Recent Studies on Healthy Nutrients Changing in Fruit Juices Processed with Non-thermal Technologies

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Abstract Fruit juices are the most preferred beverage around the world due to their high content of healthy nutrients and being source of antioxidants, such as vitamins, phenolic and carotenoid compounds. Fruit juices contain some vitamins, phenolic and carotenoid compounds having important antioxidant function that scavenge free radicals damaging cells with reacting structural molecules and reduce cardiovascular diseases. Therefore, they are unique for growth, maintenance and well-being of human life. Nowadays consumer demands have tendency around both safe to consume and minimal processed foods. Therefore, food processing industry has made an effort in order to improve processing technologies having potential to fulfill these consumer demands in final product. In the last decades, promising non-thermal food processing technologies, such as pulsed electric fields (PEF), high pressure processing (HPP), ultrasound processing (UP) and ultraviolet light processing (UVLP), have been alternatively developed to the traditional thermal pasteurization for extending shelf life and minimizing loss of healthy nutrients of fruit juices. In the present book chapter, effect of non-thermal technologies (PEF, HPP, UP and UVLP) on fruit juices, health related compounds (vitamins, phenolic and carotenoid compounds) were evaluated and discussed from the perspective of recent published research studies in the literature.

Keywords Non-thermal processing technologies · Fruit juices · Carotenoids · Vitamins · Phenolics

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Introduction

Consumer concerns about health issues resulted in changing of consumption demands and they began to increase their consciousness towards the foods containing high amount of antioxidants, minimally processed and without containing processing-induced detrimental substances. Fruit based products consumption is a marker of higher-quality diets and they must be taken daily to support healthy life. The consumption of high quality fruit juices, together with whole fresh fruit, is one of the alternative ways to fulfill daily fruit consumption goals (Francou et al. 2015). Therefore, fruit juices are among the most widely consumed ready to drink beverages due to important sources of health supported nutrients such as, phenolics, carotenoids, fibers, vitamins and minerals. A significant portion of those healthy compounds like phenolic acids, flavonoids, carotenoids, vitamin C, vitamin A and tocopherol shows antioxidant activity. Epidemiological studies indicated that antioxidant compounds are able to reduce risk of chronic diseases such as obesity, cardiovascular, cancer, inflammatory activities, diabetes, viral infection, stroke, Alzheimer's and oxidative stress-induced other malignancies (Akhtar et al. 2017; Netzel et al. 2007; Sevimli-Gur et al. 2013; Stinco et al. 2019; Temple 2000; Willett 2002). Similarly, in a research study, it was indicated that diet exposure with balanced fruit juice consumption (not exceed eight glasses/week) was associated with a lower risk of cardiovascular diseases and stroke (Scheffers et al. 2019).

Non-thermal technologies, defined as an alternative processing techniques to thermal pasteurization and sterilization, can be successfully used for both producing foods safe to consume and improving shelf-life of the foods by inactivating enzymes, spoilage and pathogenic microorganisms. Although achievement of traditional thermal processing is satisfied in extending shelf-life of fruit juices due to high inactivation of resistant enzymes, spores and microorganisms, it causes dramatic change in phenolic and carotenoid compounds, vitamins, taste and color of juices as well as increasing in undesirable substances such as furfural, hydroxymethylfurfural, furan and acrylamide. However, non-thermal processing technologies such as high pressure processing (HPP), pulsed electric fields (PEF), ultrasound processing (UP) and ultraviolet light processing (UVLP) are able to both adequately inactivate fruit juice enzymes and microorganisms and remarkably save health related nutrients and original flavor attributes of juices without or lower processing-induced detrimental substances (Agcam et al. 2014a, b, 2016; Al-juhaimi et al. 2018; Balasubramaniam et al. 2015; Dhakal et al. 2017; Dundar et al. 2019).

High pressure processing (HPP), an innovative non-thermal technology, preserves food products by using of pressures in the range of 100–800 MPa, with or without heat treatment assistance, for inactivating a variety of pathogenic and spoilage vegetative bacteria, yeasts, molds, viruses, enzymes and spores to ensure microbiologically safe foods. Those hydrostatic pressure levels have little effect on covalent bonds of the molecules existing in foods, and therefore, small molecules such as vitamins, phenolics, carotenoids, pigments and flavors do not undergo significant chemical transformation. The basic HPP system consists of high-pressure vessel, two end closures to cover the pressure vessel, headlock to close the vessel off, pressure generation pump and intensifier to reach target pressures, a system for pressure and temperature control, material handling system to load and remove the products, and finally control/monitoring system. For food processing industry, high pressure pasteurization equipment is available in both horizontal and vertical configurations having an operation capacity between 35 and 525 L. Although HPP can generally operate with batch regime, the systems as semi-batch regime are also available. When high pressure is started to transmit through the vessel, at the same time, it is transmitted to the food product equally from all sides. Therefore, during high pressure exposure, the food products are not crushed owing to this equal pressure distribution (Rastogi 2010; Balasubramaniam et al. 2015, 2016).

Pulsed electric fields (PEF) processing, which is a promising alternative to classical thermal preservation processes for liquid foods like fruit juices containing heat sensitive volatile or bioactive compounds, has capacity to inactivate microbial cells combined with low to moderate temperatures (<50 °C). In PEF treatments, food matrix is passed between two electrodes and exposed to an electrical field in the form of very short (a few µs), high-voltage (kV) pulses. The electric field strength, which is created between the couple of electrodes, can be calculated by dividing the applied voltage by the distance between the electrodes (Buckow et al. 2013). An example of PEF treatment system used for orange juice pasteurization was shown in Fig. 1. The exposure of food matrix to an electric field of moderate intensity (0.5–10 kV/cm) and relatively low energy (1–10 kJ/kg), implemented in the form of recurrent very short voltage pulses (µs or ms), induces a permeability of cell membranes that makes possible the release of juice and valuable components from the internal parts of the cells (Bobinaitė et al. 2015). Fluid or pumpable foods as fruit juices, milk, smoothies, yogurt, sauces, wine and soup-based products can be pasteurized with PEF technology instead of traditional thermal techniques. These food matrixes comprise large quantity of water and dipolar molecules making them more conductive for transition of electrical currents compared to solid foods. The PEF system unloads a high voltage pulse uniformly throughout the food in a treatment

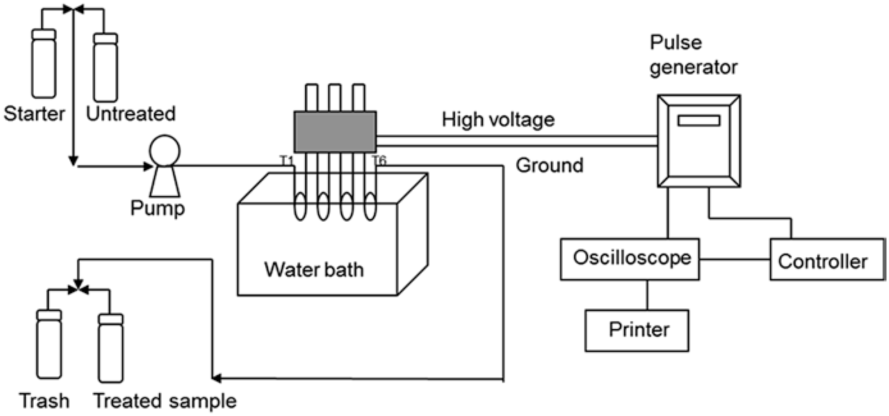

Fig. 1 Schematic diagram of pulsed electric fields (PEF) system (Agcam et al. 2014a)

chamber (Barba et al. 2017; Tiwari and Cummins 2013; Ricci et al. 2018; Toepfl et al. 2006; Ganessingh et al. 2018). Additionally, PEF treatment improves the extraction ratio of bioactive compounds like anthocyanins, carotenoids, betanines and polyphenols from foods and assists shorten extraction time and decreases solvent expenses and/or lower extraction temperatures (Puértolas et al. 2013; Boussetta et al. 2012). The main mechanism of PEF is based on the exchange or disintegration of cells exposed to sufficiently large external electric fields, which increases permeability and electrical conductivity of the cellular material (Martín-Belloso et al. 2014). The mechanism of PEF can be explained using the "electroporation" model in which the strong electric fields generate either reversible or irreversible perforation (permanent or temporary pores) of the cytoplasmic membrane causing cell leak depending on electric field intensity level (Ricci et al. 2018; Ganessingh et al. 2018). This destructive effect of PEF results with microbial or enzymatic inactivation, thereby providing the products for consumers with microbiologically-safe, high-quality (better flavor, color, texture, and high nutritional value) and enhanced efficiency in juice extraction process.

In food technology, ultrasound processing (UP) treatments mainly can be divided in two groups based on their intensity level: low and high intensity ultrasound. While low-intensity applications are generated by using small amplitude waves (at high frequency, >1 MHz) with no damage on food material and generally for analytical measurements, high intensity applications (20–500 kHz) can cause changing in microbiological or chemical properties of food (Kentish and Feng 2014). While ultrasound is generated, electrical energy is transformed to mechanical vibration by a transducer. In the laboratories and food industry, ultrasound treatments are applied in sonication water bath (Fig. 2a) or with a probe (Fig. 2b), a titanium cylinder consists of a transducer. During processing, a part of electrical energy converts to heat. Hence, ultrasound processing equipment should contain cooling systems as it can be seen in Fig. 2. Ultrasound probe can transfer high amount of energy directly to the medium, but the energy decreases while distance from probe increases. On the other hand, although an ultrasonic bath has more than one transducer at the base part of the device, generally provide lower ultrasound energy intensity to treat food material. The generated ultrasound energy causes a phenomenon in liquid foods called as "cavitation". After formation of low and high pressure regions in the medium, very small bubbles appear at the low pressure points. These bubbles can coalesce with each other; however when they reach the biggest size (also called the critical size), they collapse violently ending with temperature and pressure increasing up to 2000–5000 K and 300–1200 bar (Suslick et al. 1999).

The increasing consumers' tendency towards products with similar characteristics to fresh ones has led researchers to develop alternative processing techniques. One of the non-thermal technologies applied as an alternative to thermal pasteurization is UV-C irradiation. The inactivation mechanism of UV-C irradiation is based on the absorption of UV photons by genetic material and consequently the replication of the cell and the formation of dimers which inhibit transcription. The antimicrobial effect of UV-C light is well known and this method is used in surface disinfection of hospitals, water resources, drinking water, fruit juices and different fruits (Unluturk 2012).

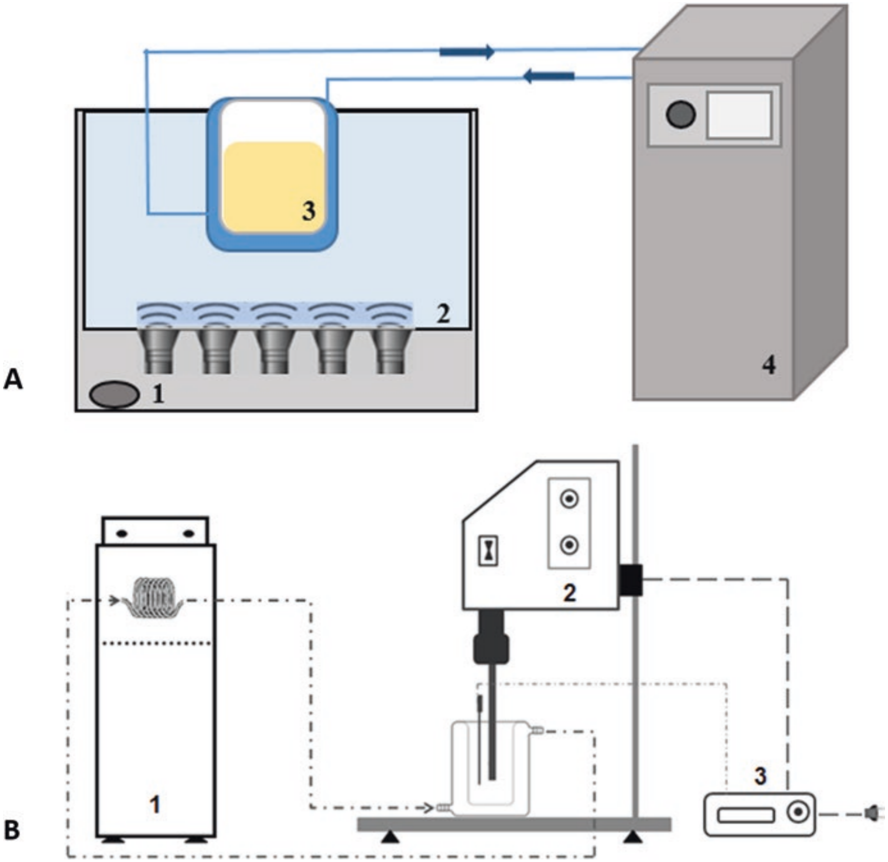

Fig. 2 Ultrasound applications with ultrasonic bath (**a**: (1) Ultrasonic bath with time controller, (2) water, (3) juice, (4) cooling water circulator for jacketed vessel) and probe (**b**: (1) cooler, (2) ultrasound equipment, (3) energy-and thermo-meter (Ağçam et al. 2017))

In the present chapter, effects of various non-thermal technologies that are the most promising for the juicing industry such as PEF, HPP, UP and UVLP on health related compounds like vitamins, phenolic and carotenoid compounds containing in fruit juices were evaluated and discussed from the perspective of recent published research studies in the literature.

Effect of High Pressure Processing (HPP) on Bioactive Compounds

The summary about bioactive compounds changing in different juice sources processed with HPP was given in Table 1. Fernández-Jalao et al. (2018) conducted a study in order to determine effect of HPP conditions on phenolic compounds of

Table 1 Short summary about bioactive compounds changing in different juice sources processed with high pressure processing (HPP)

Juice/ source	Bioactive compounds	Processing conditions	Highlights	Reference
Apple	– Ascorbic acid – Antioxidant activity	430 MPa, 7 min, room temperature	– The dramatic decrease determined in ascorbic acid during 34 days storage at 4 and 20 °C. – Antioxidant activity reduced significantly during storage periods.	Juarez-Enriquez et al. (2015)
Apple (Golden Delicious)	– Phenolic compounds – Antioxidant activity	400–600 MPa, 35 °C, 5 min	– The results showed that high pressure affected differently the phenolic compounds according to the origin of apples. – While higher antioxidant activity was determined with increasing processing pressure for Spanish-apples, lower antioxidant activity was determined for Italian-apples.	Fernández-Jalao et al. (2018)
Mango	– Ascorbic acid – Phenolic compounds – Carotenoid compounds – Antioxidant activity	400–550 MPa, 34 and 59 °C, 2–16 min	– Ascorbic acid degraded significantly at higher pressure, temperature and holding time. – Phenolic concentrations increased up to 34%. – Except violaxanthin, individual carotenoids remained unchanged. – Antioxidant activity showed increasing tendency up to 4 min processing time.	Camiro-Cabrera et al. (2017)
Strawberry	– Ascorbic acid – Anthocyanin contents	400–600 MPa, 20 °C, 1.5 or 3 min	– Ascorbic acid and anthocyanin contents were well preserved after HPP. – Thermally processed samples showed better storage stability than high pressure treated in terms of these bioactive compounds.	Aaby et al. (2018)

(continued)

Table 1 (continued)

Juice/ source	Bioactive compounds	Processing conditions	Highlights	Reference
Pineapple	– Phenolic and flavonoid content – Ascorbic acid – Antioxidant capacity	200–600 MPa, 30–70 °C, up to 20 min	– The combined high pressure-temperature conditions affected significantly bioactive components. – Phenolic contents increased up to 50 °C. – Flavonoid content was stable at the pressure levels, while decreasing after 50 °C processing temperature. – Processing temperature higher than 50 °C was responsible from ascorbic acid loss. – Dramatic decreasing was determined for antioxidant capacity of the samples processed at >45 °C	Chakraborty et al. (2015)
Pineapple	– Ascorbic acid	0.1–600 MPa, 30–95 °C, 0–15 min	– No ascorbic acid degradation was determined for processing conditions at 300–600 MPa-30 °C and up to 15 min. – Similar activation energy values for ascorbic acid degradation were calculated for both thermal and pressure-thermal treated samples.	Dhakal et al. (2018)
Orange	– Ascorbic acid – Phenolic compounds – Carotenoid compounds – Antioxidant activity	350–550 MPa, 41–68 °C, up to 10 min	– Higher ascorbic acid contents and antioxidant activity values were determined for most high pressure treated samples than untreated ones. – Phenolic compounds were not significantly affected by HPP. – Carotenoid contents of most samples processed at ≥56 °C decreased about 15% independent to applied pressure and time.	Escobedo-Avellaneda et al. (2015)

(continued)

Table 1 (continued)

Juice/ source	Bioactive compounds	Processing conditions	Highlights	Reference
Orange	– Phenolic compounds – Total phenolic, flavonoid and anthocyanin contents – Total carotenoid – Antioxidant activity	550 MPa,18 °C, 70 s	– HPP caused a significant increase in flavonoid content, while thermal pasteurization decreased anthocyanin ad flavonoid contents. – Both after processing and during storage, higher carotenoid contents were detected in HPP treated samples. – Most of bioactive compounds of HPP treated samples showed lower degradation rates than thermally treated samples during 36 days storage at 4 °C. – After treatments, HPP treated samples had higher antioxidant activity. And also, better antioxidant activity results were obtained for HPP treated samples.	Vieira et al. (2018)
Carrot	– Carotenoids – Phenolic content – Antioxidant capacity	550 MPa, 6 min	– Samples treated with HPP had higher bioactive compound concentrations than thermal treated. – Studied bioactive compound concentrations decrease significantly during 20 days storage at 4 °C.	Zhang et al. (2016)
Aronia berry	– Total phenolic – Total anthocyanin content – Antioxidant capacity	200–600 MPa, 21–33 °C, 2.5 and 5 min	– No significant decreasing was determined in bioactive compounds and antioxidant capacities of treated aronia purees. – During 8 weeks storage at 4 °C, no significant difference was obtained for total phenolic content and antioxidant capacity of the samples treated with 400 and 600 MPa-5 min, while a significant decreasing tendency was determined for total anthocyanin content.	Yuan et al. (2018a, b)

(continued)

Table 1 (continued)

Juice/source	Bioactive compounds	Processing conditions	Highlights	Reference
Kiwi fruit	– Ascorbic acid – Total phenols – Chlorophyll	500 MPa, 25 °C, 10 min	– Ascorbic acid content of the HPP treated juices was remarkably higher than thermal treated (110 °C-8.6 s) juices. – The difference between total phenol values was not significant but HPP treated samples higher than thermal treated ones. – After HPP treatments, the chlorophyll contents were determined higher than double. – HPP treated samples showed better results of ascorbic acid and chlorophyll contents during 42 days-storage, while better results of total phenols were determined in that period for thermal treated samples.	Xu et al. (2018)
Gooseberry	– Ascorbic acid – Total phenols – Antioxidant activity	200–500 MPa, 30–60 °C, 1 s–20 min	– The loss in ascorbic acid for assistance of temperature and HPP varied from 0.3% to 15.4%, while that value was determined 34% for thermal treatment at 60 °C-20 min. – Ascorbic acid degradation rate ranged between 1.57×10^{-3} and 2.013×10^{-3} m^{-1} for temperature assisted HPP. – Up to 50 °C, total phenols and antioxidant activity increased with increasing processing pressure.	Raj et al. (2019)

(continued)

Table 1 (continued)

Juice/source	Bioactive compounds	Processing conditions	Highlights	Reference
Sugarcane	– Ascorbic acid – Total phenols – Antioxidant capacity	300–600 MPa, 30–60 °C, 10–25 min	– Dramatic ascorbic acid reduction (25%) was detected at 600 MPa/60 °C/25 min. – Ascorbic acid degradation increased significantly accordingly with processing at higher pressure, temperature and time. – The highest total phenols were determined for samples processed at 600 MPa/50 °C/20 min. – Samples treated at 300–600 MPa/10–25 min and lower or equal to 50 °C showed higher antioxidant capacity than samples treated at higher temperature.	Sreedevi et al. (2018)
Mulberry	– Total monomeric anthocyanin – Anthocyanin compounds	400–500 MPa, 25 °C, 5–10 min	– At the end of storage (4 °C-30 days), the highest retention rates for total anthocyanin content and cyanidin-3-rutinoside were determined for juices treated at 400 MPa-5 min. – Higher processing time at the constant pressure caused significant reduction in anthocyanin compounds. – The juice samples processed with 75 °C-10 min lost significantly initial anthocyanin contents at the end of storage.	You et al. (2018)
Papaya	– Total carotenoids – Total phenols – Antioxidant capacity	350–650 MPa, 20 °C, 5 and 10 min	– Quality and microbiological results suggested HPP processing at 550 MPa/5 min. – Better retentions of total carotenoids, total phenols and antioxidant capacity immediately after HPP treatments. – HPP treated samples remarkably showed better stability than thermal process (110 °C-8.6 s) in terms of total phenols and antioxidant capacity during storage period (40 days/4 °C).	Chen et al. (2015)

apples collected from different regions. While the highest phenolic compounds were determined for Spanish-apples processed at 400 MPa/35 °C/5 min, for Italian-apples, it was determined at 600 MPa/35 °C/5 min. Generally, for apples from Spain, it can be said that there is a decreasing tendency in response to higher processing pressure for the most abundant phenolic compounds such as procyanidin B2, chlorogenic acid, epicatechin, phloridzin and Q-3-rhamnoside. However, the phenolic compound results for apples collected from Italy were detected as increasing response to higher processing pressure. In the same study, it was reported that significant positive correlations were found between all the antioxidant activity determinations and total phenolic in Italian and Spanish apples. Juarez-Enriquez et al. (2015) also studied shelf life stability of apple juice processed with 430 MPa/7 min high pressure conditions and results showed that ascorbic acid and antioxidant activity decreased remarkably during 34 days storage period at both 4 and 20 °C.

Effect of HPP conditions on mango pulp bioactive compounds (ascorbic acid, phenolic contents and carotenoid compounds) was performed by Camiro-Cabrera et al. (2017). According to the results, the phenolic content increased remarkably up to 34% as compared to initial concentrations at higher processing pressure. The researchers commented that high pressure is able to increase extractable phenolic compounds due to its destructive effect on cell wall and cell membrane. And also, they reported that after 8 min high pressure holding time, the phenolic content started to affect negatively. Ascorbic acid concentration started to degrade after 4 min holding time at 34 °C, while decreased significantly after all high pressure treatments at 59 °C. Comparing to untreated samples, mango pulp samples treated with high pressure showed the same carotenoid profile. However, pronounced degradation was observed for violaxanthin which is one of the most abundant carotenoids in mango pulp. Higher holding time at higher processing temperature resulted with higher carotenoid compounds degradation due to temperature sensitivity of carotenoids. The antioxidant activity of the treated samples was not affected or increased up to 39% in respect of untreated samples. Finally, the researchers suggested to process mango pulp at 550 MPa-moderate temperatures (<34 °C)-8 min in order to obtain mango pulp with the highest bioactive compounds and functionality.

Aaby et al. (2018) conducted a comparing study about effect of HPP and thermal pasteurization on strawberry puree and juice. Moreover, treated samples were followed for 49 days at 6 °C storage temperature. While thermally processed (85 °C-2 min) puree had higher ascorbic acid concentration than high pressure treated ones, juices processed with high pressure at 400 and 500 MPa had higher concentration than untreated and thermally processed juice samples. For the strawberry puree, the anthocyanin content results showed that high pressure applied purees contained higher concentration than untreated but lower than thermal pasteurized ones. However, pressurized strawberry juice, independent to the applied high pressure conditions, had higher anthocyanin contents than both thermal treated and untreated juice samples. Ascorbic acid and anthocyanin contents of treated strawberry puree and juice samples were remarkably reduced during 49 days storage period at 6 °C. It can be observed from the presented results that ascorbic acid degradation rate is higher for thermal treated samples than high pressure treated. However, at the end of the storage, anthocyanin content of thermally processed strawberry samples was determined significantly higher than samples processed with high pressure. The reason for that situation was stated by the researchers that high pressure applied strawberry samples had higher residual oxidative enzymes, such as PPO.

The combined high pressure-temperature conditions were studied for pineapple puree and changing of quality attributes of the puree, such as ascorbic acid, phenolic and flavonoid contents and antioxidant capacity, was also reported. The findings showed that the pressure increasing from 400 to 600 MPa at the constant low temperature-time and processing time increasing from 10 to 20 min at constant pressure-low temperature did not meaningfully affect ascorbic acid content, while increasing temperature from 50 to 70 °C at constant pressure and time caused significant decomposition in ascorbic acid content. For example; ascorbic acid lost for samples processed at 200 MPa and 50, 60 and 70 °C was determined as 7.3, 12.5 and 23.5%, respectively. For all pressure-time combinations, instead of decreasing in total phenolic content at higher pressure conditions, it was found an increasing in total phenolic content up to 60 °C processing temperature. However, after that processing temperature, the phenolic content started to decrease remarkably. While flavonoid content was stable for processing temperature between 30 and 50 °C, it had a significant decreasing trend for higher values of pressure-temperature and processing time. Similar tendency was determined for antioxidant capacity of pineapple puree (Chakraborty et al. 2015). Consequently, in order to obtain pineapple puree with a source of bioactive compounds, HPP conditions up to 600 MPa at ≤60 °C were suggested by the researchers. Dhakal et al. (2018) conducted a research study on ascorbic acid degradation kinetics of pineapple juice subjected to different pressure (0.1–600 MPa), temperature (30–95 °C) and holding time (0–15 min). They reported that there was no ascorbic acid degradation for pineapple juice samples treated with high pressure between 300 and 600 MPa-up to 15 min at 30 °C. However, comparing to untreated juice samples, samples treated at 75 °C and 95 °C for 60 min lost 25% and 39% of ascorbic acid content, respectively. The researchers highlighted that ascorbic acid degradation increased in the samples treated with combined pressure-thermal processing. For ascorbic acid degradation, activation energy values of thermal processing at atmospheric pressure (0.1 MPa) and combined pressure-thermal processing were calculated in the range of 14–30 kJ/mol and 17.4–43.8 kJ/mol, respectively.

A comparing study was conducted to investigate effect of HPP (550 MPa-6 min) and thermal pasteurization on (110 °C-8.6 s) carrot juice phenolic contents, carotenoid compounds and antioxidant capacity. Moreover, treated samples were stored at 4 °C for 20 days. No difference was detected between control and treated samples for lutein content. In the HPP-treated samples, both of α-carotene and β-carotene were significantly detected higher than thermal pasteurized samples. Similarly, total phenolic contents were better preserved in the juices treated with HPP but remarkably decreased for thermal treated juices. The antioxidant capacity of carrot juice samples reduced significantly after HPP and thermal treatments. However, in the samples processed with high pressure, the antioxidant capacity showed better retention than thermal processed. After 20 days storage at 4 °C, the decreasing in carotenoid contents of juices treated with HPP and thermal pasteurization were 66.7% and 72.9% for lutein, 16.2% and 26.8% for α-carotene, 11.1% and 16.6% for β-carotene, respectively. However, total phenolic contents were decreased 35.8% and 33.5% for carrot juices treated with HPP and thermal pasteurization at the end of the storage, respectively. Due to decrease in concentration of the carotenoids and phenolics, the antioxidant capacity of the treated carrot juices decreased linearly during storage period. The researchers also calculated degradation rate constant of the bioactive compounds for treated juices and, the results showed that carotenoid compounds (except lutein) and total phenolic of HPP treated samples degraded with higher reaction rate constants than thermally pasteurized samples during the storage (Zhang et al. 2016).

Yuan et al. (2018b) studied the effect of different high pressure levels (200–600 MPa) and holding times (2.5 and 5 min) on aronia berry puree bioactive compounds. High pressure treated samples had higher bioactive compound levels than untreated samples. According to the results, up to 400 MPa, the bioactive compounds had an increasing tendency but after that pressure, decreasing tendency was observed. Compared to untreated puree, total phenolic and anthocyanin contents of pressurized purees increased 3–13% and 6–17%, respectively. In addition, the researchers reported that the highest phenolic contents and antioxidant capacities were obtained at 400 MPa for 5 min. The same researchers conducted a storage study for similar product treated at 400 MPa and 600 MPa-5 min (Yuan et al. 2018a). They reported that total phenolic contents and antioxidant capacities had insignificant change during 8 weeks storage at 4 °C. However, significant reduction in total anthocyanin contents of aronia puree processed at 400 MPa-5 min was determined during the storage period. Taking into consideration the cost and energy efficiency of HPP, they suggested that the treatment at pressure of 400 MPa or 600 MPa and holding time of 5 min was effective to obtain an aronia berry puree having the lowest microbial counts with the highest bioactive compounds and antioxidant capacity.

Briefly, the results of the conducted studies by the research groups from all around the world (Table 1), associated with healthy nutrients of the various fruit juices clearly demonstrated that HPP is a promising non-thermal technology; (1) to extend shelf-life of fruit juices, (2) to obtain fruit juices closest to their initial fresh attributes and finally, (3) to produce fruit juices with high concentration of bioactive compounds. And also, it was reported that compared to traditional thermal pasteurization treated fruit juices, high pressure treated ones were nutritionally superior in terms of bioactive compounds for collected juices both immediately after processing and during shelf-life.

Effect of Pulsed Electric Fields (PEF) on Bioactive Compounds

Recently, consumers are demanding minimally processed, healthy, functional and high quality food products that have inherent flavor, fresh appearance and intense taste (Bisconsin Junior et al. 2015). PEF can be applied to tissue softening, increasing of extraction processes and pasteurization processes (Praporscic et al. 2007). Compare with to the use of heat treatments for pasteurization, PEF cannot cause protein coagulation or starch gelatinization. Moreover, covalent chemical bonds are not affected so the nutrients remain intact (Korma et al. 2016).

Results of recent studies about PEF treatment of different juices are summarized in Table 2 with regards to bioactive components. Lee et al. (2018), studied on the effects of H-PEF treatment on ascorbic acid concentration in mixed mandarin-hallabong tangor (MH) juice. An efficient pasteurization method was determined as H-PEF processing (at 70 °C (inlet temperature), 16 kV/cm–100 kJ/L) that preserves the ascorbic acid concentration, antioxidant capacity, total soluble solid, pH and also for inactivation of microbial and quality of MH juice. Bobinaitė et al. (2015) reported that the juice obtained from PEF pre-treated blueberries had a significantly higher antioxidant activity (31% increase), total phenolic content (43% increase) and total anthocyanin content (60% increase). However, PEF treatment with intensity higher than 1 kV/cm did not improve the qualitative characteristics of the blueberry juice significantly. García-Parra et al. (2017) was found the highest anthocyanins content in purees from plums pretreated with MIPEF (moderate-intensity pulsed electric fields), manufactured with ascorbic acid (AA) addition. However, the lowest contents were found in non-MIPEF pretreated, without AA addition and untreated purees. González-Casado et al. (2018) showed the significant increasing effect of the application of PEF as a pre-processing treatment on the concentration of total and individual carotenoids in tomato fruit. The PEF treatment intensity is found effective on the concentration of individual carotenoids of the product obtained from tomatoes after PEF application. The concentrations of phytoene and phytofluene were increased by 178% and 131%, respectively, tomatoes after PEF (30 pulses at 2 kV/cm, 2.31 kJ/kg) compared to untreated fruit. Also increase in lycopene concentration (4400–6072 μg/kg) was determined in tomato puree. The maximum lycopene concentration was found treated with the most intense PEF treatment (2.31 kJ/kg), leading to a 1.5-fold increase, according to untreated tomatoes.

Agcam et al. (2014a) reported the total phenolic concentration of the juices varied depending on the applied electric field intensity of PEF. The PEF treatment with 21.50 kV/cm electric field strength and 1206.2 μs ensured higher total phenolic concentration was obtained by during the storage (4 °C for 180 days) of orange juices. Untreated orange juice samples had a shelf-life of approximately 10 days, whereas both PEF and heat treated samples had a shelf life of 180 days at 4 °C. Hence, the application of PEF processing to orange juice seems to be a promising alternative to heat pasteurization in order to obtain an extended shelf-life and

Table 2 Effect of pulsed electric fields (PEF) studies on bioactive components of different juices

Juice/source	Bioactive compounds	Processing conditions	Highlights	Reference
Mixed mandarin-Hallabong tangor (MH) juice	– Ascorbic acid (AA) – Antioxidant capacity (AC)	16 kV/cm 100 kJ/L 12 kV/cm 150 kJ/L	AA and AC content of juice (H-PEF treated at 16 kV/cm–100 kJ/L) was insignificantly differ AA and AC content of juice (H-PEF treated at 12 kV/cm–150 kJ/L) was lower than control.	Lee et al. (2018)
Blueberry juice	– Total phenolic compounds (TP) – Anthocyanins (TAC) – Antioxidant activity (AA)	1, 3, 5 kV/cm 10 kJ/kg	– PEF pre-treatment significantly increased TP, TAC and AA values of blueberry (45.5–39.4% for TP, and 77.5–44.3% for TAC, 35.9–28.4% for AA).	Bobinaitė et al. (2015)
Red flesh and skin plums	– Anthocyanins – Total phenolic content	0.4 kV/cm (Moderate-Intensity Pulsed Electric Fields, MIPEF)	– Anthocyanins and the antioxidant activity slightly increased.	García-Parra et al. (2017)
Tomato pure	– Carotenoid compounds	0.4, 1.2–2 kV/cm 5, 18 and 30 pulses, 0.1 Hz	– The highest carotenoid concentrations in the tomato puree obtained in PEF-treated fruit (at 30 pulses, 2 kV/cm, 2.31 kJ/kg), 52% greater than in control.	González-Casado et al. (2018)
Orange Juice	– Phenolic compounds – Ascorbic acid	13.82 kV/cm-10.89 J-1033.9µs-31.88 °C 25.26 kV/cm-51.32 J-1206.2µs-42.60 °C	– Samples processed by PEF contained higher phenolic compound concentrations than processed by the heat. – The flavonoid and phenolic acid concentrations treated with PEF appeared to be highly stable than treated with traditional heat application during the storage (180 days). – The highest ascorbic acid content was detected at moderate PEF conditions. – Samples treated with extreme PEF conditions lost remarkably ascorbic acid content. – In juices treated at moderate PEF conditions, half-life values of ascorbic acid calculated significantly higher than thermal pasteurized ones (90 °C/10 and 20 s) during storage (180 days-4 °C).	Agcam et al. (2014a, b, 2016)

(continued)

Table 2 (continued)

Juice/source	Bioactive compounds	Processing conditions	Highlights	Reference
Exotic fruit juice	– Phenolic compound – Anthocyanin – Antioxidant capacity	25 kV/cm-32 kJ/kg-<35 °C 25 kV/cm-256 kJ/kg-<35 °C	– PEF treatment improved bioaccessibility of phenolic compounds (37.0%), anthocyanins (15.6%) and antioxidant capacity (29.4%, 26.5%, 23.5% for different antioxidant assays, respectively) compared to untreated juice.	Buniowska et al. (2017)
Blueberry juice	– Ascorbic acid (AA) – Anthocyanin	20, 25, 30, 35 kV/cm, 27, 54, 82 µs, conductivity 1.4 and 1.8 mS/cm	– The retention rate of AA in the blueberry juice after PEF was 87.87% (13.27% higher than that of the heated sample). After 30 days of storage, the anthocyanin retention of the blueberry juice samples after PEF treatment was 84.84%, which is 6.23% higher than that of the heated sample.	Chen et al. (2014)
Grapefruit juice	– Total phenolics – Total antioxidant capacity – Total anthocyanins – Total carotenoids	0, 5, 10, 15, 20, 25 kV/cm 1 kHz at 40 °C for 600 µs	– Total carotenoids content of PEF treated grapefruit juice were determined increase at field strengths of 5, 10, 15, 20 and 25 kV/cm, which was 1.92, 1.98, 2.04, 2.11 and 2.15 µg/mL, respectively, as compared to control (1.81) µg/mL. – Increase in percentage inhibition (DPPH radical), total antioxidant content and total phenolic treated with PEF.	Aadil et al. (2015a, b)
Fruit beverage	– Carotenoid compounds	35 kV/cm, 1800 µs 4 µs pulses at 200 Hz	– Increase in cis-violaxanthin + neoxanthin (16%), antheraxanthin (10%), lutein (23%) and zeaxanthin (28%).	Rodríguez-Roque et al. (2016)
Grape juice	– Ascorbic acid – Total phenolic content	15–70 kJ/kg, 1.5 kV/cm, 50 Hz, 20 µs pulse width	– Increase in ascorbic acid (19%) and total phenolic content (61%).	Leong et al. (2016)
Date juice	– Total phenolic content	35 kV/cm for 1000 µs, 100 Hz bipolar mode	– The highest phenolic content was observed after HIPEF treatment (569 mg/L) in comparison with untreated-control juice (483 mg/L).	Mtaoua et al. (2017)
Apple juice	– Ascorbic acid – Total polyphenol – Antioxidant activity	200, 300, and 400 pulses, 30 kV/cm	– The PEF processing, regardless of the number of pulses, did not significantly affect the content of AA and TP in apple juice. – PEF treatment and also the number of pulses affected antioxidant activity, which decreased just after process and also after 24 h of storage (with an exception of 400 pulses treatment).	Dziadek et al. (2019)

Grapefruit juice	– Lycopene – Anthocyanin content – Total carotenoid content – Total antioxidant capacity – Total phenolics (TP)	80 mL/min 20 kV/cm for 600 µs	– Increase in lycopene content during PEF (0.62 µg/mL), control (0.32 µg/mL). – Increase in anthocyanin content was significantly in PEF (1.58 mg/L) as compared to control (1.37 mg/L). – Total carotenoid contents were increased from 0.84 mg/mL (control) to 1.03 mg/mL. – Significant increase in total antioxidant capacity. – Significant increase in the total phenolics during PEF treatments of grapefruit juice as compared to control. – TP contents were increased to 701.1 mg/g as compared to control (640 mg/g).	Aadil et al. (2017)
Raspberries	– Total phenolics – Anthocyanins content – FRAP value	1 and 3 kV/cm 1, 6 and 12 kJ/kg 20 Hz 20 µs	– The total phenolics content of fresh raspberries was 1033.9 mg/L. – The total phenolics content of the juice was similar with control sample. – The juice obtained from frozen-thawed raspberries had significantly higher content of total phenolics (1219.3 mg/L). – Anthocyanin content and antioxidant activity values remained unchanged.	Lamanauskas et al. (2016)
Sweet cherries	– Anthocyanin compounds – Antioxidant activity	0.5–3 kV/cm, 10 kJ/kg	– PEF-assisted pressing (E = 1 kV/cm) led to a significant increase of juice yield (+40%), anthocyanins (+80%), and antioxidant activity (+27%) with respect to untreated samples. – PEF treatment intensity higher than 1 kV/cm did not significantly improved the quantitative and qualitative characteristics of juice.	Pataro et al. (2017)
Apple juice	– Total antioxidant capacity (TAC) – Total phenolic compounds (TPC) – Phenolic compounds	0–26.7 kV/cm 0–873.1 µs 10–40 °C 0–147 J/s	– The PEF treatment at 147 J/s energy level slightly increased both values to 0.029 mg/L and 50.33%. – Decrease in chlorogenic and sinapic acids. – No significant change was observed in (−)-epicatechin, caffeic acid, p-coumaric acid, ferrulic acid, quercetin, and gallic acid after PEF.	Evrendilek et al. (2017)

(continued)

a better preservation of phenolic compounds. Buniowska et al. (2017) studied on bioaccessibility of bioactive compounds after non-thermal processing of an exotic fruit juice blend sweetened with *Stevia rebaudiana*. They reported an increase in bioactive compounds bioaccessibility after PEF treatments, which improved bioaccessibility of phenolics (37.0%), anthocyanins (15.6%), and antioxidant capacity (29.4%, 26.5%, 23.5% for TEAC, ORAC and DPPH respectively). Chen et al. (2014) noticed that the PEF-treated of blueberry juice was compared with the control group, which appeared almost unchanged. After heat treatment, ascorbic acid and anthocyanin content of PEF treated blueberry juice sample was reduced by 14.78%, 3.64%, respectively. The anthocyanin content of the different treated blueberry juice dropped with the increasing of storage time. After 30 days of storage, the anthocyanin content of the control, PEF-treated and heated blueberry juice samples decreased by 22.55%, 15.15%, and 21.38%, respectively. Also, at the same storage period, ascorbic acid content of the control, PEF-treated and heated samples decreased to 30.21%, 13.96%, 25.39%, respectively.

Aadil et al. (2015a, b) suggested that PEF at 25 kV/cm could improve the quality of grapefruit juice. They determined a significant increase in percentage inhibition (DPPH-radical), total antioxidant content, total phenolics and total carotenoids in response to increase in electric field strengths, compared to control treatment. Rodríguez-Roque et al. (2016) reported a decrease up to 7.6–48.2% in the carotenoids bioaccessibility of fruit juice based beverages treated with PEF, whereas the carotenoids bioaccessibility diminished up to 63% in thermally treated beverages compared to the untreated beverages. Leong et al. (2016) evaluated the health-promoting properties of Pinot Noir grape juices obtained after PEF-treatment (15 or 70 kJ/kg). PEF pre-treatment on grapes were enhanced the release of the major anthocyanin compared to untreated grapes juice. Mtaoua et al. (2017) reported that applicability of HIPEF (35 kV/cm for 1000 μs using pulses of 4 ms pulses at 100 Hz in bipolar mode) to preserve the nutritional and physicochemical characteristics of date juice after treatment and during 5 weeks of storage (4–5 °C) by comparison to untreated juice.

Dziadek et al. (2019) reported PEF technology did not affect the content of bioactive compounds in apple juice. Moreover, PEF-treated juice did not show change in the amount of vitamin C and total polyphenols during for 72 h under refrigeration storage. Aadil et al. (2017) studied on effects of PEF on bioactive compounds of grapefruit juice. After PEF treatment, lycopene, anthocyanin, carotenoids contents and total antioxidant activity were increased from 0.32 μg/mL, 1.37 mg/L, 0.84 μg/mL, 177.48 (control) to 0.62 μg/mL, 1.58 mg/L, 1.26 μg/mL and 226.73, respectively. Lamanauskas et al. (2016) showed that mild-PEF pretreatment (1 kV/cm electric field strength and 6 kJ/kg total specific energy) was sufficient to achieve higher raspberry juice recovery and to enhance extraction of bioactive compounds from raspberry press cake left after the juice pressing. Moreover, juice recovery from raspberries was increased in the range of 9–25%, after PEF pretreatment and mechanical pressing (1.32 bar, 6 min). Press cake extracts contained significantly higher amounts of total phenolics (up to 22%), total anthocyanins (up to 26%) and higher ferric reducing antioxidant power, FRAP, (up to 24%) compared with untreated sample.

Pataro et al. (2017) reported that the application of a PEF pre-treatment expressly contributed to a further increase in the extraction of all the anthocyanin compounds of cherry fruits (cyanidin-3-rutinoside, peonidin-3-rutinoside, cyanidin-3-glucoside and pelargonidin-3-rutinoside) compare to untreated sample. Total anthocyanin content increased to 33%, 80% and 52%, PEF-treated at 0.5, 1 and 3 kV/cm, respectively. The antioxidant activity (FRAP values) of juice was increased 10.0%, 27.4%, and 15.2%, after PEF pre-treatments at 0.5, 1, and 3 kV/cm, respectively. The results demonstrated that the electroporation effect induced by PEF pre-treatment at relatively low field strength (E = 0.5–1 kV/cm) and energy input (WT = 10 kJ/kg) appeared to be sufficient for the improvement of juice yield as well as for the condensation of the anthocyanins extraction from both cherry fruits and their by-products (press cakes). Evrendilek et al. (2017) found that no significant difference was detected between the control and PEF-treated apple juice in terms of physical properties, organic acids, and polyphenols of (−)-epicatechin, caffeic acid, *p*-coumaric acid, ferrulic acid, quercetin, and gallic acid. PEF processing was also provided retention of quality characteristic and bioactive compounds without significant formation of furfural and hydroxymethylfurfural.

Finally, these promising results confirm the potential of PEF technology to improve the efficiency of the fruits conversion process to add value to food product and also enable the evaluation of food processing waste that leads to more product diversity. PEF could increase the extraction of bioactive compounds from fruit in this way increase their healthy potential. Furthermore, the use of PEF as abiotic stressor may be an appropriate strategy to increase the biological production of secondary metabolites in raw fruits and vegetables, thereby increasing their antioxidant potential (Yilmaz and Evrendilek 2017). Therefore, PEF technology has good prospects for commercial application provided that different PEF strategies are used to provide new healthy food for consumers. However, further research and development activities are needed to fully understand, optimize, and implement PEF processes (Elez-Martínez et al. 2017).

Effect of Ultrasound Processing (UP) on Bioactive Compounds

For a long time, traditional thermal treatments, sterilization or pasteurization, have been used to produce microbiologically safe juices. However, after the effects of heat on sensorial characteristics like taste or color, and bioactive properties of juice like antioxidant capacity or vitamin content, emerging technologies have started to be more popular. One of these technologies, ultrasound, is generally applied as a processing aid and pre-treatment, although ultrasound with the higher frequency levels can be effective on different features of foods.

The effects of ultrasound on bioactive components which are in fruit juices and have great importance for human health are shown in Table 3. The cavitation regulates various chemical or biological reactions including increase in the diffusion rates and disintegration of affected particles (Tiwari et al. 2009). Hence, bioactive

Table 3 Effect of ultrasound processing (UP) technology on bioactive components of different juices

Juice/source	Bioactive compounds	Processing conditions	Highlights	Reference
Pumpkin	– Carotenoid – Flavonoid – Antioxidant capacity	37 kHz, 150 W, 30 dk, 40–50–60 °C, thermosonication (TS) in ultrasonic bath	– TS-40 and TS-50 samples had a lower total carotenoid than the control. – Total carotenoid content increased with increasing temperature. – The total amount of flavonoid is higher than the heat treated samples (40, 50, 60, 70, 80 °C, 15 min). – The highest total amount of flavonoids was obtained in the TS-40. – The total amount of flavonoid decreased with the increase of temperature in the thermosonicated samples.	Demir and Kılınç (2018)
Grapefruit	– Total carotenoid – Total flavonoid – Antioxidant capacity	20, 30, 40, 50 and 60 °C, frequency (28 kHz), power (70%, 420 W), 30 and 60 min	– Maximum increase in total carotenoids was obtained in the samples processed at 60 °C during 60 min. – Total antioxidant capacity, total phenols, total flavonoids and total flavonols increased with the temperature (from 30 to 60 °C). – All compounds increased significantly at lower ultrasound processing (20 °C, 30 and 60 min).	Aadil et al. (2015a, b)
	– Carotenoid – Flavonoid – Flavonol – Lycopene – Anthocyanin – Phenolics	28 kHz, 600 W, 30 min, 20 °C, ultrasonic bath	– Increase in carotenoids. – PEF&US treatment showed higher values for carotenoids than individually treated UP and PEF juices. – PEF&US treatment appeared to be more adequate in retention of lycopene whereas US and PEF were more effective than control. – Combined treatment (PEF&US) could improve the antioxidant activity, total phenolics, flavonols, flavonoids, lycopene, and total carotenoids. – Significant increase in lycopene content was noted during UP. – Anthocyanin contents were increased significantly in UP.	Aadil et al. (2018)

Orange	– Carotenoid – Total flavonoid – Total phenolics – Ascorbic acid	1, 10, 20 and 30 min 24 kHz frequency, 105 µm, 33.31 W/mL, <46 °C	– Total carotenoids (a-carotene, β-carotene and lycopene) increased significantly in all sonicated samples. – Compared to the amount found in the control sample, a significant increase in flavonoids was found in all sonication treatments. – Sonication during 10 min at 43.4 °C gave the highest amounts. – Enhancement in most of the bioactive compounds observed in sonication of juice samples for 10, 20 and 30 min (43–45 °C) compared to control sample. – Sonication coupled with high temperature significantly enhanced orange juice quality.	Guerrouj et al. (2016)
Star fruit	– Carotenoid – Flavonoid – Ascorbic acid	15, 30, 45, and 60 min, 44 kHz, 35–40–45 °C	– Significant ($p < 0.05$) increase in antioxidant activity, total phenolic content, total flavonoid content, ascorbic acid content. – The amount of carotenoids levels were decreased slightly as the processing temperature increased to more than 35 °C. – Carotenoid levels were insignificantly increased as the sonication time increased.	Nayak et al. (2018)
Pear	– Flavonoid – Ascorbic acid – Phenolic	25, 45 and 65 °C, 10 min, 750 W probe sonicator, 20 kHz 70% amplitude	– Increase in flavonoids 17.7% (25 °C). – Decrease in flavonoid 8.9% (65 °C). – Increase in ascorbic acid content (25 °C). – 65 °C for 10 min treatment was the best in retention of ascorbic acid and other phenolic compounds. – Significant increase with ultrasound at 25 °C in ascorbic acid, total phenols and flavonoids. – The loss of compounds increased as the temperature of ultrasound treatment increased.	Saeeduddin et al. (2015)

(continued)

Table 3 (continued)

Juice/source	Bioactive compounds	Processing conditions	Highlights	Reference
Carrot	– Flavonoid – Phenolics – Ascorbic acid	15 °C, 2 min keeping pulse duration 5 s on and 5 s off 70% amplitude 20 kHz frequency	– US resulted in an increase in total phenols, total flavonoids and tannins. – Significant increase is observed in ascorbic acid. – Improved antioxidant capacity.	Jabbar et al. (2014)
	– Flavonoid – Ascorbic acid – Lycopene – Lutein	20 kHz, 70% amplitude 48 W cm^2 of ultrasonic intensity 20, 40 and 60 °C, 5 and 10 min using 5 s on/off pulse cycle	– Increase in carotenoid content. – Increase in ascorbic acid of juice treated with ultrasound at 20 °C (UP20-5 and UP20-10). – Maximum improvement in lutein, carotenoids and lycopene after thermosonication at 60 °C-10 min.	Jabbar et al. (2015)
	– Ascorbic acid – Carotenoid	40 kHz and 0.5 W/cm^2 ultrasound intensity 20, 40 or 60 min	– Total soluble solids, total sugars, total carotenoids and ascorbic acid contents were significantly improved ($p < 0.05$). – A significant increase ($p < 0.05$) in total carotenoids and ascorbic acid contents in the sample sonicated for 40 min compared to sample sonicated for 20 min and control (non-sonicated) sample. – Significant increase ($p < 0.05$) in total carotenoids and ascorbic acid contents in the sample sonicated for 40 min compared to control.	Zou and Jiang (2016)
	– Ascorbic acid – Carotenoid	24 kHz, 400 W, 22 mm probe, 50, 54, and 58 °C	– No significant difference on total carotenoid, phenolic compounds and ascorbic acid ($p < 0.05$).	Pokhrel et al. (2017)
	– Carotenoid – Ascorbic acid – Phenolic compounds	24 kHz, 120 μm amplitude, 50, 54 and 58 °C, 10 min acoustic power 2204.40, 2155.72, 2181.68 mW/mL	– Thermosonicated juice at 58 °C retained >98% of carotenoids. – Thermosonicated juice at 58 °C retained 100% of ascorbic acid. – Samples treated by ultrasound at temperatures of 50 and 54 °C retained 91.67% of the ascorbic acid content after 12 and 14 days of storage.	Martínez-Flores et al. (2015)

Plum	– Flavonoid – Total phenolic	20 kHz, 400 W, 2.5, 5, 7.5, and 10 min 40, 50, 60 and 70 °C	– A slight increase in the total phenolic content under some ultrasonic treatment conditions. – No dramatic trends were observed for the total phenolic compound content of the plum nectar. – Dramatically increased flavonoid content.	İrkilmez et al. (2017)
Acerola	– Ascorbic acid – Vitamins	18 kHz, 500 W, 13 mm probe, 1000, 3000 and 5000 W/L, 2.5, 5, 10 and 15 min, 40 °C	– Increased the availability of pro-vitamin A and vitamins B3, B5, C and E. – The retention of the major vitamins in acerola juice (vitamins A and C) was higher at lower temperatures (10–20 °C).	Santos et al. (2018)
Kiwi	– Ascorbic acid	10 and 30 min, 180 W, 40 kHz	– UP10 and US30 applied individually showed AA retentions of 84.30% and 79.96%, respectively. – No significant increase the ascorbic acid retention through storage time.	Tomadoni et al. (2017)
Blackberry	– Ascorbic acid – Total Phenols – Anthocyanin – Antioxidant activity	1500 W, 20 kHz, 80% amplitude for 25 min, with pulse duration of 4 s on and 2 s, 13 mm probe	– The ascorbic acid content decreased in thermoultrasonicated (24%) and in the pasteurized juice (9%) as compared to the control. – Higher levels of total phenols, anthocyanins; antioxidant activity by ABTS and DPPH in comparison to the control and thermally treated juices.	Manríquez-Torres et al. (2016)
	– Ascorbic acid – Antioxidant activity – Anthocyanins	20 kHz, 1500 W, 25 mm probe, 28 µm, 40–50 °C, 15–20 min	– Ascorbic acid, antioxidant activity and anthocyanin content of thermoultrasonicated juices were higher than pasteurized juice. – Total phenolic content of juices did not differ significantly ($p < 0.05$).	Cervantes-Elizarrarás et al. (2017)

(continued)

Table 3 (continued)

Juice/source	Bioactive compounds	Processing conditions	Highlights	Reference
Strawberry	– Ascorbic acid – Total Phenolic – Anthocyanin – Antioxidant capacity	0, 15 and 30 min, 20 °C and 25 kHz	– Ultrasonication (30 min) showed significant enhancement in bioactive compounds. – Ascorbic acid significantly increased in sonicated samples. – Anthocyanin level in strawberry juice samples showed significant increase. – Significant increase in antioxidant capacity and total phenolic content was determined.	Bhat and Goh (2017)
Strawberry	– Ascorbic acid – Total phenolic – Anthocyanin	150 W, 0.1–30 min, 25–75 °C	– High temperature and low ultrasound energy density combination must be applied for minimizing the change in ascorbic acid content. – Maximum total monomeric anthocyanin and total phenolic contents can be obtained at mild temperature and ultrasound energy density (~50 °C, ~230 J/g).	Dündar et al. (2019)
Apple	– Ascorbic acid – Total carotenoids – Phenolic compounds – Minerals	0, 30 and 60 min, 20 °C, 25 kHz amplitude 70%	– The contents of polyphenolic compounds and sugars significantly increased ($p < 0.05$) especially in the samples treated for 30 min. – Total carotenoids significantly increased ($P < 0.05$) in samples treated for 60 min. – Significant increase ($p < 0.05$) in chlorogenic acid, caffeic acid, catechin, epicatechin and phloridzin in sonicated apple juice. – Sonication treatments showed insignificant ($p > 0.05$) change in the total anthocyanins. – The concentrations of Na, Ca, K increased, while the concentrations of P, Mg and Cu decreased after ultrasonication.	Abid et al. (2014)

compounds are most likely affected by ultrasound. In the literature, it was showed that total carotenoid content of juice decreased in pumpkin juice while it increased mostly as in grapefruit, carrot, orange juice (Demir and Kılınç 2018; Aadil et al. 2015a, b; Martínez-Flores et al. 2015; Jabbar et al. 2015; Guerrouj et al. 2016). The ultrasound process is able to weaken the matrix of food and rupture cell walls, caused free carotenoid releasing. Also, the increase in lycopene content due to sonication treatment may be attributed to the cavitations which cause an increase in the rate of diffusion, chemical reaction and dispersing the aggregates. In ultrasound treatment, disruption of chromoplast membrane and collapse of cell-wall occurs due to the cavitation that results in release of more lycopene contents (Jabbar et al. 2014). The main reason of degradation of these carotenoids is by isomerization and oxidation. It is widely presumed that carotenoids in general undergo isomerization with thermal processing (Sánchez-Moreno et al. 2005; Shi and Maguer 2000; Van den Berg et al. 2000).

Fruits were considered as a potent source of phenolic compounds which have most importantly a vital role in human health (Aadil et al. 2015a, b). Even if the studies related with level of ultrasound treatments and juice type differ widely in the literature, the results showed that the total phenolic content of juices is generally increased slightly or significantly. The phenolic acids can be found in nature both free and bound forms. The bound phenolic acids remain bound to some structural carbohydrate and protein either through ester linkage with carboxylic groups or ether linkages with lignin through their hydroxyl groups in the aromatic ring or acetyl bonds. The increase in phenolic content may be related with the conversation of phenolic compounds to their free form. Also, hydroxyl groups formed during cavitation might be added to the aromatic rings (Bhat et al. 2011).

Aadil et al. (2018) suggested that combination of ultrasound and pulsed electric field technologies could be the best option to obtain the better results related to bioactive compounds in grapefruit juice. The increasing in ascorbic acid content may be related with the elimination of dissolved oxygen that is essential for ascorbic acid degradation during cavitation (Cheng et al. 2007). Ascorbic acid content has a direct influence on oxidative stability and its degradation caused by ultrasound processing mainly based on two pathways: thermolysis and reaction with hydroxyl radicals produced after sonolysis of water molecules found in juice (Feril and Kondo 2005). Aguilar et al. (2017) suggested that deaeration of juice before ultrasonication can be effective to reduce the ascorbic acid degradation.

Cervantes-Elizarrarás et al. (2017) showed that ultrasound can be alternative for production of microbiologically safe blackberry juice with high-quality. Abid et al. (2014) suggested that ultrasonication may improve the apple juice quality in terms of phytonutrients. Nayak et al. (2018) obtained similar results for star fruit juice after ultrasonication. Aadil et al. (2015a, b) claimed that thermosonication, the combination of ultrasound and heat, of grapefruit juice can be more preferable, because thermosonication can be applied temperature which was much less than the temperature required for a traditional thermal process. Also, Bhat and Goh (2017) showed that sonication improved the overall quality of hand-pressed strawberry juice. Therefore, it has a great importance that ultrasonication parameters (amplitude, temperature, time and frequency) should be optimized with further studies to produce juices with higher quality than the juices thermally treated. Dündar et al. (2019) reveal the effect of not only the thermosonication but also the change of parameters, ultrasound energy density and temperature, on total monomeric anthocyanin, ascorbic acid and total phenolic content of strawberry nectar and optimized the thermosonication process conditions. While Jabbar et al. 2014 suggested that combination of blanching and sonication may be preferred in juice industry to produce high-quality carrot juice with reduced enzyme activity and protected nutritional value, Aadil et al. (2018) suggested the PEF and ultrasound combination for grapefruit juice.

In conclusion, researches about ultrasonication of juices clearly showed that ultrasound energy, which is non-toxic and environmentally friendly, mostly has a positive impact on total phenolic content, anthocyanins, ascorbic acid, flavonoids, lycopene, lutein and even minerals of fruit juices (Kentish and Ashokkumar 2011).

Effect of Ultraviolet Light Processing (UVLP) on Bioactive Compounds

Thermal pasteurization is the most common processing technique which is applied to make the fruit juices microbiologically safe to consume. However, thermal processing is known to have some adverse effects on the healthy nutrients and sensory quality of the product. The increasing tendency of consumers towards products with similar characteristics to fresh produce has led researchers to develop alternative processing techniques (Tahiri et al. 2006). Non-thermal processing techniques have been developed in order to accomplish those effects. One of the non-thermal technologies applied as an alternative to thermal pasteurization is UV-C treatment. UV treatment is a disinfection method that can be applied for the inactivation of microorganisms. The treatment includes the use of radiation from the electromagnetic spectrum (from 100 to 400 nm). It is classified as UV-C (200–280 nm), UV-B (280–320 nm) and UV-A (320–400 nm) (Bintsis et al. 2000; Unluturk 2012). The highest disinfectant effect is obtained between wavelengths of 250 and 280 nm. Thus, the applications and studies concentrated mostly on UV-C treatment and the wavelength at 254 nm is used for the disinfection of water, surfaces and various liquid food products such as fruit juices (Guerrero-Beltrán and Barbosa-Cánovas 2004).

UV-A treatment has a mechanism that inactivates microorganisms by damaging proteins and creating hydroxyl and oxygen radicals that destroy cell membrane and other cellular elements. In addition, the underlying principle of UV-C treatment is based on the prevention of replication and transcription of the cells by the dimers which are formed due to the absorption of UV light by the genetic material. The UV-C treatment has also an efficient effect on enzymes (Chatterley and Linden 2010; Unluturk 2012). UV-C treatment has been used in disinfection of water systems for many years and it has been reported to be effective in inactivation of bacteria, viruses, protozoa and algae (Begum et al. 2009). This treatment is also used for surface disinfection of foods (Pan et al. 2004; Nigro et al. 1998). There are also many applications of UV-C treatment on different fruit juices such as orange juice (Torkamani and Niakousari 2011), apple juice (Gabriel 2012).

The studies on fruit juices have been accelerated after the FDA permission in 2000 for the use of low or medium pressure mercury lamps to disinfection of fruit juices (Koutchma 2009). The advantages of the UV-C treatment that it does not leave any chemical residue due to being a physical process, thus it can be considered environment-friendly, economically attractive and easy to apply (Canitez 2002; Guerrero-Beltrán and Barbosa-Cánovas 2004). While the efficacy can be changed depending on the target microorganism species or intrinsic characteristics of juices (physical, optical and chemical) and intensities or doses applied juices (Koutchma 2009). It was reported that UV-C light cannot penetrate sufficiently in a highly absorbing environment such as cloudy fruit juice and also, some enzymes (such as pectinmethylesterase (PME), polyphenoloxidase (PPO) and peroxidase (POD)) which have effect on fruit juice quality cannot be inactivated at desired level by UV treatment (Tran and Farid 2004; Noci et al. 2008). The applied UV-C intensities or doses on juices are crucial factor to understand and compare the studies in bibliography. The variability of published researches may be explained by the differences in applied UV-C doses and UV-C systems (batch or flow). Recent studies about UV-C treatment applied on various fruit juices and effects of treatment on bioactive compounds are given in Table 4.

Unluturk and Atilgan (2015) was investigated the applicability of UV-C treatment in fresh grape juice as an alternative processing method to thermal pasteurization. They succeed 5.34 log CFU/mL reduction for *E. coli* and increased microbial shelf life of the juice by twofold. However, the ascorbic acid content was decreased significantly after the treatment. Nevertheless, they concluded that UV-C treatment can be used for extending the shelf life of fresh grape juice. Islam et al. (2016) studied apple juice with different UV-C doses (0–240 mJ/cm^2). Total phenolic content was well preserved regardless of the UV-C doses and total antioxidant activity decreased when UV-C dose reached 40 mJ/cm^2, but remained unchanged until 240 mJ/cm. The authors concluded that UV-C treated foods could be sold at a higher price than thermally-processed counterparts, because they have preserved their fresh-like properties. Bhat (2016) studied with fresh tomato juice and reported that UV-C treatment increased the total phenolic content compared to control samples. Total phenolic content was detected as 27.79 mg GAE/g in untreated samples, while 60 min UV-C treated sample was 36.22 mg GAE/g. Total lycopene and ascorbic acid content in samples exhibited decreasing trend depending on increased treatment time.

As can be seen Table 4, antioxidant activity and total phenolic content values of fruit juices after UV-C treatment are variable. The effect of UV-C treatment on those values was changed depending on juice type, settled UV-C treatment conditions and analysis method that applied to detect this type of bioactive compounds. Authors attributed the increase polyphenol contents in UV treated samples, degradation of conjugated phenolic compounds, accretion of polyphenolic compounds as a mean

Table 4 Effect of ultraviolet light processing (UVLP) studies on bioactive components of different juices

Juice/source	Bioactive compounds	Processing conditions	Highlights	Reference
Strawberry	– Antioxidant activity – Total phenolic content	UV-C doses 2.2 kJ/m^2, 25 °C, 0–60 min, static UV reactor	– Decrease in total phenolic content. Antioxidant activity did not change after 15 min exposure.	Bhat and Stamminger (2015)
Grape	– Ascorbic acid	– A continuous flow UV reactor – UV average intensity was 5.1 ± 2.8 mW/cm^2, 32.5 min, 9.92 J/cm^2 of UV dose was absorbed by the juice	– The dramatic decrease determined in ascorbic acid after treatment. – A significant ascorbic acid decrease was detected for control samples on the third day of storage, and continued to decrease after this time.	Unluturk and Atilgan (2015)
Mango	– Total carotenoid – Ascorbic acid – Total polyphenol content – Total flavonoid content – Antioxidant activity	UV-C doses 3.525 J/m^2 15, 30, 60 min at 25 °C static UV reactor	– UV-C treatment (15–30 min) increased carotenoid content. – AA content decreased depending on exposure time. – UV-C treated juice samples showed higher-total polyphenol, flavonoid content and antioxidant activity when applied 15–30 min. – UV-C treatment increased shelf life (4 weeks longer than freshly squeezed juice).	Santhirasegaram et al. (2015)
Tomato	– Antioxidant activity – Total phenolics content – Total lycopene content – Ascorbic acid content	Average dose 2.16 J/m^2, 15, 30 and 60 min, 25–26 °C	– Depending on exposure time antioxidant activity increased significantly. – UV-C treatment exhibited a significant increase in the total phenolics content. – Total lycopene content decreased slightly. – Ascorbic acid showed significant decrease only at 60 min of UV-C.	Bhat (2016)

Apple	– Polyphenols • chlorogenic acid, • phloridzin, • epicatechin • catechin – Polyphenolic content – Antioxidant activity	UV-C doses ranging from 0 to 240 mJ/cm, a low-pressure mercury lamp emitting at 254 nm	– Chlorogenic acid and phloridzin were decreased linearly with treatment. (−)-epicatechin content also decreased significantly as a function of UV dose, while catechin content showed a strict increase. – The total phenol content was almost stable (ranged from 9.79 (control) to 9.48 (treated) mg GAE/100 mL). – Antioxidant activity of control (18.94%) and treated juice (16.49%) showed only minor changes. – Increasing dose from 40 to 240 mJ/cm did not result in a significant change in antioxidant activity.	Islam et al. (2016)
Carrot (with yerba mate extract)	– Total polyphenol content – Total antioxidant activity	UV-C doses 2 kJ/L 15 min, 20–50 °C	– UV-C treated juice samples (at 50 °C) showed the highest total polyphenol content (720.2 ± 70.0 μg GAE/mL). – Polyphenol content and antioxidant activity of a high turbidity juice blend preserved during the storage (24 days at 4 °C).	Ferrario et al. (2018)
Melon	– Phenolic compounds – Antioxidant activity	UV intensity was 13.44 W/m^2, 20 min	– A positive impact on color maintenance detected. – Total phenolics content were not different in untreated and treated juices. – After 13 days of storage; the antioxidant activity of untreated juices decreased significantly. – The antioxidant activity was well preserved after treatment.	Fundo et al. (2019)

of defense against UV radiation, change in polyphenol oxidase enzyme activities. The decreasing level of ascorbic acid is attributed to the UV-C treatment conditions (was performed directly in air, long treatment time) and possibly could have generated very minimal heat and might cause initiation of oxidation process. Authors also concluded that the efficacy of UV-C treatment depends on nature of juices and exposure doses, the attained results displayed that this application can be considered as an alternative to heat pasteurization. However, most UV lamps containing mercury, which makes them very toxic to both environment and human, also most systems used in studies were batch.

Conclusion

Consumer concerns about health issues caused a dramatic change in consumption demands and they began to increase their consciousness towards the foods containing high amount of antioxidants, minimally processed and without containing processing-induced detrimental substances. Fruit juices, due to important sources of health supported nutrients such as, phenolics, carotenoids, fibers, vitamins, minerals, and antioxidative compounds, are among the most widely consumed ready to drink beverages.

Non-thermal technologies, which are alternative processing techniques to thermal pasteurization and sterilization, can be successfully used for both producing foods safe to consume and improving shelf-life of the foods by inactivating enzymes, spoilage and pathogenic microorganisms. On the one hand, traditional thermal processing is satisfied in extending shelf-life of fruit juices due to high inactivation of resistant enzymes, spores and microorganisms. However, it causes dramatic change in phenolic and carotenoid compounds, vitamins, taste and color of juices as well as increasing the level of undesirable substances. On the other hand, non-thermal processing technologies such as high pressure processing (HPP), pulsed electric fields (PEF), ultrasound processing (UP) and ultraviolet light processing (UVLP) are able to both adequately inactivate fruit juice enzymes and microorganisms, and remarkably save health related nutrients and original flavor attributes of juices without (or lower) processing-induced detrimental substances. Moreover, the findings of the various studies carried out by the different research groups from all around world generally indicated that the fruit juices treated with non-thermal technologies were especially superior in terms of health related compounds for the juices both immediately after processing and during shelf-life, compared to traditional thermal pasteurization treated ones.

Although the benefits and potentiality of the discussed non-thermal technologies were clearly demonstrated by many research studies, commercialization of them is still not enough. According to the general views, at least, those technologies will be used as assistant of traditional thermal processing in the near future. In order to ensure the use of non-thermal technologies with rapid spread in the fruit juice industry, the following critical points must be clearly evaluated:

- Investment costs of non-thermal technologies are relatively higher than classical technologies. In order to reduce investment costs to acceptable levels, governments and other funding agencies must support the universities to conduct the researches about non-thermal technologies; and industrial organizations relating with production of non-thermal technologies. Thus, the ways to produce non-thermal processors with lower cost can be increased.
- Immediately after processing and during shelf-life of the products, studies concerned with processing-induced detrimental substances formation such as furfural, hydroxymethylfurfural, furan, acrylamide, and reactive oxygen species are still limited. This point is very important to be sure that treated juices must be free of these substances. Therefore, the research must be focused on these undesirable substances formation in the fruit juices.
- Inactivation kinetics of enzymes, spores and microorganisms must be clearly characterized, in order to obtain minimally processed and safe to consume fruit juices.
- To achieve rapid inactivation of enzymes, spores and microorganism without causing significant composition changing, with/without heat assistance, combined effects of non-thermal technologies must be put forth with future studies.
- For non-thermal technologies, like thermal pasteurization norms, optimum processing conditions must be characterized as operation norms for each fruit juice.
- Regulations about non-thermal technologies must be developed accordingly with recent scientific findings. This will help to spread non-thermal technologies faster for products extended shelf-life without a threat to health.
- Although the researchers declared no-risk in consumption of the products processed with non-thermal technologies, the scientific studies associated with long term exposure must be conducted in order to collect toxicological evidences.

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