV absorption coefficient, pH, viscosity, and soluble solids content) that can affect destruction of juice attributes after exposure to UV light.

Characterization of UV light systems

For fluids with low or close to zero UV light transmittance, such as fresh fruit or vegetable juices, the design of a continuous UV system, UV dose, and its mixing efficiency defines process performance, and consequently, delivery of UV photons. The majority of the reported studies were conducted using custom-made lab-scale UV devices in continuous and batch systems.

A well-defined UV treatment system will include information such as lamp characteristics, lamp power (W), lamp wavelength (nm), description of the reactor (continuous flow conditions or batch apparatus), the number of lamps used, and, in the case of a continuous system, the number of passes through the reactor. These parameters of UV units and processing conditions are summarized in Table 1 for the collected UV processing studies. Three types of lab-scale UV continuous systems were used: annular systems in laminar and turbulent flow, coiled-tube systems in Dean flow and Taylor-Coutte systems. Additionally, the results from the application of 3 commercial UV units, including CiderSure (thin-film laminar flow; FPE, N.Y., U.S.A.), Salcor module (Dean flow in coiled tube, turbulent; Calif., U.S.A.) and SurePure (thin film, turbulent; SupePure Inc. Zug, Switzerland) are reported in this review.

Batch reactors were designated as either collimated beam units or having direct overhead exposure. Collimated beam systems are used in water treatment bio-dosimetry studies with narrow and focused bands of UV light in a cylindrical tube which extends from the light source (lamp) to the sample. Direct overhead exposure refers to an uncontained light source which is simply located above the sample.

Energy evaluation in UV systems

The UV dose is a critical process parameter that defines microbial efficacy and impact of UV light on delivering a fresh-like product. In order to properly evaluate the UV dose in a system, it is necessary to classify it in terms of the energy data information (from manufacturer or measured) and according to the UV source, the system, and product characteristics. All the variables mentioned below are defined in the Nomenclature section.

The general form of the UV dose (or fluence) calculation is given in the form of Eq. (1):

$$E = I \cdot t \tag{1}$$

where E, I, and t are the UV dose, irradiance (W/cm^2), and exposure time (s), respectively, defined depending on the classification below.

In continuous UV systems, the total applied UV dose (E_{UV}), either in Joules per liter of liquid (J/L) (Eq. (2)) or Joules per unit area (J/cm^2) (Eq. (3)), is calculated based on the total output power of the UV source (P_{UV}), in Watts. Such data are given by the manufacturer or by the equipment energy consumption information. The time used in the calculation is the fluid average residence time in the UV system. E_{UV} is independent of the material being irradiated and of the configuration of the system. It is important for researchers reporting UV dose in continuous systems to supply all the necessary system parameters required for dose calculation in both kJ/L and J/cm^2. Interconversion between these units will allow for proper comparison of UV dose values among researchers and commercial applications.

$$E_{UV} = \frac{P_{UVN}}{\dot{V}} = \frac{L_N \cdot P_{UV}}{\dot{V}} \tag{2}$$

$$E_{UV} = \frac{P_{UV}}{A_l} \cdot t \tag{3}$$

The total output power in the UV-C range ($P_{UV\text{-}C}$) is typically around 30% or 10% of the total wattage for LPM and MPM lamps, respectively (Rodriguez-Gonzalez and others 2015). In batch UV systems, the *incident* UV dose (H_0), J/cm^2, is often reported and can be defined as the energy that is actually incident at the surface of the product. H_0 is calculated based on the incident UV irradiance or fluence rate (I_0), W/cm^2 on the surface of the product (Eq. (4)). I_0 is provided by the manufacturer, but its value should be also measured with a radiometer at a controlled distance from the UV source and the measurement has to be checked periodically in order to take into account the decrease in lamp power during its lifetime. The time used in the calculation is the total exposure time of the fluid in seconds. Fluence rate is defined as the total radiant power incident from all directions onto an infinitely small sphere of cross-sectional area dA, divided by dA (Bolton and Linden 2003) and UV dose is the fluence rate multiplied by the exposure time. H_0 depends on the configuration of the system, but it is independent of the material being irradiated.

$$H_0 = I_0 \cdot t \tag{4}$$

For comparison purposes, the applied UV dose in continuous UV systems was expressed in kJ/L; the applied UV dose in batch systems was expressed in J/cm^2. The *absorbed* UV dose (H_r), J/cm^2, takes into account parameters of the system and of the liquid product. H_r is the radiant UV energy that is actually absorbed by the medium and its constituents (homogeneous fluid) and is available for driving a photo-reaction. H_r is calculated for continuous and batch systems based on the absorbed UV irradiance or fluence rate (I_r), W/cm^2 by the product (Eq. (5)). I_r is calculated in 2 different ways depending on whether the UV system is continuous (Eq. (6)) or batch (Eq. (7)). In the case of continuous systems, the time used in the calculations is the UV exposure time or average period of time in which each volume of the liquid is in close contact with the surface of the lamp sleeve. Total exposure time is considered in the calculations of batch systems, either agitated or not in a thin layer. H_r depends on the UV light-absorbing characteristics (absorption coefficient) of the material being irradiated and on the configuration of the system.

$$H_r = I_r \cdot t \tag{5}$$

Absorbed UV irradiance or fluence rate (I_r) in a continuous flow UV system can be calculated using Eq. (6) (Gomez-Lopez and others 2012):

Table 1–UV continuous and batch processing conditions of reported fruit and vegetable juices

Juice	UV system					Reference
	Lamp type	Lamp power (W)	Lamp wavelength (nm)	Reactor type	No. of lamps/passes	
Continuous UV treatment						
Apple	LPM, UV-C	30	254	Annular	1/1	Caminiti 2012a
Apple	LPM,UV-B and C	36, 8.3	254, 290 to 315	Coiled tube	2/25	Muller 2014
Apple	LPM, UV-C	8	254	Thin–film in series	8/1	Gayán 2013
Apple cider	LPM, UV-C	3.8	254	Taylor-Couette	1/10	Orlowska 2014
Carrot	LPM, UV-C	65	254	Dean flow system (Salcor)	24/1	Koutchma 2009
Coconut milk	LPM, UV-C	17	254	Annular	1/1	Ochoa-Velasco 2014
Grape	LPM, UV-B and C	36, 8.3	254, 290 to 315	Coiled tube	2/25	Muller 2014
Grape *(white and red)*	LPM, UV-C	28	254	Coiled tube	9/1	Pala 2013a
Grape	LPM, UV-C	15	254	Annular	7/5	Unluturk 2014
Grape *(white)*	LPM, UV-C	15	254	Annular	7/8	Unluturk 2015
Guava nectar	LPM, UV-C	65	254	Dean flow system (Salcor)	24/1	Koutchma 2009
Lemon-melon	LPM, UV-C	15	254	Annular	4/8	Kaya 2015
Lilikoi	LPM, UV-C	65	254	Dean flow system (Salcor)	24/1	Koutchma 2009
Mango nectar	LPM, UV-C	25	254	Annular in series	2/54.1	Guerrero-Beltran 2006
Orange/carrot blend	LPM,UV-C	30	254	Tubular, rising film		Caminiti 2012b
Orange	LPM, UV-C	28	254	Coiled tube	9/4	Pala, 2013b
Orange	LPM, UV-C	65	254	Dean flow system (Salcor)	24/1	Koutchma, 2009
Orange	LPM, UV-C	30	254	Laminar, vertical thin film	1/12	Torkamani 2011
Orange	LPM, UV-C	30	254	Laminar, vertical thin film	1/6, 8	Tran 2004
Pitaya	LPM, UV-C	17	254	Annular	1/1	Ochoa-Velasco 2013
Pineapple	LPM, UV-C	–	254	Laminar thin-flow, CiderSure 3500-B	8	Goh 2012
Pineapple	LPM, UV-C	–	254	Laminar thin-flow, CiderSure 3500-B	8	Sew 2014
Pineapple	LPM, UV-C	–	254	Laminar thin-flow, CiderSure 3500-B	8	Chia 2012
Pineapple	LPM, UV-C	65	254	Dean flow system (Salcor)	24/1	Koutchma 2009
Pomegranate	LPM, UV-C	28	254	Coiled tube	9/5	Pala 2011
Watermelon	LPM, UV-C	65	254	Dean flow system (Salcor)	24/1	Koutchma 2009
Watermelon	LPM, UV-C	75	254	Coiled tube, Dean flow	1/1	Feng 2013
Watermelon	LPM, UV-C	9	254	Coiled tube	1/12	Zhang 2011
Batch UV treatment						
Acetic buffer (pH 4.0)	LPM, UV-C	–	185, 254	Overhead exposure	2	Sampedro 2014
Apple	LPM, UV-C	15	254	Overhead exposure in thermostated cell	–	Manzocco 2009
Apple	MPM, UV-B and C	2660	248 to 312	Collimated beam	1	Orlowska 2013
Apple	LPM, UV-C	20	254	Collimated beam	1	Orlowska 2013
Apple	LPM	10	254	Collimated beam	3	Tikekar 2011
Apple	LPM, UV-C	30	254	Overhead exposure	1	Noci 2008
Apple	LPM, UV-C	–	254	Overhead exposure	1	Zhu 2014
Apple (Golden)	MPM, UV-B and C	400	250 to 740	Overhead exposure in dark chamber	1	Falguera 2011
Coconut water model solution	MPM, UV-B and C	400	250 to 740	Overhead exposure in dark chamber	1	Augusto 2015
Grape (Dauphine)	MPM, UV-B and C	400	250 to 740	Overhead exposure in dark chamber	1	Falguera 2013a
Grapefruit (4 and 10 °C)	LPM, UV-C	36	254	Overhead exposure in dark chamber	3	La Cava 2015
Mango	LPM, UV-C	30	254	Overhead exposure	1	Santhirase-garam 2015
Orange	LPM, UV-C	15	254	Collimated beam	1	Taze 2015
Orange	LPM, UV-C	–	185, 254	Overhead exposure	2	Sampedro 2014
Pear (Flor de Invierno)	MPM, UV-B and C	400	250 to 740	Overhead exposure in dark chamber	1	Falguera 2014
Phosphate buffer (pH 6.8)	LPM,UV-C	15	254	Overhead exposure in dark chamber	5	Haddouche 2015
Phosphate buffer (pH 7.0)	LPM, UV-C	15	254	Overhead exposure in thermostated cell	–	Manzocco 2009
Sodium phosphate buffer (pH 5.0, 25 °C)	MPM, UV-B and C	400	250 to 740	Overhead exposure in dark chamber	1	Falguera 2013b
Sodium phosphate (pH 4.0, 25 °C), Sodium acetate (pH 7.0, 25 °C)	LPM, UV-C	–	185, 254	Overhead exposure	2	Sampedro 2014
Starfruit	LPM, UV-C	–	254	Overhead exposure	1	Bhat 2011
Tiger nuts' milk	LPM, UV-C	9	254	Overhead exposure in dark chamber	1	Corrales 2012

$$I_r = I_0 \cdot \frac{r_0}{r} \cdot exp\left[-\alpha_\lambda \cdot (r - r_0)\right] \quad (6)$$

Absorbed UV irradiance or fluence rate ($I_{r\,avg}$) in batch UV systems (Bolton and Linden 2003):

$$I_{r\,avg} = I_0 \cdot RF \cdot PF \cdot WF \cdot DF \quad (7)$$

where

$$WF = \frac{1 - 10^{-a_\lambda l}}{a_\lambda l \ln(10)} \quad (8)$$

$$DF = \frac{L}{(L + l)} \quad (9)$$

The *delivered* UV dose (H_d), J/cm^2, is the remaining available energy (that has not been absorbed by the other constituents of the fluid) that is actually delivered to the microorganisms. The delivered or effective UV dose is typically estimated by using biodosimetry or actinometry approaches.

The values of the applied UV doses for all selected studies were evaluated based on the available reported data. The reported and calculated UV dose values for continuous and batch UV treatments of juices are summarized in Table 2 and 3.

Calculation of absorbed UV irradiance was not possible for any of the studies as there were insufficient data given in order to use Eqs (5) to (9). Those equations are to be considered as possible approaches, once there are other ways to calculate and measure the absorbed UV irradiance. In the cases when the authors did measure or calculate those values, they are presented in Table 2 as reported data. Another point to be noted is that the approach suggested by Bolton and Linden (2003) (Eqs (7) to (9)) is mainly applied for water or similar liquids.

Flow conditions

Commercial UV systems for liquids are typically flow-through systems characterized by a nonuniform distribution of residence time (RTD) and, consequently, distribution of UV exposure time. The flow rate/pattern strongly influences the total applied UV dose, because the position and the residence time of the microorganisms in certain regions of the irradiance field can vary. Flow characteristics were evaluated for reported UV parameters of juices for the range of flow rates tested and for each product through the calculation of the Reynolds number (Re) as shown in Eq. (10), where velocity (v) is calculated as in Eq. (11). The Re numbers had to be calculated because viscosity, system geometry, flow rate/pattern, and temperature varied (Table 2).

$$\mathrm{Re} = (V_L \times d \times \rho)/\mu \quad (10)$$

$$V_L = \dot{V}/A_C \quad (11)$$

Based on the UV system characteristics extracted from the studies (Table 1), additional calculations of Re numbers were performed.

As can be seen from Table 2, the majority of studies in continuous flow UV systems reported the value of total applied UV dose (E_{UV}). Where sufficient data were present, E_{UV} was used to calculate the corresponding $E_{UV\text{-}C}$ value which better represents the actual UV dose. The reported or calculated UV doses covered a broad range from 0.15 up to 933.6 kJ/L. In regards to incident UV dose, which was calculated for comparison purpose with batch UV systems, the H_0 values covered the range from 7.6 to 53100 mJ/cm^2, with the average range between 100 and 1756 mJ/cm^2. Also, it should be mentioned that many studies did not achieve the U.S. FDA recommended turbulent flow regime of Re > 2000. As can be seen from Table 2 and 3, the majority of studies reported the microbial efficacy only in terms of the reduction of total plate aerobic counts, yeasts and molds, and often *Escherichia coli* bacteria. Achieving 5-log reductions of the most resistant pathogen of concern for specific juice category was not the objective.

Surprisingly, the UV dose tested in commercial UV systems in microbial inactivation studies appeared to be lower than in lab-scale and pilot-scale UV systems. The typical range of UV doses reported in continuous commercial systems was between 1.5 to 7 kJ/L, which is similar to previously reported values required to achieve 5-log reductions of various juice and milk pathogens also in continuous commercial UV systems (1.38 to 2.0 kJ/L) (Keyser and others 2008; Koutchma and others 2009; Crook and others 2015). However, pilot-scale continuous systems reported 5-log reduction with UV doses as high as 186.7 kJ/L (Unluturk and Atilgan 2014). This suggests that noncommercial UV systems are often inefficient at delivering the theoretical UV dose to the target microorganism. Table 3 shows that the absorbed UV dose was more commonly reported in batch UV systems than in continuous systems. Nevertheless, incident UV dose was still the most commonly reported form of UV dose in batch systems. The reported or calculated incident UV doses showed a wide range from 5.9 to 1269000 mJ/cm^2. According to reported microbial inactivation studies in juices, the range of UV dose values to achieve 5-log reduction of juice pathogens was between 14.3 and 2500 mJ/cm^2 (Fan and Geveke 2007; Koutchma and others 2009). The development and use of standard approaches for UV dose evaluation and reporting data for achieving required microbial reduction of target pertinent pathogen in juices will allow to establish equivalent processing conditions in UV systems with different designs and compare UV dose effects on quality and nutrition attributes.

Physicochemical properties of juices treated with UV light

Product composition, soluble solids content, color, and overall chemistry of the juice product have a major impact on both the absorption properties and the effectiveness of UV processing. In addition to pH, the physicochemical quality parameters that are typically controlled in juices and that are reported here include pH, total and titratable activity, soluble solids content, viscosity, and UV light absorption coefficient. The physicochemical properties of various reported juices are shown in Table 4.

These juices can be grouped into low acid, acid, and high acid categories (Table 5). The acidity of juice has to be considered to identify a pertinent target organism. Consequently, the UV resistance of the pertinent pathogens will define the value of the minimum UV dose necessary to achieve the 5-log reduction requirement or Food Safety Objective (FSO). The processing effects of nonthermal treatments (HPP and UV light) should be compared based on equivalent treatment conditions resulting in a similar FSO. Guidance on selecting the pertinent microorganism for juices for purposes of meeting the 5-log pathogen reduction requirement is provided by the U.S. FDA in "Juice HACCP Hazards and Controls Guidance" (FDA, U.S. 2004).

UV light processing did not significantly impact the pH, soluble solids content, and turbidity of juices (data not shown). The majority of the authors did not measure properties of juices such

Table 2–Reported and calculated UV dose values and microbial inactivation for continuous UV treatment of fruit and vegetable juices

Juice	Reported			Calculated Applied UV-C dose, $E_{UV\text{-}C}$ (kJ/L)					
	Applied UV dose, E_{UV} (kJ/L)	Incident UV dose per pass, H_0 (mJ/cm^2)	Absorbed UV dose per pass, H_r (mJ/cm^2)	Per pass	Total	Re	Tested organisms	SLR	Reference
Apple	–	–	53100	24.5	24.5	65	NA	–	Caminiti 2012a
Apple	100.5	–	–	1.2	30.1	1002	TAPC	0.5	Muller 2014
							Y&M	1.5	
Apple	27.1	–	–	8.1	8.1	210	*EC*	5.0	Gayan 2013
Apple	–	–	–	1.5	1.5	4352	*EC*	5.0	Koutchma 2009
Apple cider	–	–	4.5	0.2	1.5	2344	*EC*	4.6	Orlowska 2014
Carrot	–	–	–	1.5	1.5	4352	TAPC	3.0	Koutchma 2009
							EC	3.0	
Coconut milk	–	102.6	–	0.2	0.2	44	EC	4.1	Ochoa-Velasco 2014
							ST	4.1	
							TAPC	2.0	
							Y&M	1.3	
Garden vegetable	–	–	–	1.5	1.5	4352	*EC*	1.9	Koutchma 2009
Grape	100.5	–	–	1.2	30.1	1015	TAPC	2.0	Muller 2014
							Y&M	2.0	
Grape	583.5	–	–	35.0	175	5	EC	3.8	Unluturk 2014
							LAB	4.1	
							Y	1.6	
Grape *(white)*	933.6	–	1240	35	280	5	*EC*	5.34	Unluturk 2015
Grape *(white and red)*	12.6 or 25.2	–	–	12.6	12.6	1404	–	–	Pala 2013a
Grape *(white)*	12.6 or 25.2	–	–	12.6	25.2	1404	TAPC	3.5	Pala 2013a
							Y&M	2.7	
Grape *(red)*	12.6 or 25.2	–	–	12.6	25.2	1404	TAPC	3.6	Pala, 2013a
							Y&M	2.9	
Guava nectar	–	–	–	1.5	1.5	4352	TAPC	1.3	Koutchma 2009
							Y&M	1.6	
Lemon-melon	2.5	–	–	4.7	37.9	169	*EC*	>6	Kaya 2015
Lilikoi	–	–	–	1.5	1.5	4352	*EC*	5.0	Koutchma 2009
Mango nectar	–	–	–	2.0	108.0	–	TAPC	2.7	Guerrero-Beltran 2006
							SC	5.0	
Orange-carrot blend	–	–	10620	6.1	6.1	15	*PF*	5.0	Caminiti 2012b
Orange	48.1	–	–	12.0	48.1	81	TAPC	2.8	Pala 2013b
							EC	5.7	
							Y&M	0.34	
Orange	7.2	–	–	0.6	7.2	–	–	–	Torkamani 2011
Orange	3.6	–	87.8	0.6	3.6	–	TAPC	1.0	Tran 2004
			119				Y&M	1.0	
Orange	4.8	–	–	0.6	4.8	–	TAPC	–	Tran 2004
							Y&M		
Orange	–	–	–	1.5	1.5	4352	TAPC	1.3	Koutchma 2009
							Y&M	1.6	
							EC	0.8	
Pitaya	–	102.6	–	0.2	0.2	203	ZB	1.8	Ochoa-Velasco 2013
							TAPC	1.76	
Pineapple	–	7.5	–	4.6	4.6	1076	NA	–	Goh 2012
Pineapple	–	11.23	–	7.0	7.0	712	NA	–	Sew 2014
Pineapple	–	53.42	–	7.0	7.0	714	TAPC	3.0	Chia 2012
							Y&M	3.0	
Pineapple	–	–	–	1.5	1.5	4352	TAPC	1.3	Koutchma 2009
							Y&M	1.6	
Pomegranate	62.4	–	–	12.5	62.3	1418	TAPC	1.8	Pala 2011
							EC	6.1	
							Y&M	1.45	
Watermelon	–	–	–	1.5	1.5	4352	NA	–	Koutchma 2009
Watermelon	37.5	–	–	11.3	11.3	–	TAPC	1.5	Feng 2013
							EC	2.6	
							YM	1.0	
Watermelon	9.7	–	–	1.2	13.9	–	NA	–	Zhang 2011

Re, Reynolds number; NA, not available; SLR, specific log reduction; TAPC, total aerobic plate count; Y, yeast; Y&M, yeast and mold; LAB, lactic acid bacteria; *EC*, *Escherichia coli*; *ST*, *Salmonella typhimurium*; *ZB*, *Zygosaccharomyces bailii*; *SC*, *Saccharomyces cerevisiae*; *AA*, *Alicyclobacillu acidoterrestris*; *PF*, *Pichia fermentans*.

Table 3–Reported and calculated UV dose values and microbial inactivation for batch UV treatment of fruit and vegetable juices and model systems

Juice	Reported			Calculated	Tested organism	SLR	Reference
	Incident UV dose, H_0 (mJ/cm^2)	Absorbed UV dose, H_r (mJ/cm^2)	Measurement of absorbed dose	Incident UV dose, H_0 (mJ/cm^2)			
Acetic buffer (pH 4.0)	58.2	–	–	–	NA	–	Sampedro 2014
Apple (clear)	–	–	–	12483	NA	–	Manzocco 2009
Apple	–	10	–	–	NA	–	Orlowska 2013
Apple	–	–	–	–	TAPC	2.2	Noci 2008
Apple	3390	–	–	–	NA	–	Tikekar 2011
Apple	–	84.2	–	2339	NA	–	Zhu 2014
Apple (Golden)	–	–	Actinometry	–	NA	–	Falguera 2011
Coconut water model solution	–	–	Actinometry	85	NA	–	Augusto 2015
Grape (Dauphine)	–	–	Actinometry	–	NA	–	Falguera 2013a
Grapefruit (4 and 10 °C)	–	3940	Actinometry	–	NA	–	La Cava 2015
Malic acid (0.5%, pH 3.3)	13400	–	–	–	NA	–	Tikekar 2011
Mango	–	–	–	1269000	TAPC	1.2	Santhiraseg-aram 2015
					EC	1.0	
					Y&M	0.8	
Orange	–	108.4	Biodosimetry	1584	Y	1.5	Taze 2015
Orange	58.2	–	–	–	NA	–	Sampedro 2014
Pear (Flor de Invierno)	–	–	Actinometry	431280	NA	–	Falguera 2014
Phosphate buffer (pH 6.8)	4800	–	–	4800	NA	–	Haddouche 2015
Phosphate buffer (pH 7.0)	–	–	–	6210	NA	–	Manzocco 2009
Sodium phosphate (pH 5.0, 25 °C)	–	–	–	–	NA	–	Falguera 2013b
Sodium phosphate (pH 7.0, 25 °C)	5.8	–	–	5.9	NA	–	Sampedro 2014
Sodium acetate (pH 4.0, 25 °C)	58.2	–	–	58.5	NA	–	Sampedro 2014
Starfruit	–	–	–	777	TAPC	2.0	Bhat 2011
					Y&M	2.0	
Tiger nuts' milk	4230	–	Actinometry	4230	TAPC	3.0	Corrales 2012
					Y&M	3.0	

SLR, specific log reduction; TAPC, total aerobic plate count; Y, yeast; Y&M, yeast and mold; *EC*, *Escherichia* coli; *ZB, Zygosaccharomyces bailii*; *AA, Alicyclobacillu acidoterrestris*; *PF, Pichia fermentans.*

Table 4–Essential physicochemical properties of UV-treated fruit and vegetable juices

Juice	pH	Soluble solids content	Viscosity *(Pa.s)*	Absorption coefficient *(cm^{-1})*	Reference
UV continuous treatment					
Apple	3.7	11.2	0.003[a]	–	Caminiti 2012a
Apple	3.8	13.8	0.003	52.4	Muller 2014
Apple	4.0	–	0.003 [a]	–	Gayán 2013
Apple cider	3.7	12	0.002	17.4	Orlowska 2014
Carrot	3.8	9.5	0.010	–	Koutchma 2009
Carrot/orange	3.8	9.0	0.052 [a]	–	Caminiti 2012b
Grape	3.7	–	0.023	36.5	Unluturk 2014
Grape (white)	4.0	18.6	0.023 [a]	12.3	Unluturk 2015
Grape	3.7	–	0.003	43.4	Muller 2014
Grape (white)	4.0	21.9	0.003[a]	–	Pala 2013a
Grape (red)	3.4	19.2	0.003[a]	–	
Guava nectar	6.3	9.1	0.005	–	Koutchma 2009
Lemon-melon	3.9	8.7	0.003 [a]	14.9	Kaya 2015
Lilikoi	3.0	11.0	0.0056	–	Koutchma 2009
Mango nectar	3.8	13.0	–	–	Guerrero-Beltran 2006
Orange	4.1	11.6	0.052 [a]	–	Pala 2013b
Orange	3.3	7.4	0.052	–	Koutchma 2009
Orange	–	10.5	–	–	Tran 2004
Pitaya	5.8	7.0	0.005 [a]	–	Ochoa-Velasco 2013
Pineapple	4.0	13.5	0.053 [a]	–	Chia 2012
Pineapple	4.0	14.2	0.053	–	Koutchma 2009
Pomegranate	3.4	16.3	0.003 [a]	–	Pala 2011
Watermelon	5.2	8.1	0.0067	–	Koutchma 2009
Watermelon	5.3	9.5	–	–	Feng 2013
UV batch treatment					
Apple	3.5	11.6	0.00139	13.9 to 20	Orlowska 2013
Apple	3.7	12.8	–	–	Noci 2008
Apple	3.9	10.7	–	–	Falguera 2011
Apple	3.2	11.1	–	24.8	Zhu 2014
Grape (Dauphine)	3.2	17.1	–	–	Falguera 2013a
Grapefruit (4 °C)	3.2	9.7	–	–	La Cava 2015
Grapefruit (10 °C)	2.9	11.8	–	–	
Mango	4.6	14.7	–	–	Santhirasegaram 2015
Orange	3.7	13.7	–	71.7	Taze 2015
Orange	3.8	–	–	–	Sampedro 2014
Pear(Flor de Invierno)	4.9	11.7	–	–	Falguera 2014
Starfruit	4.4	9.1	–	–	Bhat 2011
Tiger nuts' milk	7.0	–	–	–	Corrales 2012

[a] Viscosity values were estimated in order to calculate the Re number.

Table 5–pH categories of UV-treated fresh fruit and vegetable juices

High acid (pH < 3.5)	Acid (pH < 4.6)	Low acid (pH > 4.6)
Lemon	Mango nectar	Watermelon
Passion fruit (Lilikoi)	Pineapple	Cantaloupe
Pomegranate	Lemon-melon	Pitaya
Apple cider	Carrot/orange	Carrot
Grape		Guava nectar
Orange		Tiger nuts
Carrot (acidified)		Pear
Grapefruit		Coconut milk
Starfruit		Garden vegetable

as viscosity or absorption coefficient. However, these properties are critical in terms of their impact on UV dose delivery and for the proper estimation of the applied and absorbed UV dose. Additionally, viscosity of juices impacts the hydrodynamic behavior of the liquid in the UV system and, consequently, the delivery of UV photons in treated juice.

UV absorbance or percent transmittance of juices has been identified as a critical factor for UV processing. Pigments, organic solutes (sugars and organic acids), and suspended matter increase the absorption and reduce the transmission of UV light, thereby lowering the performance efficiency of UV treatments and affecting the level of nutrient destruction. The reported UV absorption characteristics varied for clarified juice products, ranging from 12.3 cm^{-1} for apple juice up to 43 cm^{-1} for grape juice. The absorption coefficient of turbid unfiltered juices with particles reached 71.7 cm^{-1} in the case of orange juice (Table 4).

Ye and others (2007) reported that the color lightness (L^*) of apple juice was correlated directly with the absorption coefficient: the higher the L^* value the higher the absorption coefficient of apple juice was observed. Also, the correlation between absorption coefficients and vitamin C contents was found. In general, larger values of vitamin C were correlated with larger absorption coefficients of juices. As a result of this, the understanding of UV light effects on the destruction of vitamin C during treatment becomes critical from the UV dose delivery point of view.

UV sensitivity of health-related constituents

Vitamins. Vitamin destruction after exposure to UV light is a concern because some vitamins are considered light-sensitive. It is usually stated that water-soluble, light sensitive vitamins include C (ascorbic acid), B12 (cobalamin), B6 (pyridoxine), B2 (riboflavin), and folic acid. Fat- soluble, light-sensitive vitamins include A, K, E (alpha-tocopherol), and carotene. It has also been reported that vitamin D could be photochemically altered by UV light (Spikes 1981). However, all these vitamins differ greatly in their basic photosensitivity and in the wavelength of the light involved. The effect of UV light on degradation of vitamins C, A, B6, B1, carotenoids, and retinol was studied in 6 fruit juices (apple, grape, orange, pear, mango, and pineapple) and 2 vegetable juices (garden vegetable and carrot). The UV effects are summarized in Table 6 for continuous systems and in Table 7 for batch systems along with the calculated UV dose.

Most studies reported the effect of UV treatment on vitamin C content because of its importance in fresh juices. Vitamin C is characterized by high UV light absorbance within the germicidal wavelength range (peak at about 260 nm) but it does not absorb light significantly above 300 nm. The average residual content of vitamin C following UV treatment in all the reported juices was 77.9%. Tikekar and others (2011) and Unluturk and Atilgan (2015) reported the lowest residual vitamin C contents at 33% in apple juice and 1.8% in grape juice with UV doses of 3390 mJ/cm^2 and 280 kJ/L, respectively. It should be noted that these UV doses slightly exceed those necessary for 5-log reduction of pathogenic organisms (Section "Flow conditions"). With the exception of these 2 studies, the average residual vitamin C content was 83.7 ± 11.9%. Orlowska and others (2013) reported that UV treatment of apple juice with a LPM lamp at 253.7 nm at 10 mJ/cm^2 reduced the vitamin C content by only 1.30%. At a similar UV dose of 14.3 mJ/cm^2, Hanes and others (2002) showed a 5-log reduction of oocysts in apple cider. This shows that UV doses capable of producing 5-log reduction in juices can have minimal impact on vitamin C content. In a study of vitamin C degradation in pineapple juice, UV-treated samples at 53.4 mJ/cm^2 retained a higher residual content during a 13-wk storage period than thermally processed pineapple juice (Chia and others 2012). Specifically, UV-treated pineapple juice retained 50% of its initial vitamin C content for 10 wk, whereas the thermally treated juice reached the same mark after 8 wk. Furthermore, UV-treated pineapple juice showed significantly higher vitamin C levels during the initial 7 wk of the storage period when compared to thermally treated juice. Goh and others (2012) also reported that pineapple juice showed higher vitamin C levels after UV treatment (12.7 mg/100 g) at 7.5 mJ/cm^2 when compared to thermal treatment (10.1 mg/100 g). The authors observed a similar trend in vitamin C content during a 2-wk storage period.

The degradation rate of vitamin C by UV light at 3390 mJ/cm^2 in apple juice was explored by Tikekar and others (2011). The authors determined that degradation was significantly increased in the presence of 10% fructose. Furthermore, unlike previously mentioned studies, vitamin C loss following a 35h storage period was shown to reach 60% after UV treatment at 1200 mJ/cm^2,as opposed to untreated juice which showed negligible loss of vitamin C. The degradation of vitamin C during storage was also shown to be highly dependent on temperature, occurring much faster at 25 than at 4 °C.

Vitamin A is another vitamin of great importance in fresh juices because it contributes to more than 2% nutritional value to the Recommended Daily Allowance. According to Koutchma and others (2009), destruction of vitamin A did not exceed 11% in orange juice and no destruction was found in carrot juice after treatment in the commercial Salcor UV module at the applied UV dose of 1.5 kJ/L. The degradation level of vitamin B6 in orange juice did not exceed 16.2%. Vitamin B1 showed no degradation in apple juice and 40% degradation in orange juice. Also, from the same study, no loss of retinol was reported in carrot juice and garden vegetable juice.

Carotenoid content in mango juice samples subjected to batch UV treatment at 317250 mJ/cm^2 exhibited an enhancement in extractability (6%) as compared to the control (Santhirasegaram and others 2015). The authors attributed the carotenoid enhancement to alteration of the carotenoid-binding protein, consequently increasing the availability of free carotenoids. In addition, the formation of UV photons may cause inactivation of enzymes responsible for the loss of carotenoids, thus improving carotenoid extraction yield. However, at a maximal UV dose of 1269000 mJ/cm^2, carotenoid content decreased by 4%.

Figure 1 illustrates the relationship between percent residual vitamin content and UV dose in continuous flow systems, which is also summarized in Table 6. The results from Unluturk and Atilgan (2015) were omitted from Figure 1 due to abnormally high UV dose when compared to the other studies (280 kJ/L). The results suggest that the use of UV light at dose levels that

Table 6–Reported effects of continuous UV processing on the destruction of vitamins in fruit and vegetable juices

Vitamin	Juice product	Remaining content (%)	Calculated UV dose (kJ/L)	Reference
C	Apple	75	8.1	Gayán 2013
	Apple	98.3	1.5	Koutchma 2009
	Carrot	100	1.5	Koutchma 2009
	Garden vegetable	100	1.5	Koutchma 2009
	Grape (white)	1.8	280	Unluturk 2015
	Orange	91	48.1	Pala 2013b
	Orange	83.4	1.5	Koutchma 2009
	Orange	83	4.8	Tran 2004
	Orange	82	7.2	Torkamani 2011
	Pear (Flor de Invierno)	79	–	Falguera 2014
	Pineapple	77	4.6	Goh 2012
	Pineapple	90	7.0	Chia 2012
A	Carrot	100	1.5	Koutchma 2009
	Garden vegetable	93.5	1.5	Koutchma 2009
	Orange	89.1	1.5	Koutchma 2009
Carotenoids	Carrot	100	1.5	Koutchma 2009
	Garden vegetable	93.5	1.5	Koutchma 2009
	Orange	51.4	1.5	Koutchma 2009
B6	Orange	83.8	1.5	Koutchma 2009
B1	Apple	100	1.5	Koutchma 2009
	Orange	60	1.5	Koutchma 2009
Retinol	Carrot	100	1.5	Koutchma 2009
	Garden vegetable	100	1.5	Koutchma 2009

Table 7–Reported effects of batch UV processing on the destruction of vitamins in fruit and vegetable juices

Vitamin	Juice product	Remaining content (%)	Calculated UV dose (mJ/cm^2)	Reference
C	Apple	99	10	Orlowska 2013
	Apple	95	10	Orlowska 2013
	Apple	94.3	–	Falguera 2011
	Apple	33	3390	Tikekar 2011
	Apple	55	2339	Zhu 2014
	Grape (Dauphine)	71	–	Falguera 2013a
	Grapefruit (4°C)	65	3940	La Cava 2015
	Grapefruit (10°C)	74		
	Mango	77, 88	1269000	Santhirasegaram 2015
	Starfruit	80	777	Bhat 2011
Carotenoids	Mango	97	1269000	Santhirasegaram 2015

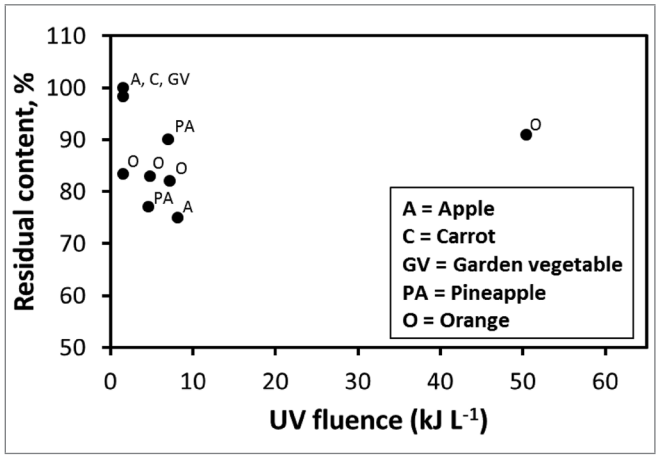

Figure 1–Effect of UV dose in continuous-flow systems on residual content of vitamins (C, A, carotenoids, B1, B6, and retinol) in fresh fruit and vegetable juices.

provide microbiological safety is not considered to pose significant nutritional concerns. Specifically, we report that UV dose values between 1 and 10 kJ/L resulted in a 20% decrease in residual vitamin content in the majority of studied juices. However, a linear decrease in residual vitamin content with increasing UV dose is not evident from the data, even when extrapolated to 50.4 kJ/L.

Enzymes. The stability of juice quality and nutritional properties is often dependent on the activity of the enzymes present in plants. Limited and often controversial information is available in the literature in regards to the effect of UV light on activity of certain enzymes associated with fresh juices including polyphenol oxidase (PPO), peroxidase (POD), lipoxygenase (LOX), and pectin methylesterase (PME). PPO is responsible for enzymatic browning in many juices. This copper-containing enzyme catalyzes the oxidation of various phenolic substrates; of particular importance is the oxidation of *o*-dihydroxy phenols to *o*-quinones, whose polymerization leads to the formation of undesirable brown pigments (Terefe and others 2014). POD catalyzes the oxidation of a wide variety of compounds in the presence of hydrogen peroxide. When acting on phenolic compounds, POD contributes to enzymatic browning much like PPO. PME causes undesired cloud instability in citrus juices. It catalyzes the hydrolysis of methyl ester groups from pectin and leads to the formation of a calcium pectate gel that causes cloud loss. LOX is responsible for the generation of volatile flavor compounds and free radicals in many juices. It catalyzes the oxidation of polyunsaturated fatty acids into hydroperoxides. This process also leads to loss of nutritional quality and color. Here, we show studies that investigated the effect of UV treatment in continuous and batch systems on the activity of PPO, POD, LOX, and PME enzymes in buffers and various

Table 8–Reported residual activity (%) of oxidative enzymes in continuous UV-treated fruit and vegetable juices, buffers, and model systems

Media	PPO RA[a] (%)	PME RA[a] (%)	PRO RA[a] (%)	POD RA[a] (%)	LOX RA[a] (%)	Calculated UV dose (kJ/L)	Reference
Apple	15.8	–	–	–	–	30.1	Muller 2014
Apple	86.1	–	–	–	–	8.1	Gayán 2013
Apple	114.5	–	–	–	–	1.5	Orlowska 2014
Carrot/orange	–	82	–	–	–	24.5	Caminiti 2012b
Grape	60.9	–	–	–	–	30.1	Muller 2014
Mango nectar	19	–	–	–	–	108	Guerrero-Beltran 2006
Orange	–	100	–	–	–	4.8	Tran 2004
Orange	–	92	–	–	–	7.2	Torkamani 2011
Pineapple	–	54.4	63.1	–	–	7.0	Sew 2014
Sodium acetate	4.1	–	–	–	–	30.1	Muller 2014
Watermelon	–	41	–	–	–	13.9	Zhang 2011

[a]RA, remaining activity as a percentage of original.

Table 9–Reported residual activity (%) of oxidative enzymes in batch UV-treated fruit and vegetable juices, buffers, and model systems

Media	PPO RA[a] (%)	PME RA[a] (%)	PRO RA[a] (%)	POD RA[a] (%)	LOX RA[a] (%)	Calculated UV dose (mJ/cm^2)	Reference
Acetic buffer (pH 4.0)	31	–	–	17	55	58.5	Sampedro 2014
Apple	99.5	–	–	97	–	–	Noci 2008
Apple (Golden)	0	–	–	0	–	–	Falguera 2011
Apple (clear)	10	–	–	–	–	12,483	Manzocco 2009
Coconut water model solution	2	–	–	1	–	85	Augusto 2015
Grape (Dauphine)	20	–	–	0	–	–	Falguera 2013a
Orange	75	–	–	97	–	58.5	Sampedro 2014
Pear (Flor de Invierno)	0	–	–	0	–	–	Falguera 2014
Potassium phosphate (pH 7.0)	10	–	–	–	–	58.5	Sampedro 2014
Phosphate buffer (pH 6.8)	10	–	–	–	–	4,800	Haddouche 2015
Sodium acetate (pH 4.0, 25 °C)	88	–	–	94	84	5.9	Sampedro 2014
Sodium phosphate (pH 5.0, 25 °C)	–	–	–	<1	–	–	Falguera 2013b
Sodium phosphate (pH 7.0, 25 °C)	77	–	–	15	54	58.5	Sampedro 2014
Tiger nuts' milk	–	–	–	13.9	–	4,230	Corrales 2012

[a]RA, residual activity as a percentage of original content.

fruit and vegetable juices such as apple, carrot, orange, grape, and mango nectar (Table 8 and 9). Proteolytic activity (PRO), which is a measure of total protease enzyme activity, was only reported in pineapple juice. Residual activity of enzymes following UV treatment was reported or calculated as the percent remaining activity following the highest reported dose when compared to untreated enzymes.

In general, the inactivation of juice enzymes was affected by UV dose, wavelength, and juice composition. The UV doses in the reported enzyme studies varied in a broad range from 1.5 to 108 kJ/L. The highest enzyme inactivation occurred with MPM lamps in clear apple, grape, and pear juices as well as in buffered solutions. Complete inactivation of enzymes was only reported with the use of a MPM lamp, which was an identical Phillips 400 W unit, emitting UV light between 250 and 740 nm with the highest intensity at 415 nm, in all the reported studies. The average combined residual enzyme activity with LPM lamps in juices and buffers was 66% and 42%, respectively as opposed to 3% and 2% with MPM lamps (Table 8 and 9).

The majority of studies investigated PPO and PME activity in fresh apple juice and orange juice. The enhancement of PPO residual activity by 14.5% after UV treatment at 1.5 kJ/L in apple cider was reported by Orlowska and others (2014). This effect was attributed to release of the enzyme from plant tissues due to disruptive effects of the hydrodynamic stresses or fragmentations of apple particles. Noci and others (2008) reported that, relative to fresh apple juice, PPO and POD activities were unaffected by UV treatment after a 30-min exposure to a 30 W UV-C lamp at 30 cm distance in a thin layer (incident UV dose not reported). After exposure to UV light at room temperature and doses up to 8.1 kJ/L, PPO residual activity of 86.1% in apple juice was observed by Gayán and others (2013). The same author did not find statistically significant differences among the residual activity of PPO in freshly squeezed apple juice by thermal treatment (77.3%) and by UV treatment at room temperature (86.1%). The higher applied UV dose at the level of 30.1 kJ/L caused lower residual activity (15.8%) of PPO (about 3-fold smaller) in apple juice as was reported by Müller and others (2014). However, higher residual PPO activity of 60.9 ± 14.2% was reported in grape juices at this same dose. The highest effect of UV light on PPO enzyme activity was reached in buffer, followed by mango, grape and apple juices, and this decreasing order can be attributed to the attenuation of UV energy in the juices or by the different sensitivities in enzyme structure resulting from their different origins.

PME was shown to be the most UV-resistant enzyme tested, with an average residual activity of 73.9% among all the tested juices. Tran and Farid (2004) reported no reduction of PME activity in orange juice by UV light following exposure at 73.8 mJ/cm^2, whereas the residual activity of this enzyme was significantly decreased (30%) by mild heat at 70 °C for 2 s. Caminiti and others (2012b) reported the retention of 82% of PME activity after exposure to UV light at 6.1 kJ/L in the blend of fresh orange and carrot juices. When the impact of UV light on orange juice quality and shelf-life was investigated by Torkamani and Niakousari (2011), no palpable relationship between UV light and PME inactivation was found. Sew and others (2014) showed that PME and proteolytic activity in freshly made pineapple juice were affected by mild heat treatment but not UV dose. The same authors were also the only ones to have studied proteolytic activity in juice, finding 63% residual activity pineapple juice at 7.0 kJ/L. The studies performed by Manzocco and others (2009) revealed that UV treatment using a LPM lamp at 6210 mJ/cm^2 can completely inactivate PPO activity in aqueous buffer solution (Table 9). At 2732 mJ/cm^2, 10% of PPO residual activity was reported in buffer,

while the same inactivation in clear apple juice required a UV dose of 19841 mJ/cm^2. This demonstrates increased UV sensitivity of enzymes in buffered solutions as opposed to juice. No studies were reported in terms of the effect of juice absorption properties on enzyme inactivation. However, even in buffered solutions, the reported UV doses are much higher than those required to attain 5-log reduction of pathogenic organisms. Hence, these results also demonstrate that enzymes, such as PPO, are highly resistant to UV light at 253.7 nm and the fact that inactivation with UV light occurs as a consequence of protein aggregation as opposed to thermal denaturation.

According to Sampedro and others (2014), the most influential factor for inactivation of LOX, POD, and PPO in buffer was pH, exposure time, and temperature, respectively. The combination of UV light and heat resulted in complete enzyme inactivation in the tested pH range between 4 and 7. The UV treatment efficacy also increased in an acidic environment. The differences in enzyme resistance were explained by the presence of iso-enzymes with different thermal resistance properties. This could be the case for LOX and POD where several labile and resistant forms have been observed in different vegetable matrices (Morales-Blancas and others 2002). Photo-reactivation and dark repair of enzymes are possible side effects that may reduce the food quality and shelf-life of UV-treated products. In general, residual enzyme activity after UV treatment was not restored after storage for 24 h at refrigeration conditions with or without light exposure.

The reviewed data suggest there is limited impact of UV treatment on fruit and vegetable juice enzymes at doses required to achieve 5-log reduction. We were able to show a decrease in PPO activity with increasing UV dose in the range between 1.5 and 108 kJ/L in continuous flow systems (Figure 3). Insufficient data prevented us from developing similar models for other enzymes. Also, UV light from MPM lamps was shown to be more effective than light from LPM lamps at reducing residual enzyme activity. Unfortunately, the majority of studies that reported the effects of MPM lamps did not report UV dose.

Polyphenols and other antioxidants. Fresh fruit and vegetable juices are natural sources of bioactive compounds such as phenols and other antioxidants. The effect of UV treatment on total antioxidant activity, total phenolic content, lycopene, and total anthocyanins was reported for fruit juices such as apple, coconut milk, grape, orange, pomegranate, pineapple, pitaya, and watermelon (Table 10 and 11). Residual content or activity as a percentage of the untreated original juice sample was used to assess the impact of UV treatment.

Overall, UV light did not induce any significant change in antioxidant activity and total phenolic content compared to a fresh control for all tested juices. The maximum reduction of antioxidant activity was 37% in pitaya juice (Ochoa-Velasco and Guerrero Beltrán 2013) at 0.2 kJ/L, while on average the remaining content was 91.6 ± 11.8% for all treated juices. Enhancement in antioxidant activity by 10%, likely as a result of the release of membrane-bound antioxidants, was reported in coconut milk at 0.2 kJ/L (Ochoa-Velasco and others 2014). The average remaining total phenolic content in all reported juices was 88.8 ± 12.7%. Noci and others (2008) reported the highest degradation of total phenolic content at 30% in apple juice, while a 20% to 30% increase in total phenolic content in mango juice was observed by Santhirasegaram and others (2015) following exposure at 126900 mJ/cm^2.

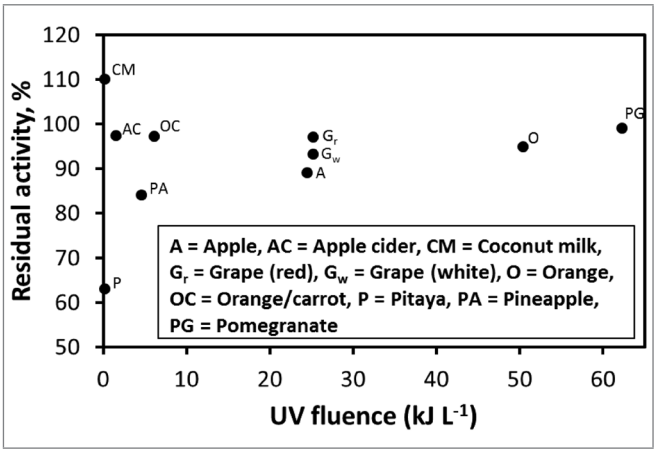

Figure 2–Effect of UV dose in continuous-flow systems on residual activity of antioxidants in fresh fruit juices.

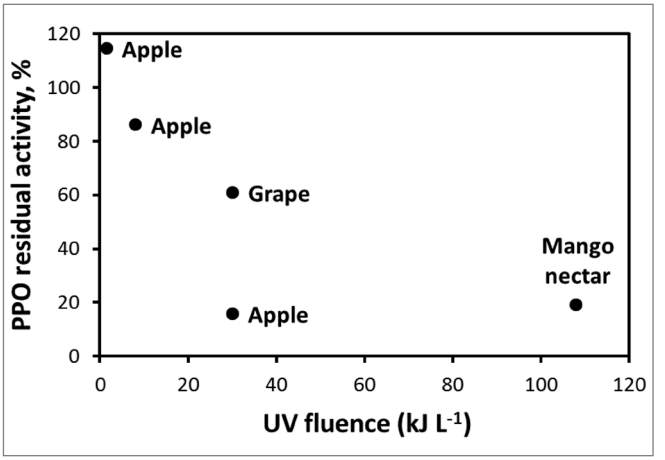

Figure 3–Effect of UV dose in continuous-flow systems on residual activity of polyphenol oxidase (PPO) in fresh fruit juices.

Anthocyanins are a widespread group of plant phenolic compounds that have been regarded as a natural alternative to replace synthetic food colorants. Recently, increased attention has been given to their potential health benefits in preventing heart diseases and cancers due to their powerful antioxidant properties (He and Giusti 2010). Pala and Toklucu (2011) found that UV light reduced anthocyanin content of pomegranate juice by 8.4% at 62.4 kJ/L as compared to 23.6% following thermal treatment (90 °C, 2 min). Pala and Toklucu (2013a) reported that UV light reduced anthocyanin content in red grape juice by 8.7% at 25.2 kJ/L as compared to 11.9% following thermal treatment (85 °C, 15 min).

In summary, percent remaining antioxidant activity as well as polyphenol and anthocyanin contents of the reported juices were well retained following UV treatment. Figure 2 and 3 illustrate the relationship between percent residual activity of antioxidants and polyphenols, respectively, and UV dose in continuous-flow systems, which are summarized in Table 10 and 11. The reviewed data suggest that UV treatment is a better processing method to retain heat labile health-promoting compounds, such as polyphenols, anthocyanins, and other antioxidants, as opposed to thermal treatment.

Table 10–Reported effects of continuous UV treatment on antioxidants and polyphenols in fruit and vegetable juices

Juice	LP RC[a] (%)	TA RC[a] (%)	TAA RA[b] (%)	TPC RC[a] (%)	Calculated UV dose (kJ/L)	Reference
Apple	–	–	89	100	53.1	Caminiti 2012a
Apple cider	–	–	97.3	96.7	1.5	Orlowska 2014
Coconut milk	–	–	110	73	0.2	Ochoa-Velasco 2014
Grape (white)	–	–	93.2	98	25.2	Pala 2013a
Grape (red)		91.3	97	96.8		
Orange	–	–	94.9	97	48.1	Pala 2013b
Orange/carrot blend	–	–	97.2	98	6.1	Caminiti 2012b
Pomegranate	–	91.6	97	97	62.4	Pala 2011
Pineapple	–	–	–	83.5	7.0	Chia 2012
Pineapple	–	–	84	91	4.6	Goh 2012
Pineapple	–	–	–	75.6	7.0	Sew 2014
Pitaya	–	–	63	88	0.2	Ochoa-Velasco 2013
Watermelon	96	–	–	99	11.3	Feng 2013

LP, lycopene; TA, total anthocyanins; TAA, total antioxidant activity; TPC, total phenol content; [a]RC, residual content as a perecentage of original; [b]RA, residual activity as a percentage of original content.

Table 11–Reported effects of batch UV treatment on antioxidants and polyphenols in fruit and vegetable juices

Juice	LP RC[a] (%)	TA RC[a] (%)	TAA RA[b] (%)	TPC RC[a] (%)	Calculated UV dose (mJ/cm^2)	Reference
Apple	–	–	81.1	70	–	Noci 2008
Apple (Golden)	–	–	–	100	–	Falguera 2011
Mango	–	–	89.5	121 to 131	1269000	Santhirasegaram 2015
Grapefruit (4 °C)	–	–	95	–	3940	La Cava 2015
Grapefruit (10 °C)			98			
Pear (Flor de Invierno)	–	–	–	109	–	Falguera 2014
Starfruit	–	–	103	106	777	Bhat 2011
Tiger nuts' milk	–	–	71	–	4230	Corrales 2012

LP, lycopene; TA, total anthocyanins; TAA, total antioxidant activity; TPC, total phenol content; [a]RC, residual content as a perecentage of original; [b]RA, residual activity as a percentage of original content.

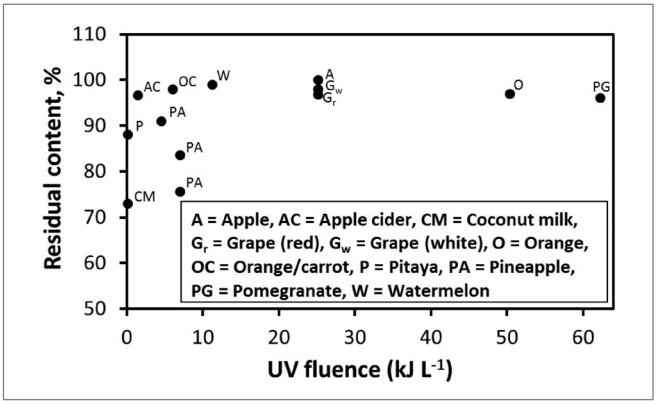

Figure 4–Effect of UV dose in continuous-flow systems on residual total phenolic content in fresh fruit juices.

Effect of UV light on color and sensory attributes

Color. Some of the above-mentioned health-related compounds are directly linked to quality attributes of juices such as color and flavor. The color characteristics (lightness, redness, and yellowness) after UV light treatment have been studied in apple, orange, pineapple, mango, watermelon, pomegranate, peach, lemon, and grape juices, as well as apple cider and carrot blend. The majority of studies reported insignificant color change in most of the juices and concluded that UV treatment also retained the color attributes of the fresh juices much more so than thermal processing. Tran and Farid (2004) reported that UV treatment of reconstituted and fresh orange juice at 147.6 mJ/cm^2 had no significant impact on the color of both products. Quantitative color measurements were not reported. Chia and others (2012) showed that UV treatment at 53.4 mJ/cm^2 retained color attributes such as lightness ($L^\star$), chroma, and hue angle ($a^\star$ and $b^\star$) of pineapple juice more so than thermal processing during a 13-wk storage period. The feasibility of UV light to maintain the initial color and reduce browning has also been observed in mango juice and nectar, orange/carrot blend, grape, and watermelon juices (Guerrero-Beltran and Barbosa-Canovas 2006; Caminiti and others 2012b; Feng and others 2013; Unluturk and Atilgan 2014).

Müller and others (2014) concluded that untreated apple juice became browner during storage and attributed this to the action of PPO. In contrast, UV-treated apple juice at 100.5 kJ/L showed no further browning during the storage period due to UV-induced inactivation of PPO. However, differences in $L^\star$, $a^\star$, and $b^\star$ values were observed in UV-treated grape juice. In this case, a sufficient quantity of PPO remained active after UV treatment to cause browning in the grape juice during refrigerated storage.

Results obtained in red juices, such as watermelon juice, showed that UV treatment at 37.5 kJ/L had a positive impact in maintaining the redness ($a^\star$ value) during a 37-d storage period when compared to untreated juice (Feng and others 2013). It was also shown that UV processing at 25.2 and 62.4 kJ/L enhanced anthocyanin pigments and polymeric color of red grape juice and pomegranate juice compared with heat treatment, respectively (Pala and Toklucu 2011; Pala and Toklucu 2013a).

Another parameter associated with color change in juices is nonenzymatic browning index (NEBI) that indicates the browning of juice due to the Maillard reaction, subsequently causing color changes and loss of nutrients. Santhirasegaram and others (2015) reported a minor increase in NEBI values in mango juice processed by UV light at 1269000 mJ/cm^2 (NEBI = 0.1) and thermal treatment at 90 °C for 1 min (NEBI = 0.13) compared to the untreated sample (NEBI = 0.06). Noci and others (2008) also reported minor differences in NEBI values following UV treatment relative to untreated juice (ΔNEBI = 0.036), while large differences were observed in heat-treated juices at 72 and 94 °C (ΔNEBI = 0.209, 0.265). This further illustrates the ability

of UV light to achieve a product with similar characteristics to freshly squeezed juice.

Ibarz and others (2005) used an MPM lamp in a batch system to study the effect of UV light on apple, peach, and lemon juices with different soluble solids contents and different browning degree. It was found that UV light produced effects which counteract juice browning. Specifically, the increase in brightness of juices following exposure to UV light was reported. The colorimetric parameters a^* and b^* decreased with the exposure time, indicating that the UV exposure can counteract or degrade colored polymers responsible for enzymatic browning. The research indicated that UV light is a feasible process for prevention of undesirable browning and can improve color characteristics.

Sensory. Very limited published studies are available in regards to effects of UV processing on sensory attributes of juices. Current studies have focused on orange and apple juices as well as apple cider. Pala and Toklucu (2013b) reported that UV processing of freshly squeezed orange juice at 48.1 kJ/L could assure its safety and improve its sensory attributes in comparison with heat treatment. The authors used a 9-point hedonic scale to show that consumer acceptability of UV treatment lowers the sensory rating of orange juice from 6.2 to 4.1, whereas heat treatment was scored the lowest at 3.4. The authors also used a triangle test to show insignificant differences between untreated and UV-treated orange juice. Furthermore, significant differences were shown between UV-treated and heat-treated orange juice. Donahue and others (2004) also used the triangle test to show no significant changes in apple cider sensory values after UV treatment at 17.5 mJ/cm^2, as compared to an untreated control. Caminiti and others (2012a) used a 9-point hedonic scale to report that consumer acceptability of apple juice did not significantly change following UV treatment at 5.31 J/cm^2 (score = 6.2) when compared to the untreated sample (score = 6.7). However, at 53.10 J/cm^2 panelists reported a significant dislike for apple juice color and overall acceptability (score = 3.1). This was confirmed with color analysis as noticeable changes in ΔE were observed at UV doses of 26.6 J/cm^2 and higher.

Summary

Forty-two research studies reported UV processing of 20 types of fresh juices in low-acid, acid, and high-acid pH categories. Out of 20 types of studied juices only 3 products (carrot, garden vegetable, and orange-carrot blend) belong to vegetable juices. Apple and orange fruit juices were the most-studied products in terms of the application of UV light processing to improve safety and extend shelf-life. The use of UV light treatment is not considered to pose any new nutritional safety concerns when used at doses required to achieve 5-log reduction of pathogenic organisms. The majority of studies concluded that when compared to thermal processing, UV treatment is able to better preserve the quality and nutritional attributes of the juices. Depending on the UV processing dose and specific nutrient(s), UV light may have a positive, neutral, or negative effect on nutrient and enzyme retention. In general, it has been concluded that vitamins C, A, and B6 are relatively unaffected by UV treatments. The reviewed data also suggest that there is limited impact of UV treatment on fruit and vegetable enzymes and limited change in total phenolic content, antioxidant activity, and anthocyanins when compared to a fresh control for all tested juices. The majority of studies also reported insignificant color change in most of the juices and concluded that UV treatment also retained the color attributes of the juices much greater than thermal processing. In certain cases, UV light can have beneficial effects on health-related compounds and quality attributes of juices such as color.

The reported or calculated UV doses in the studies varied in a broad range from 0.15 to 933.6 kJ/L in continuous systems and from 5.9 to 1269000 mJ/cm^2 in batch systems. Overall, the experimental UV doses were often much higher than those required to achieve 5-log reduction. It was concluded that the UV dose applied in commercial UV systems appeared to be lower than in custom-made pilot UV systems used in the reported research. The range of UV doses calculated or reported in commercial UV units is typically between 1.5 and 7 kJ/L, whereas the same range in lab/pilot-scale units was between 0.2 and 933.6 kJ/L. Some results were generated in the batch lab devices using Petri dishes or trays in a thin layer under extended treatment times. In fact, it was typically difficult to determine how and why the authors chose a particular combination of UV process conditions. This can be an indication that the low performance efficiency of lab/pilot-scale processing could lead to otherwise unnecessary overexposure by UV light. Therefore, results found in the literature are likely poorer than would be expected at commercial-scale. The analysis of the results also indicates the importance of using the correct UV system and UV dose measurement, control, and reporting.

Thus, it can be concluded that UV light technology is highly promising for prolonging the shelf-life of fresh juices of plant origin while preserving nutritional compounds and could be used as a nonthermal and nonchemical alternative to thermal treatment. The success of UV technology depends on the correct alignment of the UV source and system parameters to the specific demands of the UV juice application.

Gaps in knowledge

Due to the fast growth of the premium juice market, more focused studies should be conducted on the effects on UV-based preservation on vegetable juices and juice blends. The loss of health-related nutrients and development of off-colors and off-flavors during UV processing of juices requires further investigation as a function of UV dose and UV system performance. In order to determine the most beneficial use of UV light, it is necessary to test each juice product for its UV spectral response. Attempts should be made to minimize the damaging effects of UV light on juice antioxidants, color, and sensory attributes. In addition, knowledge of the degradation kinetics of vitamins, enzymes, and bioactive compounds by UV light will allow optimization of microbial inactivation of pathogenic and spoilage organisms in juices while minimizing losses of these health-related compounds. Special attention should be given to the beneficial effects of UV light such as increase in enzyme activity, enhancement of some antioxidant contents and color improvement after UV treatment and during storage.

UV light has shown to be responsible for only mild undesirable nutrient changes and also some potential as a new technological tool to improve juice quality by promoting highly desirable effects. The key knowledge for turning the detrimental effects of UV light into beneficial ones could lie in light-control of biological and chemical systems such as enzymes and other compounds.

To properly address the knowledge gaps in regards to the impact of UV processing on health-related nutrients, quality, and sensory attributes, and consumer acceptance of the technology, future studies are needed to include the entire investigation for specific fruit and vegetable juices at commercial-scale.

Part 2: Introduction to High-Pressure Processing of Juices

HPP, otherwise known as high-hydrostatic pressure (HHP) and ultra-high-pressure processing (UHP), is a nonthermal batch process that subjects juice products, or other foodstuffs, already sealed in their final packaging to high-pressure. The food and its final packaging are treated together so that the entire pack remains a "secure unit" until it is opened by the user. Commercial-batch vessels have internal volumes ranging from 35 to 525 L, allowing food manufacturing facilities of various sizes to implement HPP technology. Avure Technologies (USA-Sweden), Hiperbaric (USA-Spain), and MULTIVAC (USA-Germany) are major suppliers of commercial-scale HPP equipment. Although not as readily used, semi-continuous HPP systems are also available and are generally used to directly process liquid products that are then aseptically packaged. This equipment is available from such companies as MULTIVAC and Uhde HPT (Hagen, Germany).

Depending on the processing conditions, HPP is capable of either completely or partially inactivating microorganisms, enzymes, viruses, and, to a lesser extent, bacterial spores (U.S. FDA 2000; Chakraborty and others 2014; Koutchma 2014). The main parameters influencing HPP antimicrobial efficacy are pressure, temperature, exposure time, product parameters, type of packaging, and baro-tolerance of the organism in question. Depending on the capabilities of the HPP unit, the applied pressure can range between 200 and 900 MPa. However, the minimum pressure required to inactivate vegetative microorganisms at ambient temperatures is 400 MPa and, hence, the more common pressure range associated with commercial HPP is between 400 and 600 MPa (Smelt and others 2001). HPP does not compromise the structure of low-molecular-weight compounds associated with nutritional or sensory quality, due to the inherent stability of covalent bonds at pressures below 2000 MPa. However, biological systems begin to experience intermolecular and intramolecular bond cleavage at pressures above 400 MPa (Knorr and others 2006). This leads to inactivation of microorganisms while having minimal effects on food chemistry. Higher processing temperatures can be used in combination with HPP during treatment of pressure-resistant organisms such as bacterial spores. Sample temperature during HPP treatment can be below 0 °C or above 100 °C and exposure time or HPP cycle time can range from a millisecond to 20 min (FDA, U.S. 2000).

The U.S. FDA has no objections to the use of HPP for juice products with the stipulation that 5-log reduction of the pertinent pathogen of concern is achieved (FDA, U.S. 2004). Health Canada has also issued no objection to the use of HPP for fruit and vegetable juices at 600 MPa with an exposure time between 2 and 9 min for shelf-life extension (Health Canada 2014).

Typically it is considered that at low and mild processing temperatures (0 to 40 °C), HPP has minimal effects on such valuable quality parameters of fresh juices as vitamins, antioxidants, color, and flavor. The second part of this review will focus on the effects of HPP on quality and health-related constituents of fresh juice products. Attention will be given to the influence of pressure, temperature, and exposure time on post-HPP changes to juices. For the analysis, HPP effects on 24 different fruit and vegetable juices reported in 50 peer-reviewed research articles and other research documents were reviewed. Almost all the tested juices were prepared by mechanical extraction from freshly purchased fruits and vegetables. In order to compare the reported results, the residual content of vitamins, antioxidants, and enzyme activity in juices were summarized. The majority of the HPP units used in the collected studies were either lab-scale or pilot-scale (30 mL to 7 L capacity) with the exception of one 215-L industrial unit. Data were only selected from studies which provided all 3 HPP treatment parameters, including pressure, exposure time, and temperature. Aside from the use of mild heat, HPP combination treatments were omitted.

Physicochemical properties of juices treated with HPP and microbial effects

The physicochemical properties of various reported juices, including pH and soluble solids content, along with the experimental HPP parameters are summarized in Table 12. These juices are grouped into low-acid, acid, and high-acid categories (Table 13). A total of 19 juices were derived from fruit origin and the remaining 5 were derived from vegetables.

The average applied pressure used in the studies was 525 ± 167 MPa, with the most common pressure being 600 MPa. Room temperature was the most commonly used in the studies, with the average value being 25 ± 12 °C. Finally, exposure time varied anywhere from 1 to 60 min. This range of HPP parameters did not significantly impact physicochemical properties of juices, including pH and soluble solids content.

The majority of the reviewed studies did not report the microbial effect of HPP in juices. The reported data on microbial reduction presented in Table 12 mainly include HPP effects on total viable counts, aerobic counts, yeasts and molds, and spoilage lactic bacteria. No effects of HPP on pathogenic organisms were reported in the selected articles. In average, at the commercial pressure level of 600 MPa up to 4 to 5 log reduction of total microflora was observed. The data regarding HPP sensitivity of spoilage organisms (yeasts, molds, and lactic bacteria) are inconclusive.

HPP sensitivity of health-related constituents

Vitamins. Table 14 shows the remaining contents of vitamin C, A, E, and carotenoids following HPP treatment as reported in 19 studies of fruit and vegetable juices. The effect on vitamin C was the most commonly measured nutritional parameter following HPP treatment. These studies showed, with great consistency, excellent retention of residual vitamin C content at 92.1 ± 9.6% in all the reported juices. The most intense HPP conditions were reported by Jayachandran and others (2015) using 600 MPa at 60 °C for 15 min with litchi/lemon/coconut water. Under these conditions, vitamin C degradation was only 18%. The largest vitamin C loss was reported in tomato juice at 24% using 500 MPa at 25 °C for 10 min (Hsu and others 2008). Hartyáni and others (2011) were the only authors to report increased yields of vitamin C due to extraction. Specifically, they reported a 3% increase in vitamin C following HPP treatment of orange juice at 600 MPa at 15 °C for 10 min.

The characterization of vitamin C degradation during high-pressure treatment was studied by Oey and others (2006). The authors showed that vitamin C degradation at both elevated and atmospheric pressure is directly proportional to the soluble oxygen concentration in the solution. This confirms that vitamin C degradation during HPP treatment is primarily caused by oxidation. Moreover, the addition of sugar (such as 10% sucrose) has a protective effect on vitamin C degradation by decreasing the concentration of soluble oxygen (Taoukis and others 1998). Vitamin C was also shown to be more pressure-resistant in fruit-based food products as opposed to vegetable-based products (Oey and others 2008). We were unable to confirm this trend in our review due

Table 12–HPP parameters and microbial inactivation for various reported fruit and vegetable juices

Juice	pH	Soluble solids content (°*Brix*)	HPP parameters			Tested organism	SLR	Reference
			Pressure (MPa)	Temp. (°C)	Time (min)			
Apple	–	–	450	50	60	NA	–	Bayindirli 2006
Apple *(cloudy)*	3.1	12.1	500	20	10	NA		Buckow 2009
Apple *(Granny Smith)*	3.3	10.0	600	25	16	NA	–	Falguera 2013b
Apple	3.4	12.1	430	25	7	NA	–	Juarez-Enriquez 2015
Apple	–	–	500	25	3	TAB	3.0	Kim 2012
Blood orange	–	–	600	20	15	NA		Torres 2011
Blueberry	3.0	7.4	600	25	15	NA	–	Barba 2013
Cantaloupe	5.6 to 5.8	12.0	500	22	20	NA	–	Ma 2010
Carrot	6.0	–	800	10	36.18	NA	–	Balogh 2004
Carrot	6.0	–	250	35	15	TAB	5.5	Dede 2007
Carrot	–	–	500	40	15	NA	–	Gong 2015
Carrot	–	–	600	25	10	NA	–	Kim 2001
Carrot	6.5	–	600	25	10	NA	–	Park 2002
Carrot	6.5	8.9	600	10	5	NA	–	Picouet 2015
Chinese bayberry	2.7	10.9	600	25	10	NA	–	Yu 2013
Cucumber	6.6	3.0	500	25	2	TAB	2.0	Zhao 2013
						Y&M	4.0	
Grapefruit	3.0	8.9	600	15	10	NA	–	Hartyani 2011
Grapefruit	3.5	13.0	550	25	10	TPC	4.83	Gao 2015
						Y&M	4.15	
Green asparagus	5.9	3.8	600	25	20	TMB	5.0	Chen 2015
Green bean	–	–	500	20	10	NA	–	Indrawati 2000
Kiwifruit	–	–	600	30	30	NA	–	Fang 2008
Litchi/lemon/coconut water	4.2	13.6	600	60	15	NA	–	Jayachandran 2015
Mandarin	–	10	600	25	10	NA	–	Ogawa 1990
Mixed citrus	–	–	600	25	6	NA	–	Butz 2003
Orange	–	–	450	50	60	NA	–	Bayindirli 2006
Orange	4.2	9.0	600	45	3.25	TAB	4.0	Bisconsin-Junior 2014
						Y&M	4.0	
Orange	3.9	12.31	600	25	5.76	NA	–	Boff 2003
Orange (Valencia)	4.3	8.7	600	20	1	TAB	7.8	Bull 2004
Orange (Navel)	3.8	12.2				Y&M	4.8	
						TAB	4.5	
						Y&M	3.1	
Orange	3.7	10.6	600	15	10	NA	–	Hartyani 2011
Orange	3.8	11.6	350	25	2	NA	–	Katsaros 2010
Orange	–	–	400	40	1	NA	–	Plaza 2011
Orange *(Navel)*	–	–	600	40	4	NA	–	Polydera 2004
Orange	–	–	600	5	1	NA	–	Vervoort 2011
Orange/milk	3.9	14.4	400	26.6	9	*LP*	≥5.0	Barba 2012a
Peach	–	–	600	25	10	NA	–	Rao 2014
Papaya/mango/orange	–	–	500	15	15	NA	–	Carbonell-Capella 2013
Pomegranate	3.8	16.2	400	20	5	TAB	4.53	Chen 2013
						Y&M	3.69	
Sea buckthorn	2.8	9.5	600	35	5	NA	–	Alexandrakis 2014
Tangerine	3.0	10.2	600	15	10	NA	–	Hartyani 2011
Tomato	4.5	–	250	35	15	TAB	4.5	Dede 2007
Tomato	4.5	5.1	500	30	10	NA	–	Gupta 2011
Tomato	–	–	500	25	10	TVC	3.0	Hsu 2008
						EB	2.1	
						LAB	4.2	
						Y	3.7	
						M	3.6	
Tomato	–	–	550	20	12	NA	–	Rodrigo 2007
Tomato	–	–	800	65	30	NA	–	Stoforos 2002
Watermelon	5.8	9.6	600	25	60	NA	–	Liu 2012
Watermelon	–	–	900	60	60	NA		Zhang 2011

NA, not available; SLR, specific log reduction; TVC, total viable count; TAB, total aerobic bacteria; Y&M, yeast and mold; Y, yeast; M, mold; TPC, total plate count; TMB, total mesophilic bacteria; *LP*, *Lactobacillus plantarum*; EB, Entero-bacteria; LAB, lactic acid bacteria.

to statistically insufficient data for vegetable juices as compared to fruit juices.

The average residual carotenoid contents in tomato, carrot, and orange juices were reported following HPP treatment and shown to be 102.6 ± 39.6%, with some studies showing increases and others showing minor degradations. Carotenoids showed the largest examples of enhancement following HPP treatment when compared to other reported nutrients. Hsu and others (2008) observed a 62% increase in tomato juice carotenoids following HPP treatment with 500 MPa at 25 °C for 10 min. Similarly, Plaza and others (2011) observed a 45% increase in orange juice carotenoids following HPP treatment with 400 MPa at 40 °C for 1 min. Single studies with orange juice and orange/milk juice of vitamin A and E, respectively, showed 35% and 7% increased residual content following HPP treatment. Further research is required to establish clear trends in HPP-induced effects on vitamin A and E in fruit and vegetable juices.

The contour plot of vitamin C residual content following HPP treatment suggests that the greatest degradation (30% to 40%) occurs at pressures of 400 to 550 MPa in combination with high exposure time (10 to 20 min) (Figure 5). According to this, common industrial HPP conditions (600 MPa, 25 °C, 2 to 9 min) do

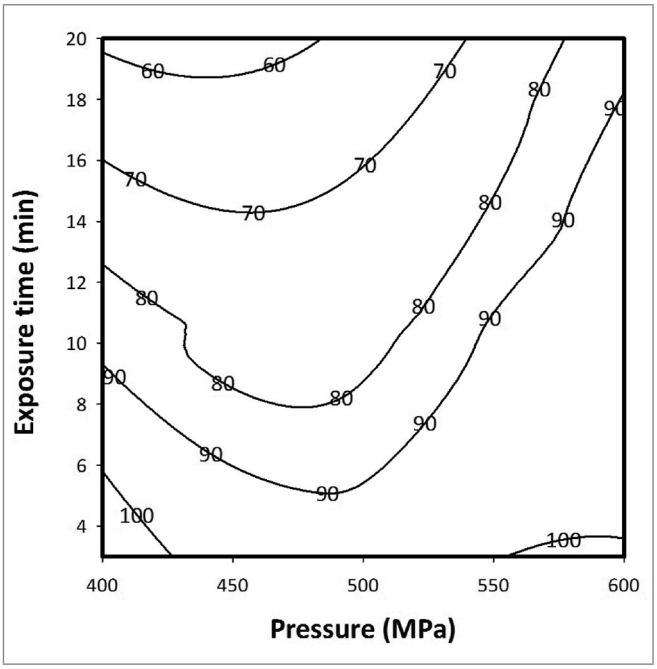

Figure 5–Contour plot illustrating the effects of HPP parameters, exposure time, and pressure, on vitamin C residual content (%) following HPP treatment of fruit and vegetable juices at 25 °C.

Table 13–pH categories of HPP-treated fresh fruit and vegetable juices

High acid (pH < 3.5)	Acid (pH < 4.6)	Low acid (pH > 4.6)
Apple	Orange	Papaya/Mango/Orange
Mixed citrus	Pomegranate	Green asparagus
Grapefruit	Blood orange	Carrot
Tangerine	Tomato	Watermelon
Blueberry	Orange/milk	Green bean
Sea buckthorn	Litchi/lemon/coconut water	Cucumber
Chinese bayberry	Peach	Cantaloupe
Mandarin		
Kiwifruit		
Passion fruit		

not favor vitamin C degradation. Insufficient data prevented us from generating similar information for other vitamins. In summary, moderate pressure alone has a minimal effect on juice vitamins, with remaining contents in the range of 87% to 100%. The destruction of vitamins in fruit and vegetable juices during HPP treatment in the reported studies was minimal and showed great consistency throughout the various studies.

Enzymes. The summary of findings on the effects of HPP on residual activity of quality-related enzymes PPO, POD, PME, and LOX in fruit and vegetable juices is presented in Table 15. In total, 14 juices from 28 studies were exposed to HPP conditions ranging from pressures of 200 to 900 MPa, temperatures from 10 to 60 °C, and exposure times from 1 to 60 min.

In general, pressure treatment may cause activation or inactivation of enzymes. Low pressure (<100 MPa) has been shown to activate certain monomeric enzymes such as PPO (Buckow and others 2009); possibly due to extraction from cellular compartments. However, activation of PPO has also been reported at pressures as high as 700 MPa (Terefe and others 2014).

Thermal denaturation of enzymes differs from pressure-induced denaturation. At pressures above 300 MPa, most enzymes begin to undergo irreversible denaturation at room temperature; while reversible changes tend to occur below this pressure (Knorr and others 2006; Terefe and others 2014). Unlike thermal denaturation, which effects enzyme covalent bonding, pressure only affects the tertiary and quaternary structure of enzymes (Balny and Masson 1993). This occurs as a result of water entry into the core of the enzymes during pressure treatment, which is followed by the destabilization of hydrophobic and electrostatic interactions which hold the tertiary and quaternary structures together (Chakraborty and others 2014; Terefe and others 2014).

Enzyme inactivation depends on the type of juice as well as the processing conditions. This is due to the fact that some enzymes are more pressure-resistant than others. For example, certain enzymes can withstand pressures up to 1000 MPa (Terefe and others 2014). Typically, pressure in combination with heat is required for full inactivation of enzymes. Enzyme activity following HPP treatment is determined by a number of variables including origin of the enzyme, availability and nature of the substrates, pH, medium composition, temperature, as well as HPP conditions (Ludikhuyze and others 1996; Fernandez Garcia and others 2002; San Martin and others 2002).

The reported data of enzymes in fresh juices showed various resistance levels to HPP. PPO and PME were the most studied enzymes and showed similar residual activity values following treatment. In both cases, higher-than-average values were reported by several authors. For example, Falguera and others (2013b) and Buckow and others (2009) reported residual activity of PPO in apple juice at 71.5% and 60% using 600 MPa at 25 °C for 16 min and 500 MPa at 20 °C for 10 min, respectively, whereas for PME Kim and others (2001) showed a 29% increase in enzyme activity relative to the control in carrot juice, and Gao and others (2015) and Park and others (2002) reported 77.5% and 44% residual activity in grapefruit and carrot juices, respectively. If these 5 studies are excluded, the average residual activity for PPO and PME in the remaining 23 studies is 10.0 ± 5.0% and 12.6 ± 5.5%, respectively. The majority of residual activity values for PPO and PME are reported to be between 0% to 20%.

Among the 4 reported enzymes, POD appears to be the most pressure-resistant in the group. Its average residual activity following HPP treatment among 8 reported juices was 47.5 ± 31.9%, with the majority of values lying in the 20% to 60% range. Gao and others (2015) reported an increase in POD activity (10%) following HPP treatment of grapefruit juice using 550 MPa at 25 °C for 10 min. No other authors reported increased activity of POD. The lowest residual activity of POD following HPP treatment was reported by Jayachandran and others (2015) at 0.7% in litchi/lemon/coconut milk using 600 MPa at 60 °C for 60 min. This suggests that the use of high temperature is required in combination with HPP to achieve complete inactivation of POD.

The average residual activity of LOX in 5 reported studies, including cantaloupe, carrot, cucumber, green bean, and tomato juice, was 31.3 ± 29.9%. LOX was the least studied of the enzymes and although it appears to have similar pressure-resistance as POD, further studies are required with this enzyme. The highest residual activity of LOX following HPP treatment was reported for cucumber juice at 80% using 500 MPa at 25 °C for 2 min (Zhao and others 2013). Rodrigo and others (2007) were the only authors to report complete inactivation of LOX following HPP treatment. This was accomplished in tomato juice using 550 MPa at 20 °C for 12 min. The overall effect of HPP on enzyme activity is fairly complex and unpredictable. The distribution of percent residual

Table 14–Reported effects of HPP processing on the destruction of vitamins in juices

Vitamin	Juice product	Remaining content (%)	HPP parameters			Reference
			Pressure (MPa)	Temp. (°C)	Time (min)	
C	Apple	96	500	25	3	Kim 2012
	Blood orange	92	600	20	15	Torres 2011
	Blueberry	93	600	25	15	Barba 2013
	Carrot	90	250	35	15	Dede 2007
	Carrot	76	500	40	15	Gong 2015
	Chinese bayberry	96	600	25	10	Yu 2013
	Grapefruit	96	600	15	10	Hartyani 2011
	Grapefruit	91.2	550	25	10	Gao 2015
	Green asparagus	87	600	25	20	Chen 2015
	Litchi/lemon/coconut water	81.8	600	60	15	Jayachandran 2015
	Mixed citrus	96	600	25	6	Butz 2003
	Orange	103	600	15	10	Hartyani 2011
	Orange/milk	91	400	26.6	9	Barba 2012a
	Papaya/mango/orange	92	500	15	15	Carbonell-Capella 2013
	Peach	85	600	25	10	Rao 2014
	Tangerine	120	600	15	10	Hartyani 2011
	Tomato	76	500	25	10	Hsu 2008
	Tomato	95	250	35	15	Dede 2007
Carotenoids	Carrot	87	600	10	5	Picouet 2015
	Carrot	99.8	500	40	15	Gong 2015
	Carrot	47	600	25	10	Kim 2001
	Orange	145	400	40	1	Plaza 2011
	Tomato	75	500	30	10	Gupta 2011
	Tomato	162	500	25	10	Hsu 2008
A	Orange	135	400	40	1	Plaza 2011
E	Orange-milk	107	400	26.6	15	Barba 2012a

Table 15–Reported residual activity (%) of enzymes in HPP-treated fruit and vegetable juices

Juice	PPO RA* (%)	PME RA* (%)	POD RA* (%)	LOX RA* (%)	HPP parameters			Reference
					Pressure (MPa)	Temp (°C)	Time (min)	
Apple	9	–	–	–	450	50	60	Bayindirli 2006
Apple *(Granny Smith)*	71.5	–	–	–	600	25	16	Falguera 2013b
Apple	0	0	–	–	430	25	7	Juarez-Enriquez 2015
Apple *(cloudy)*	60	–	–	–	500	20	10	Buckow 2009
Cantaloupe	8.8	–	77.9	5.4	500	22	20	Ma 2010
Carrot	–	10	–	–	800	10	36.18	Balogh 2004
Carrot	–	–	20.7	–	500	40	15	Gong 2015
Carrot	10.1	129	36.6	–	600	25	10	Kim 2001
Carrot	13	44	–	21	600	25	10	Park 2002
Cucumber	–	–	–	80	500	25	2	Zhao 2013
Grapefruit	–	77.5	110	–	550	25	10	Gao 2015
Green bean	–	–	–	50	500	20	10	Indrawati 2000
Kiwifruit	–	–	57.6	–	600	30	30	Fang 2008
Litchi/lemon/coconut water	8.2	–	0.7	–	600	60	15	Jayachandran 2015
Mandarin	–	10	–	–	600	25	10	Ogawa 1990
Orange	–	7	–	–	450	50	60	Bayindirli 2006
Orange	–	~10	–	–	600	25	3	Nienaber 2001
Orange	–	15	–	–	600	45	3.25	Bisconsin-Junior 2014
Orange	–	20.2	–	–	600	25	5.76	Boff 2003
Orange *(Valencia)*	–	10	–	–	350	25	2	Katsaros 2010
Orange *(Navel)*	–	0	–	–	600	40	4	Polydera 2004
Orange	–	8	–	–	600	5	1	Vervoort 2011
Peach	18.8	–	49.6	–	600	25	25	Rao 2014
Sea buckthorn	–	10	–	–	600	35	5	Alexandrakis 2014
Tomato	–	~2	–	–	800	65	30	Stoforos 2002
Tomato	–	27.8	–	–	200	25	10	Hsu 2008
Tomato	–	–	–	0	550	20	12	Rodrigo 2007
Watermelon	12.3	23.2	57.6	–	600	25	60	Liu 2012
Watermelon	–	36	–	–	900	60	60	Zhang 2011

* RA, residual activity as a percentage of original content.

activity for all 4 reviewed enzymes following HPP treatment is shown in Figure 6. As a whole, HPP is effective at inactivation of PPO, POD, PME, and LOX, since 53% of residual activity values from all the reported juices fall in the 0% to 20% range and 17% fall in the 20% to 40% range. However, no obvious correlation exists between studies that achieved effective enzyme inactivation and ones that did not. For example, Falguera and others (2013b) reported 71.5% residual activity of apple juice PPO using 600 MPa at 25 °C for 16 min whereas Juarez-Enriquez and others (2015) reported complete inactivation of apple juice PPO under milder conditions (430 MPa, 25 °C, 7 min). In the case of carrot juice PME, Kim and others (2001) and Park and others (2002) reported residual activity values of 129% and 44%, respectively, under the same HPP conditions (600 MPa, 10 min, 25 °C). From the range of HPP conditions used at 25 °C, enzyme inactivation was limited at low pressure (200 to 300 MPa) in combination with high

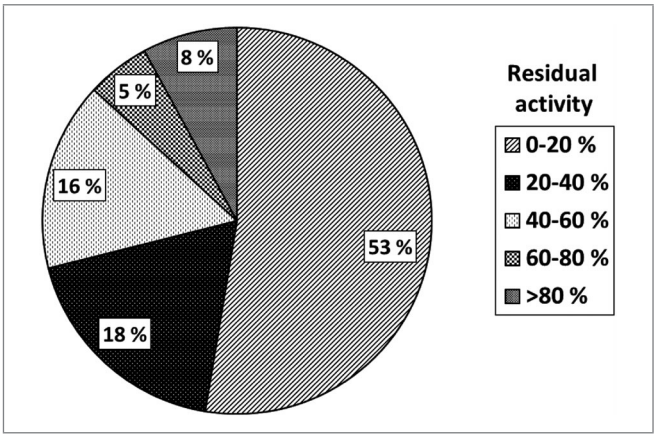

Figure 6–Combined distribution of percent residual activity values of PPO, POD, PME, and LOX enzymes following HPP treatment in fresh fruit and vegetable juices.

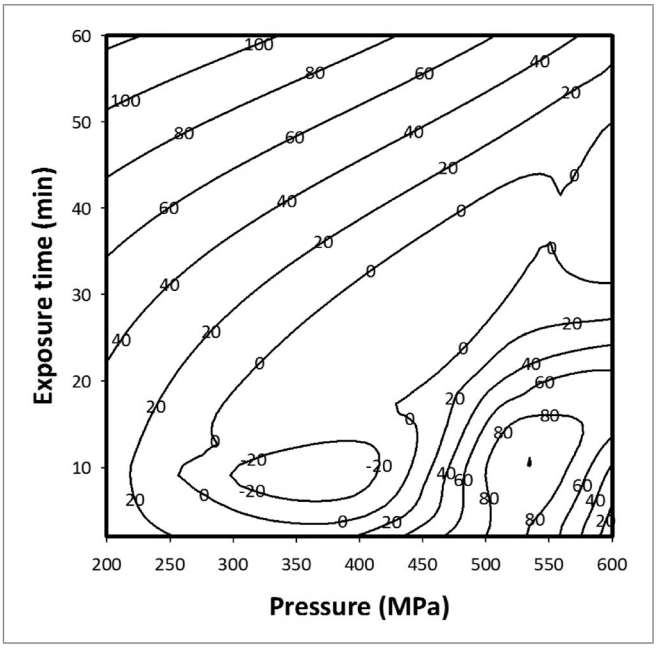

Figure 7–Contour plot illustrating the effects of HPP parameters, exposure time, and pressure, on the residual activity (%) of PPO, POD, PME, and LOX following HPP treatment of fruit and vegetable juices at 25 °C.

exposure time (40 to 60 min) as well as at pressures between 500 and 550 MPa in combination with exposure times of 0 to 15 min (Figure 7). However, as these studies demonstrate, making accurate predictions on HPP-induced enzyme inactivation based solely on juice type and HPP conditions remains a challenge. Depending on the desired enzyme activity following HPP treatment, various parameters affecting residual activity (described earlier) will have to be taken into account on a case-to-case basis in order to determine HPP conditions for optimum enzyme activity.

Polyphenols and other antioxidants. Table 16 shows the summary of residual contents of anthocyanins and polyphenols and also antioxidant activity in 15 types of juices following HPP treatment. The analyzed processing conditions were at pressure levels between 250 and 600 MPa, temperatures of 20 to 35 °C, and exposure times of 3 to 60 min. Similar to vitamins, the effect of HPP

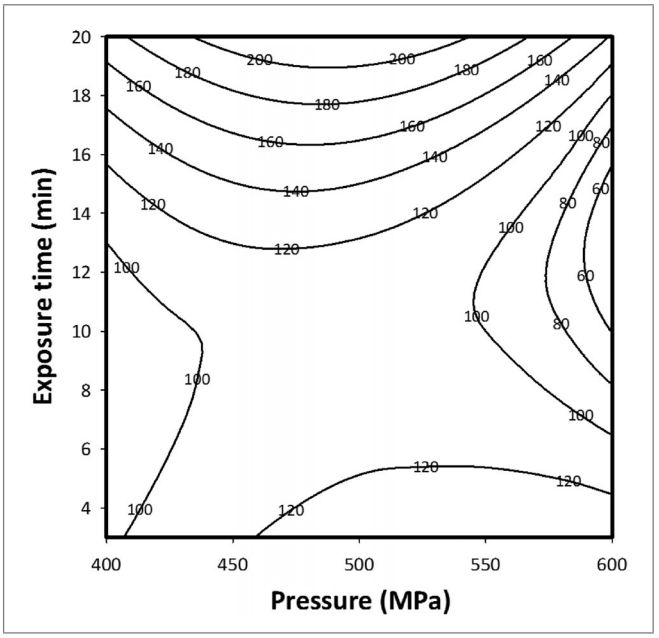

Figure 8–Contour plot illustrating the effects of HPP parameters, exposure time, and pressure, on antioxidant activity (%) following HPP treatment of fruit and vegetable juices at 25 °C.

on these compounds was minimal and fairly consistent among the reviewed studies.

Anthocyanins had the lowest retention in the group with an average residual content of 86.2 ± 25.9% following treatment. The lowest content was reported at 29% in pomegranate juice using 600 MPa at 25 °C for 10 min (Ferrari and others 2010). Total phenolic content was retained well with an average residual content of 92 ± 12.7%. The lowest content was also reported by Ferrari and others (2010) at 58%. Total phenolic content showed the least variability following HPP treatment. Antioxidant activity was retained with an average residual activity of 101.1 ± 23% with the lowest value reported by Barba and others (2013) at 52% in blueberry juice using 600 MPa at 25 °C for 15 min.

All 3 parameters showed significantly increased levels as compared to the control by at least 2 authors (Kim and others 2012; Barba and others 2013; Chen and others 2013, 2015; Jayachandran and others 2015). This suggests that when HPP is used for 5-log inactivation of pathogenic organisms in juice, chemical quality parameters such as vitamins, polyphenols, and antioxidants are either well retained or increased due to extraction. The contour plot of antioxidant activity during HPP treatment at 25 °C shows that the lowest residual activity levels (~80%) occur at pressures around 600 MPa and exposure times of 10 to 16 min (Figure 8). Under all other conditions residual activity values are either unchanged or enhanced.

Effect of HPP on color and sensory attributes

Color. Table 17 summarizes the effect of HPP treatment from 18 studies on the color of 14 different juice types. Similar to UV treatment, HPP did not have a significant impact on juice color when using conditions required for 5-log inactivation of pathogenic microorganisms. Two studies, including those by Zhang and others (2011) and Hartyáni and others (2011), reported significant or "great noticeable" ($\Delta E = 6.0$ to 12.0) net changes in color in watermelon juice ($\Delta E = 8.0$) (900 MPa, 60 °C, 60 min) and in orange juice ($\Delta E = 9.3$) (600 MPa, 15 °C,

Table 16–Reported effects of HPP on antioxidants and polyphenols in fruit and vegetable juices

Juice	TA RC[a](%)	TAA RA[b] (%)	TPC RC[a](%)	HPP parameters Pressure (MPa)	Temp. (°C)	Time (min)	Reference
Apple	–	129	–	500	25	3	Kim 2012
Blood orange	99	–	–	600	20	15	Torres 2011
Blueberry	101	52	106	600	25	15	Barba 2013
Carrot	–	87	–	250	35	15	Dede 2007
Chinese bayberry	98	–	–	600	25	10	Yu 2013
Grapefruit	–	100	99	550	25	10	Gao 2015
Litchi/lemon/coconut water	–	128	88	600	60	15	Jayachandran 2015
Orange-milk	–	88-93	92	400	26.6	9	Barba 2012a
Papaya/mango/Orange	101	94	93	500	15	15	Carbonell-Capella 2013
Mixed citrus	–	105	88	600	25	6	Butz 2003
Pomegranate	89	102	103	400	20	5	Chen 2013
Pomegranate	29	–	58	600	25	10	Ferrari 2010
Green asparagus	–	138	93	600	25	20	Chen 2015
Tomato	–	89	–	250	35	15	Dede 2007
Watermelon	–	–	100	600	25	60	Liu 2012

TA, total anthocyanins; TAA, total antioxidant activity; TPC, total phenol content.
[a]RC, residual content as a perecentage of original; [b]RA, residual activity as a percentage of original content.

Table 17–Effect of HPP treatment on color of fresh fruit and vegetable juices

Juice	ΔL	Δa	Δb	ΔE	HPP parameters Pressure (MPa)	Temp. (°C)	Time (min)	Reference
Bayberry	–0.6	–0.9	2.2	2.5[a]	600	10	5	Yu 2013
Blueberry	–	–	–	1.1	600	25	15	Barba 2013
Blood orange	3.2	2.4	2.1	4.5[a]	600	20	15	Torres 2011
Carrot	–	–	–	0.3	250	35	15	Dede 2007
Carrot	–	–	–	3.8	500	40	15	Gong 2015
Carrot	–0.6	–1.2	–3.0	3.3[a]	600	10	5	Picouet 2015
Cucumber	0.5	0	0.2	0.6	500	25	2	Zhao 2013
Grapefruit	–0.3	–0.2	–0.1	0.6	550	25	10	Gao 2015
Grapefruit	–	–	–	2.1	600	15	10	Hartyani 2011
Litchi/lemon/coconut water	–	–	–	5.1	600	60	15	Jayachandran 2015
Orange	–	–	–	0	600	20	1	Bull 2004
Orange	–	–	–	9.3	600	15	10	Hartyani 2011
Orange/milk	–	–	–	3.1	400	26.6	9	Barba 2012a
Pomegranate	–0.8	0.2	0.6	0.8	400	20	5	Chen 2013
Pomagranate	0.5	2.0	1.3	0.5	600	25	10	Ferrari 2010
Papaya/mango/orange	–	–	–	3.5	500	15	15	Carbonell-Capella 2013
Tangerine	–	–	–	2.6	600	15	10	Hartyani 2011
Tomato	–	–	–	0	250	35	15	Dede 2007
Watermelon	–1.8	–0.7	–7.8	8.0	900	60	60	Zhang 2011
Watermelon	2.0	0	–0.1	2.0	600	25	60	Liu 2012

[a]Calculated ΔE value; ΔL, Δa, and Δb values represent the net change compared to a fresh control; color difference scale based on ΔE (not noticeable = 0 to 0.5, slightly noticeable 0.5 to 1.5, noticeable 1.5 to 3.0, well noticeable 3.0 to 6.0, great noticeable 6.0 to 12.0).

10 min), respectively. Zhang and others (2011), who used the most intense HPP conditions among the reviewed reports, also reported a decrease in L^*, a^*, and b^* values, indicating a decrease in lightness, redness, and yellowness of the watermelon juice, which is a common indication of browning. The net change in L^* and a^* were "noticeable" ($\Delta L = -1.8$) and "slightly noticeable ($\Delta a = -0.7$), whereas b^* experienced the most significant change at "great noticeable" ($\Delta b = -7.8$). The authors also showed that changes in a^* of watermelon juice were more pronounced at 300 and 900 MPa as opposed to 600 MPa at 60 °C for 60 min. The likely reason for the great increase in ΔE reported in this study is that HPP conditions (900 MPa, 60 °C, 60 min), particularly the increased temperature and treatment time, far exceeded those required for 5-log reduction. Thermal processing often has a much greater impact on juice color as opposed to HPP treatment alone. Hartyáni and others (2011) observed significant or "great noticeable" color change in orange juice ($\Delta E = 9.3$) and noticeable changes in tangerine ($\Delta E = 2.6$) and grapefruit ($\Delta E = 2.1$) juices under much milder HPP conditions of 600 MPa at 15 °C for 10 min.

A total of 6 studies reported "well noticeable" ($\Delta E = 3.0$ to 6.0) changes in juice color. Barba and others (2012a) reported a net change in orange juice-milk color of 3.1 following HPP treatment (400 MPa, 26.6 °C, 9 min). Specifically, a decrease in L^*, a^*, and b^* values was observed. The authors achieved 5-log reduction of *Lactobacillus plantarum* using 200 MPa at 26.6 °C for 5 min. At these HPP conditions, a "slightly noticeable" net color change of 1.0 was reported. Further, it was shown that thermal treatment capable of achieving the same 5-log reduction (90 °C, 15 min) produced a larger net color change ($\Delta E = 5.4$) than any of the HPP treatments. Carbonell-Capella and others (2013) showed a correlation between HPP pressure and exposure time to color stability of a papaya/mango/orange juice mixture at 15 °C. The authors reported a "not noticeable" color change at 300 MPa for 5 min ($\Delta E = 0.5$), a "noticeable" change at 500 MPa for 5 min ($\Delta E = 1.9$), and a "well noticeable" change at 500 MPa for 15 min ($\Delta E = 3.5$). Torres and others (2011) reported an increase in a^* and L^* values of blood orange juice following HPP treatment using 600 MPa at 20 °C for 15 min, which lead to a total color difference of $\Delta E = 4.5$ (calculated). Jayachandran and others (2015) and Gong and others (2015) also observed "well noticeable" changes in color in litchi/lemon/coconut water ($\Delta E = 5.1$) and carrot juice ($\Delta E = 3.8$) following HPP treatment

using 600 MPa at 60 °C for 15 min and 500 MPa at 40 °C for 15 min, respectively. These increased ΔE values are also likely the result of browning caused by high temperatures and prolonged exposure times.

Aside from the above-mentioned studies, the 12 remaining studies all reported insignificant or "not noticeable" to "slightly noticeable" changes in color following HPP treatment. This was expected considering that HPP was shown in this review to have a minor impact (degradation or enhancement) on color-associated compounds such as carotenoids, anthocyanins, and polyphenols. In summary, it appears that HPP, at conditions required for 5-log reduction of pathogenic microorganisms, has limited impact on the color of fruit and vegetable juices.

Sensory. As with color, HPP was shown to be effective at maintaining acceptable sensory qualities of juices. A total of 5 studies reported the effects of HPP treatment on orange, carrot, yellow passion fruit, cantaloupe, and peach juice sensory attributes. In all reported studies, a trained panel was used for determining juice sensory attributes. Baxter and others (2005) showed that HPP-treated (600 MPa, 20 °C, 1 min) navel orange juice had stable sensory properties and was deemed acceptable by a trained sensory panel and a consumer panel for up to 12 wk of storage at 4 °C when compared to an untreated control stored at –20 °C. Trained panelists graded the juices based on various quality descriptors pertaining to color, odor, and taste, whereas the consumer panel graded the juices for acceptability using a 9-point hedonic scale. Both the HPP-treated and thermally-treated (85 °C, 25 s) juices were shown to have similar color, odor, and taste attributes when compared to the untreated control following the storage period. In addition, GC-MS analysis of 20 key aroma compounds following the storage period showed very comparable results for HPP-treated and untreated juice. Laboissière and others (2007) also indicated that HPP treatment (300 MPa, 25 °C, 5 min) of yellow passion fruit juice results in no significant sensory changes as compared to fresh and untreated juice. The authors used a trained sensory panel with quantitative descriptive analysis (QDA) and principal components analysis (PCA) to show that HPP-treated and untreated natural yellow passion fruit juice had similar sensory attributes such as natural aroma and flavor, acid aroma, presence of suspended particles, and phase separation. However, thermally treated commercial juices were associated with attributes such as artificial, cooked, and fermented aroma and taste. Ma and others (2010) used a difference test to show that no significant sensory difference exists between HPP-treated (400 and 500 MPa, 22 °C, 20 min) and nontreated cantaloupe juice according to a trained panel. Fernández García and others (2001) used a triangle test to show defects in odor and aroma of orange/lemon/carrot juice when treated at 800 MPa at 4 °C for 5 min. Otherwise, at 500 MPa for 5 min, sensory qualities were comparable to the control. In storage studies at 4 °C for 21 d, the sensory attributes of the HPP-treated juice were shown to be more stable than those of the untreated juice. The ability of HPP to preserve juice sensory qualities was reported by other authors as well (Polydera and others 2003; Rao and others 2013; Picouet and others 2015).

Summary

Fifty research studies reported HPP processing of 24 types of fresh fruit and vegetable juices in low-acid, acid, and high-acid pH categories. Orange, carrot, and tomato juices were the most reported in the HPP studies. HPP was shown to preserve physicochemical properties, vitamin content, and antioxidant activity of fruit and vegetable juices at conditions required to achieve 5-log reduction of pathogenic microorganisms. Vitamin C was the most studied vitamin from a group including vitamin A, E, and carotenoids. It was shown to have high and consistent retention following HPP treatment with an average residual content of 92.1 ± 9.6%. Similar results were reported with the residual content of anthocyanins and total phenols as well as total antioxidant activity. Anthocyanins showed modest stability and consistence following HPP treatment with an average residual content of 86.2 ± 25.9%. Total phenolic content had similar retention characteristics to vitamin C with an average residual content of 92 ± 12.7%. Juice antioxidants were highly conserved and often prone to enhancement, showing an average residual activity of 101.1 ± 23% following HPP treatment. Several instances of enhancement in residual content or activity following treatment were reported with all the examined vitamins and antioxidants.

HPP-induced inactivation of common spoilage enzymes, PPO, POD, PME, and LOX, showed fairly unpredictable results. The 2 most-studied enzymes, PPO and PME, were inactivated by approximately 90% in the majority of reported juices. However, several authors reported higher-than-average residual activity values (44% to 129%) for both enzymes using 500 to 600 MPa at 20 to 25 °C for 10 to 16 min. One author reported enhancement of PME activity following treatment and no enhancement in activity was reported for PPO. POD was shown to be the most pressure resistant of the 4 enzymes, with residual activity values following HPP treatment often remaining in the 20% to 60% range in all reported juices. LOX was the least-studied of the 4 enzymes and appears to have a similar response to pressure as POD. Overall, many discrepancies still exist with respect to HPP-induced enzyme inactivation in juice products. We have observed large variations in residual activity values of enzymes that are treated under very similar, if not identical, HPP conditions. This is likely attributed to the fact that enzyme stability in fruit and vegetable juice is dependent on a wide variety of factors including origin of the enzyme, availability and nature of the substrates, pH, medium composition, temperature, as well as HPP conditions.

As in the case with UV light, overprocessing was often observed in the HPP studies. Several authors have shown that 5-log reduction of pathogens such as *Escherichia coli* O157: H7 and *Listeria monocytogenes* in apple and orange juices can be achieved with pressures ranging from 241 to 550 MPa, exposure times from 1 to 5 min, and temperatures from 20 to 30 °C (Rupasinghe and Yu 2012). These parameters, particularly exposure time and temperature, were often exceeded in the reported studies and, therefore, likely contributed to unnecessary nutrient losses following HPP treatment.

Conclusions

The effects of UV light and HPP processing on quality and nutritional content of fresh fruit and vegetable juices were reviewed in 92 studies (UV light: 42, HPP: 50). It was determined that both processing methods showed only minor degradation of juice physicochemical properties, vitamin content, and antioxidant activity at conditions required to achieve 5-log reduction of pathogenic microorganisms. However, over-processing was common among all the studies—often leading to an unnecessary decrease in quality and nutritional parameters. In the case of UV light, this was mostly evident in lab-scale and pilot-scale units as opposed to commercial-scale units. Residual content or activity of vitamin C, total phenols, and antioxidants following UV light (83.7% to 91.6%) and HPP treatment (92% to 101.1%) showed only minor decreases with comparable values. Residual activity

of juice spoilage enzymes PPO and PME was decreased more so following HPP (10% to 12.6%) as opposed to UV light (50% to 73.9%) treatment. Further research is required to determine the effects of UV light and HPP on both fruits and vegetables enzymes such as PPO, POD, PME, and LOX. As seen particularly with HPP, the discrepancies were found in reporting enzyme activity under similar processing conditions. This review is important for the commercialization and successful growth of UV light and HPP technologies as nonthermal preservation methods in the premium cold-pressed juice market.

Nomenclature

Symbol	Description
A_l	Surface area of the UV lamp quartz sleeve, cm^2
α_λ	Decadic absorption coefficient or absorbance for a 1-cm path length at a λ (nm) wavelength, cm^{-1}
DF	Divergence factor; for path lengths less than 5 cm, the DF is given by Eq. 9
E	UV energy, dose or fluence, J/cm
H_0	Incident UV fluence or dose, J/cm^2
H_r	Absorbed UV fluence or dose, J/cm^2
I	Power data, irradiance or fluence rate, W/cm^2 or W/L
I_0	Incident UV irradiance or fluence rate, radiometer reading at the center of the product and at a vertical position so that the calibration plane of the detector head is at the same level as the surface of the fluid, W/cm^2
I_r	Absorbed UV irradiance or fluence rate, W/cm^2
$I_{r\,avg}$	Average absorbed UV irradiance or fluence rate in a batch system, W/cm^2
l	Vertical path length of the sample in the container (such as a Petri dish), cm
L	Distance from the UV lamp to the surface of the sample, cm
L_N	Number of UV sources
PF	Petri factor, measured according to Bolton and Linden (2003)
P_{UV}	Output power of the UV source, W
$P_{UV\text{-}C}$	Output power of the UV-C source, W, is typically 30% or 10% of the total wattage of the UV lamp, for LPM and MPM lamps, respectively (Rodriguez-Gonzalez and others 2015)
P_{UVN}	Output power of N UV sources, W
r	Radius of the chamber, cm
r_0	Radius of the UV lamp quartz sleeve, cm
RF	Reflection factor ($RF = 1 - R$), R is the reflected fraction. For air and water: $R = 0.025$ and $RF = 1 - 0.025 = 0.975$
t	Time (average residence time, total or partial exposure time), s
$\dot{V}$	Volumetric flow rate of treated fluid, L/s
WF	Water factor or liquid factor (LF) is calculated according to Eq. (8)

Author Contributions

Tatiana Koutchma – Researched prior studies, interpreted results, compiled data, and drafted the manuscript. **Vladimir Popović** – Researched prior studies, interpreted results, compiled data, and drafted the manuscript. **Valquiria Ros-Polski** – Researched prior studies, analyzed and interpreted results, and compiled data. **Anthony Popielarz** – Reviewed drafted manuscript, drafted sections of the introduction and aided in drafting other parts of the review.

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