Chapter

Novel Non-Thermal Processing Technologies: Impact on Food Phenolic Compounds during Processing

Josephine Ampofo and Michael Ngadi

Abstract

In recent times, food consumption has advanced beyond simply meeting growth and development needs to include the supply of ingredients that can protect against diseases. Among such non-nutritive ingredients are phenolic compounds. These are benzene-ringed secondary metabolites produced in plants upon exposure to environmental stress. Previous studies have linked phenolic compounds to bioactive benefits (e.g., antioxidative, anti-inflammatory, and anti-cancer) with these bioactivities dependent on their biochemical structure and concentrations of individual phenolic compounds present in the food system. However, majority of plant foods are thermally processed into ready-to-eat forms, with these processing methods potentially altering the structure and subsequent bioactivities of endogenous phenolic compounds. Thus, the aim of this chapter is to highlight on emerging non-thermal novel technologies (such as pulsed electric field, radiation, ultrasonication, high hydrostatic pressure processing and high pressure carbon dioxide processing) that can be exploited by the food industry to preserve/enhance bioactivities of phenolic compounds during processing.

Keywords: Phenolic compounds, Bioactivity, Non-thermal processing, Functional food

1. Introduction

In recent times, food consumption has advanced beyond simply meeting growth and development needs to include the supply of ingredients that can offer protection against diseases. The demand for such foods can be attributed to proven research data and advocacy by nutrition regulating bodies of the direct relationship between food composition and risks of diseases [1]. Food components that offer protection against disease development are known as bioactive compounds, with majority of these compounds reported as secondary metabolites. Secondary metabolites are non-nutritive compounds produced in plants as protection agents against oxidative stress upon exposure to above-threshold environmental conditions [2]. Among such non-nutritive secondary metabolites are phenolic compounds.

Phenolic compounds are benzene-ringed metabolites, with at least one phenol unit and one or more hydroxyl substituents [3]. Literature has reported about 10, 000 different classes of phenolic compounds, with these classes presented within three main groups including phenolic acids (e.g., hydroxycinnamic and hydroxybenzoic acids), flavonoids (e.g., anthocyanin, proanthocyanidins, flavonols etc.,), stilbenes (e.g., resveratrol and piceatannol etc.,), tannins (e.g., hydrolysable and condensed tannins), lignin, lignans and coumarins [4]. Different in-vitro and in-vivo studies have demonstrated bioactive capacity of phenolic compounds through their antioxidant, anti-inflammatory, anticancer, antidiabetic, cardiovascular protection and anti-cholesterol health effects. However, these reported bioactive properties are dependent on the type, concentration and biochemical structure of phenolic compounds present in a food system. Structurally, the bioactive capacity of phenolic compounds is dependent on factors such as the number and position of hydroxyl groups on the aromatic ring, hydrogen atoms of the adjacent hydroxyl groups (*o*-diphenol) present in the A, B and C rings of flavonoids, and the presence of double bonds in the benzene ring and oxo functional group (C=O) [5].

Nevertheless, majority of plant foods are subjected to different processing methods prior to consumption, with these processing methods causing changes in the biochemical stability and subsequent bioactivity of phenolic compounds present in the food. Naturally, phenolic compounds are present in foods as free or glycosylated (i.e., bound to protein and carbohydrate molecules), and are released from the food matrix during processing [6]. It is no doubt that, majority of traditional and industrial food processing methods are thermal intensive, with literature reporting a decrease in their concentrations of phenolic compounds and their subsequent bioactivities during transformation into ready-to-eat food products. Therefore, the food industry is continuously searching for alternative non-thermal techniques that can help retain/increase concentrations and bioactivities of phenolic compounds during processing. In this chapter, we focused on current non-thermal food processing technologies such as ultrasonication, high hydrostatic pressure processing, radiation, high pressure carbon dioxide processing and pulsed electric field. We seek to bring to light our understanding of their principles of operation, as well as how these novel non-thermal technologies influence yield and bioactivities of phenolic compounds during processing of some plant-based food products.

2. Thermal food processing and its effects on food phenolic compounds

Majority of plant foods are thermally processed into their ready-to-eat and stable forms. Notable examples of thermal processing techniques include roasting, microwaving, boiling, steaming and drying. However, research has demonstrated changes in food bioactive compositions such as phenolics during thermal processing. For instance, boiled broccoli showed reduced concentrations of caffeic acid (2.2 mg/100 g), quercetin (10 mg/100 g) and antioxidant capacity compared to their raw forms (caffeic aicd-6.6 mg/100 g and quercetin – 23.5 mg/100 g) [7]. Similarly, roasted coffee beans showed reduced phenolic levels and antioxidant capacity. These changes were attributed to oxidation by the triggering of non-enzymatic trans-glycosylation of phenolics into melanoidin as a result of Maillard reaction. Additionally, oxidation of phenolic compounds into their less bioactive forms such as quinones, and (−)-catechin into (+)-catechin has been reported as a result of thermal processes such as roasting [8]. Due to these bioactive reductions,

there is a collective effort by researchers to develop non or medium thermal techniques that can help enhance/maintain phenolic levels along food processing.

3. Novel non-thermal food processing

It is no doubt that, the key purpose of agro processing is to convert raw food materials into their stable ready-to-eat forms through the inactivation of endogenous enzymes and microorganisms. Compared to thermal processing, non-thermal processing involves the application of no or minimal heat to a food system in order to inactivate spoilage enzymes and microbes, without compromising its nutrients, bioactive and organoleptic characteristics [9]. At household and industrial levels, the main advantage of non-thermal processing over thermal processing, is its capacity to exhibit thermal processing benefits while conserving the freshness and phytochemical composition of the food system under low energy consumption. Thus, non-thermal techniques can be considered as green alternatives for production of consumer-acceptable foods with rich composition of bioactive compounds such as phenolics. Examples of novel non-thermal processing techniques currently being applied in the food industry include high hydrostatic pressure processing, ultrasonication (acoustic emissions), radiation, pulsed electric field and high-pressure carbon dioxide processing. Therefore, the objective of this section is to discuss the underlining principles of key non-thermal processing techniques, with the main focus on how they influence concentrations and bioactivities of phenolic compounds during the conversion of food systems into ready-to-eat forms.

3.1 High hydrostatic pressure (HHP) processing

Compared to thermal food processing techniques, HHP processing is advantageous to the food industry due to its limited effects on nutritional and organoleptic qualities, as well as its negating effect on food size and geometry [10]. Basically, HHP involves the exposure of food systems to 100–1,000 MPa through a pressure transmitting medium (i.e., water or any other food grade solvent) at room or mild temperatures [11]. Depending on the density of the solvent and food components, temperature during HHP processing can increase by 3°C at every 100 MPa [12]. Therefore, the efficiency of HHP is dependent on parameters such as temperature, pressure level, pressure holding time, liquid/solid ratio, solvent type and solvent concentration [13]. When a food system is exposed to HHP, covalent bonds linking tightly packed cellular structural walls and membranes are broken, leading to cellular increment in porosity and permeability. Based on this principle, it can be postulated that, HHP processing can lead to (1) structural defragmentation for enhanced extraction of free and bound phenolic compounds (2) liberation of endogenous enzymes such as polyphenol oxidase and peroxidase which can cause degradation of phenolic compounds into *o*-quinones with subsequent reduction in their bioactivities. Thus, the pressure level and temperature applied during HHP are very crucial in order to avoid the generation of increasing temperatures and excess structural damage, which can negatively influence the yield and stability of phenolic compounds during processing. However, according to Heinz and Buckow [14] the low compressibility of covalent bonds compared to weak energy bonds, enables the native structures of low molecular weight molecules (such as phenolic compounds, vitamins and minerals) to be preserved during HHP processing, compared to macromolecules such as starch and protein.

Over the years, the food industry has mainly exploited HHP on commercial scale for preservation of plant foods (e.g., vegetables, juice and beverages) and muscle foods (e.g., meat, seafood and fish). Literature has reported mixed data on impacts of HHP on food phenolic compounds, with some reporting incremental changes and others showing an opposite trend. Patras et al. [15] studied the effect of HHP (i.e., 400 and 600 MPa for 15 min) on phenolic composition of strawberry puree. According to their study, strawberry puree treated with 400 MPa showed higher concentrations of phenolic compounds compared to the puree treated with 600 MPa and the control, with phenolic composition of the 600 MPa treated strawberry puree insignificantly different from the control. In this same study, the concentrations of anthocyanins and other phenolic compounds in blackberry pressure treated puree were increased by 108% with 200 MPa for 5 to 5 min, whereas blackberry puree treated with 400 MPa for 5 to 15 min showed phenolic increments by 92%, compared to their control counterparts. A similar trend was observed with apple treated HHP samples, where a pressure of 600 MPa induced a 75% loss of phenolic compounds after pasteurization, compared to their 400 MPa treated samples which showed significant retention of phenolic compounds [16]. Irrespective of this initial trend, Keenan and his colleagues interestingly observed an opposite trend when the HPP treated apple samples were stored for 14 and 21 days, where the apples treated with 600 MPa significantly retained their composition of phenolic compounds compared to their 400 MPa alternatives. In another study, Huang et al. [17] observed increased antioxidant activity and levels of phenolic compounds (i.e., +/− catechin, chlorogenic acid, neochlorogenic acid, epicatechin, ferulic acid and *p*-coumaric acid) with HHP treated apricot nectar. Similarly, manuka honey treated with HPP at 600 MPa (10 min, 25°C) showed increased concentration of phenolic compounds after 12 weeks of storage [18]. In another research investigated by Shen et al. [18], HHP (400, 500 and 600 MPa) treated jujube (*Ziziphus jujuba* Mill.) showed improved concentrations of phenolic compounds with increasing pressure, with the highest concentrations of total phenolic content (7.9%) and flavonoids (18.4%) obtained with 600 MPa.

Overall, reports showing increased concentrations of phenolic compounds can be linked to the structural damage of cell walls and membranes by HHP, thus increasing porosity and facilitating the release of bound phenolic compounds from structural carbohydrates and proteins. Also, reports showing decreased concentrations of phenolic compounds at high pressure levels were attributed by authors to the presence and activation rates of endogenous polyphenol oxidases and peroxidases during HHP as discussed earlier in this section. Thus, in order to retain/enhance the composition of food phenolic compounds and their accompanied bioactivities, HHP should be regulated between room temperature or slightly above, in order to avoid or limit the formation of oxidative undesirable products accompanied with high thermal treatments. Further data on how phenolic composition of foods changed upon exposure to HPP are displayed in **Table 1**.

3.2 Pulsed electric field (PEF) processing

PEF has gained much attention in the food industry due to its appreciable preservation capacity in comparison with high thermal pasteurization. According to Picart and Cheftel [24], PEF is advantageous over high thermal processing due to its capacity in inactivating microorganisms, while still preserving the nutritional and sensory quality attributes (e.g., colour, flavour and texture) of the food. Majority of the

Food type	HHP parameters	Effect on phenolics	Reference
Rough rice sprout	0.1–100 MPa	Increases total phenolic compounds after 24 h sprouting	[19]
Corn cob	600 MPa; 15 and 60 min, 20–60°C	+ 20% ferulic acid concentration at 15 min and 60°C	[20]
Watercress	0.1–600 MPa; 1.5–33.5 min; 20°C	Increased yield of phenolic acids, flavonoids and total phenolic content at 600 MPa and 1.5–7.8 min	[21]
Aronia berry puree	200–600 MPa; 2.5–5 min; 21–33°C	+ 3–13% total phenolic content; + 6–17% total anthocyanin content	[22]
Purple-skinned pelota pears (peels and pulp)	100, 300 and 600 MPa; 5 min; 17–34°C	+ 8.7% piscidic acid; + 55.9% hydroxybenzoic acid glycosides in peels at 350 MPa/5 min and 100 MPa/5 min, respectively. + 133.2% isorhamnetin glycosides in peels	[23]
Red-skinned Sanguinos prickly pears (peels and pulp)	100, 300 and 600 MPa; 5 min; 17–34°C	+ 90.6% retention of total piscidic acids and a general decrease in total phenolic compounds	[23]

Table 1.
Effect of high hydrostatic pressure (HHP) on phenolic composition of selected food systems.

literature on PEF has been reported with food preservation, with dearth reports on its effects with phenolic compounds. Primarily, the principle of PEF involves the application of short pulses of high electric fields through a product placed between a set of electrodes [24]. When a food material is exposed to PEF, the generated electrical fields are able to create electroporation across the cell membranes, thus leading to cell membrane porosity as a result of structural disintegration [25]. The efficiency of PEF depends on factors such as electrical field strength, exposure time, applied energy density, pulse width and shape, pulse frequency and applied food characteristics (e.g., pH and electrical conductivity) as discussed by Mañas and Pagán [26].

With respect to phenolic compounds, PEF can be used to exploit their concentrations and bioactivities from two approaches: (1) since phenolic compounds are mainly stored in the tightly packed cell wall and membranes, structural damage can enhance extraction and subsequent concentrations of phenolic compounds from storage cells compared to their native forms; (2) creation of structural porosity can induce oxidative stress in the food system, thus leading to the stimulation of biosynthesis pathways responsible for the production of antioxidants such as phenolic compounds [2]. For example, red cabbage treated with PEF showed a 2.15 times enhanced anthocyanin yield compared to the non-PEF treatment [27]. Luengo et al. [28] also reported an increased yield of total phenolic compounds with PEF treated tomatoes and grapes. Similarly, concentrations of phenolic compounds after treating borage (*Borago officinalis*) leaves with PEF were significantly enhanced, according to the work of Segovia et al. [29], with the authors also observing enhanced antioxidant capacities. In another study reported by Liu et al. [30–31], PEF treated onions showed 2.2 and 2.7 times increased total phenolics and flavonoid levels, compared to their control forms. Results from this study also showed enhanced antioxidant capacities with PEF treated onions. Their observation with enhanced antioxidant capacities can be attributed to the increased yield of phenolic compounds and the possibility of extracting other groups of bound

phenolic compounds that were otherwise trapped in the cellular walls of the control samples. Regarding extraction efficiency and yield of phenolic compounds from plant foods, lots of positive literature has been reported with PEF applications and shown in **Table 2**.

PEF has also been associated with increased yield of fruit juice phenolic compounds and bioactivity. For juice application, the most exploited potential effects of PEF include colour, pH, acidity, soluble solids, concentration of phenolic compounds and activity of polyphenol oxidase (i.e., the enzyme responsible for juice browning through the degradation of phenolic compounds into *o*-quinones) [1]. PEF treated tomato juice showed higher concentrations of chlorogenic acid and quercetin, compared to their thermal treated alternatives [33]. In another study by Agcam et al. [34], concentrations of caffeic acid were enhanced with PEF treated tomato juice over storage time, whereas the concentrations of *p*-coumaric acid reduced over storage. The authors attributed their findings to the increased activity of hydroxylase, leading to the conversion of *p*-coumaric acid into caffeic acid along the storage period. Simultaneous to the tomato juice, the authors further reported the highest concentrations of total phenolic compounds (443.42 mg/GAE) with PEF treated orange juice, compared to their thermal treated forms (439.07 mg/GAE). Other authors such as Boussetta et al. [35] also postulated positive correlations between PEF and maximization of phenolic compounds during winemaking. Confirming their postulation is the work of Puértolas et al. [36], where an electric field of 5 kV/cm increased the yield of total phenolic compounds of wines developed from treated Cabernet Sauvignon grapes. A similar interesting observation that proved the relationship between pulse type and exposure time is the study of Delsart et al. [37], where PEF (4 kV/cm at 1 ms and 0.7 kV/cm at 200 ms) exposed Cabernet Sauvignon grapes showed improved extraction kinetic effects on vacuolar and parietal tannins, respectively.

Besides extraction and fruit juices, PEF has also been investigated with whole foods. Wiktor et al. [38] investigated different PEF intensities (1.85, 3 and 5 kV/cm) and pulse numbers (10, 50 and 100 exponential shaped pulses) on accumulation of phenolic compounds and antioxidant capacity in apple (var. Ligol). After their research, Wiktor and his colleagues [38] observed the highest total phenolic content and antioxidant capacity with apple tissues treated with 1.85 kV/cm at 10 pulse. Similar to their study, Soliva-Fortuny et al. [39] observed the highest yield of total phenolic content (13%) and flavone-3-ol (92%) with PEF treated apple, compared to control. Despites these positive results, it's also important to highlight that, some studies have reported reduced levels of phenolic compounds in foods treated with PEF. For instance, the findings of Odriozola-serrano et al. [33] and Aguilar-Rosas et al. [40–41] demonstrated significant reductions of phenolic compounds in strawberry and apple

Food type	PEF parameters	Effect on phenolics	Reference
Orange, pomelo and lemon fruits	3 kV/cm	+ 50% increased extraction yield	[32]
Blackberries (*Rubus fruticosus*)	PEF of 13.3 kV/cm; 10 μs pause after each 100 pulse	Sixfold higher compared to high voltage electric discharge (HVED)	[13]
Basil leaves	2, 3 and 4 kV/cm; 1, 2 and 3 min	The highest of 115.203 mg GAE/ 100 g at 3 kV/cm for 2 min	[25]

Table 2.
Effect of pulsed electric field (PEF) on phenolic composition of selected food systems.

juices, respectively, upon treatment with PEF, with these authors correlating their observations to oxidative activities of polyphenol oxidase. In a normal unfractured cell, endogenous enzymes such as polyphenol oxidase are tightly held in packed membranes. However, when the cell is exposed to PEF, the induction of cellular porosity will lead to their release from tightly packed membranes, thus initiating oxidative reactions in the presence of oxygen and substrates such as phenolic compounds. However, these explanations are based on theoretical assumptions. Deeper studies investigating the presence and catalysis of polyphenol oxidase and peroxidase in PEF treated food systems should be conducted, in order to provide scientific proof of their activities, as well as threshold levels of PEF parameters to be applied towards the control/limitation of polyphenol oxidase/peroxidase activities.

3.3 Ultrasound (US)

In recent years, ultrasound (US) has gained attention in the food industry for pasteurization and preservation purposes. Unlike HHP, US is not only limited to inactivation of microorganism's, but also includes the deactivation of enzymes [1]. For food processing purposes, US can be divided into two categories (1) low intensity US (lower than 1 W/cm^2), which is a non-destructive approach used to measure the structure, composition and flow rate of a food (2) high intensity US (between 10 and 1000 W/cm^2), which involves the use of high frequencies to cause structural damage to the tissues and membranes of the exposed food system [42]. Among these two approaches, high intensity US is the most applied in the food industry with respect to phenolic compounds for (a) enhancing extraction yield of phenolic compounds from food materials (b) induction of oxidative stress in a food system by causing tissue cavitation and porosity, towards the stimulation of biosynthetic pathways (i.e., phenylpropanoid and shikimate pathways) responsible for the production of phenolic compounds as defense agents against induced oxidative stress [2].

According to Toma et al. [42] when US is applied to a food system, there is the formation of cavitation bubbles which creates a pressure zone change up to 400 km/h, leading to increased porosity, rupturing or removal of cell membranes for enhanced mass transfer from the cells interior upon collapsing. Yu et al. [43] treated Romaine lettuce (*Lactuca sativa* var. longifolia) with US (25 kHz, 2 kW, 1–3 min) and observed increased total phenolic content, compared to the control. From this same research, storage studies showed 22.5% increased phenolic concentrations after 60 h of storage with US treated Romaine lettuce (1 min treatment time) than their control forms. In another study involving black cumin (*Nigella sativa*), pretreatment with US (30, 60 and 90 W; 25 kHz; 30, 45 and 60 min) showed increasing total phenolic concentrations (ranges of 93.21 to 106.6 ppm) with increasing US conditions. The authors also observed enhanced antioxidant capacity with US treated black cumin and attributed this trend to the 5% increased total phenolic content in US treated samples compared to the control **Table 3** [47]. gives a summary of phenolic composition changes in some foods after US exposure.

Similarly, common bean (*Phaseolus vulgaris*) sprouts treated with US (180 and 360 W; 40 kHz; 30, 45 and 60 min) showed increased accumulation trend of phenolic compounds and antioxidant capacities with increasing US treatment parameters [2]. From this study, the highest level of total phenolic acids (216.7 mg/100 g), total flavonoids (203.5 mg/100 g), total anthocyanins (30.35 mg/100 g) and total antioxidant capacities (98%) were observed with 360 W (60 min) US treated common bean sprouts at 9 h of sprouting compared to the control. The authors further observed

Food type	US parameters	Effect on phenolics	Reference
Tomato (*Lycopersicon esculentum*) fruit	25 kHz; 1 kW; 1, 2, 3 and 4 min	+ 17.05% total phenolic content with 1 min US time. All US treatments showed higher antioxidant capacities than control	[44]
Black currant fruit (*Ribes nigrum* L.)	150 W; 40 kHz; amplitude-10, 40 and 70%; 3, 6 and 10 min	+ 4% total phenolic content (10 min; 70% amplitude) compared to control; + 20% total anthocyanin content (10 min; 70% amplitude) compared to control	[45]
Orange juice	24 kHz; 1, 10, 20 and 30 min	+ 63 and 64% levels of total phenolics and flavonoids with US (30 min) compared to control	[46]

Table 3.
Effect of ultrasound (US) on phenolic composition of selected food systems.

increased levels of oxidative stress markers (i.e., hydrogen peroxide, catalase and peroxidase) and activities of phenolic triggering enzymes (i.e., phenylalanine ammonia-lyse and tyrosine ammonia-lyase) with increasing US conditions. Thus, confirming with literature that US can improve the yield and bioactivity of food phenolic compounds through the induction of oxidative stress and triggering of the phenylpropanoid pathway. In another study, grape juice treated with ultrasound showed increased concentrations of phenolic compounds by 114.3%, compared to the control [48]. Naturally, phenolic compounds occur in foods as free or bound forms. According to Lieu and Le [48] the capacity of ultrasound to breakdown covalent bonds linking phenolic compounds bounded to cell wall components (i.e., carbohydrates and proteins) led to their release and observed increased yield. These explanations explain the report of Khan et al. [49], where orange peels treated with US (150 W) showed the highest yield of naringin (70.3 mg GAE/100 g), hesperidin (205.2 mg GAE/100 g) and total phenolic composition (275.8 mg GAE/100 g). Besides the principle of cavitation discussed previously in this section, another explanation for this increasing trend has been postulated by Khan et al. [1] to the addition of hydroxyl functional group to aromatic compounds such as phenolics during ultrasonication.

3.4 Radiation

Light is one of the most essential factors for plant growth and development. Plant foods grown in the field use sunlight for photosynthesis and production of bioactive metabolites such as phenolic compounds, whereas those grown commercially under controlled conditions use artificial light sources to meet their needs for photosynthesis and production of secondary metabolites such as phenolic compounds. Thus, changes in light quality, quantity, intensity and duration can be exploited to influence the final yield and bioactivities of phenolic compounds in different food systems [50]. According to Bantis et al. [51], five wavelength ranges including red (660–700 nm), far-red (700–750 nm), blue (495–400 nm), UV-A (400–315 nm) and UV-R8 (315–280 nm) has been described with respect to plant radiation. Among these wavelengths, blue, green, red and white are the most reported, with respect to accumulation and bioactivities of food phenolic compounds. Upon exposure to sunlight or artificial light, changes in the light parameters can induce oxidative stress, which are sensed by proteinaceous receptors on cell membranes, for subsequent triggering of metabolic pathways responsible for the production of secondary metabolites such

as phenolic compounds [52]. For example, blue light was demonstrated by Qian et al. [52] to improve the biosynthesis of phenolic compounds through enhanced stimulation of malonyl CoA and coumaroyl (key substrates associated with the phenylpropanoid pathway for biosynthesis of phenolic compounds).

For controlled processing, artificial lighting technology such as light emitting diode (LED) has been proven by previous studies to be effective for accumulation of phenolic compounds in diverse human food crops, among other artificial light technologies such as high sodium pressure (HSP) and high-intensity discharge (HID). LED is the most preferred radiation technology among agroprocessors due to their efficient use of energy and capacity to produce food products rich in nutrients and bioactive secondary metabolites comparable to blue, green, red and far-red treated foods [53]. In the study of Alothman et al. [54], effect of UV-C (dose: 2.158 J/m^2) on flavonoid, total phenolics and vitamin C compositions were evaluated. From their result, total phenolic content and flavonoid levels were significantly increased with UV-C treated banana and guava, whereas no significant increments were observed with UV-C treated pineapple fruits and control. In another study, UV-C treated freshly cut mangoes showed increased concentrations of flavonoids and total phenolic compounds with increasing UV-C exposure time (10, 20 and 30 min) [55].

Also, black, red and white rice varieties were treated with gamma irradiation (10 kGy) and its influence on free and bound phenolic composites were investigated by Shao et al. [56]. According to their study, gamma irradiated white, red and black rice varieties produced the highest yield of bound phenolic compounds at 19.7, 40.2 and 59.5 mg GAE/100 g, respectively. The authors observed significant changes in bound phenolic compounds with all varieties of gamma irradiated rice, compared to free phenolic compounds. Bound phenolic compounds in cereal grains are covalently bonded to other cell wall fragments, thus the observation of Shao et al. [56] can be attributed to the capacity of gamma irradiation to break the covalent bonds, cause depolymerization of higher molecular weight phenolic compounds into smaller molecular weight phenolic compounds such as gallic and ferulic acids. Azad et al. [57] studied the impact of different LEDs such as blue (450–495 nm), green (510–550 nm) and fluorescent lamps on accumulation of phenolic compounds in soybean (*Glycine max* L.) sprouts at different sprouting stages (3, 4, 5, 6 and 7 days). According to their results, total phenolic content and isoflavones were maximum with blue light (at days 5 and 6), compared to the green and fluorescent light treated sprouts. Furthermore, the antioxidant capacity (DPPH) observed with blue light treated soybean sprouts were significantly higher than the other investigated LED treatments. Blue light treated soybean sprouts exhibited DPPH capacity of 75%, whereas the green and fluorescent treated sprouts showed 69 and 58%, respectively. Further literature demonstrating the effect of light on different food systems are displayed in **Table 4**.

3.5 High pressure carbon dioxide (HPCD) processing

Due to the connection between thermal pasteurization and degradation of organoleptic and nutritional qualities, the food industry is continuously searching for alternative techniques that can provide the advantages of thermal processing without compromise on nutritional and sensory attributes. High pressure carbon dioxide (HPCD) processing is a nonthermal mechanism applied for food pasteurization by using pressurized CO_2 between 0.1 MPa and 50 MPa [62]. Some advantages of HPCD include low cost, non-toxicity, non-inflammability and renewability of CO_2 [63]. Factors that influence the efficiency of HPCD processing include food structure, CO_2

Food type	Light parameters	Effect on phenolics	Reference
Blueberry (*Vaccinium corymbosum* L.) leaves	Red, 661 nm- 24 μmol/m^2/s Blue, 417 nm- 6 μmol /m^2/s 12, 24, 48 h	Increased total phenolic content and antioxidant capacity with blue light at 12 h, compared to the control. Level of monomeric anthocyanins were improved up to 24 h with blue light, after which there was a decreasing trend. Red light deceased monomeric anthocyanins than with control and blue light.	[58]
Green and purple basil (*Ocimum basilicum*) plants	UV-B (16.0 μmol / m^2/s) 1H2D; 1 h/d for 2 days 2H2D; 2 h/d for 2 days 1H5D; 1 h/d for 5 days 2H5D; 2 h/d for 5 days Control; no UV-B	+ 80–169% total flavonoid content with green basil UV-B treatments, compared to control. Increased antioxidant capacity with all UV-B treatments. + 37–79% total flavonoid content and antioxidant capacity with purple basil UV-B treatment (2H5D) than control.	[59]
Habanero pepper (*Capsicum chinense*)	Combined Blue (48 W/m^2, 0, 1.5 and 3 min) and UV-C (11.3 W/m^2) Time: 0, 0.5 and 1 min	Increased levels of total phenolics, flavonoids and antioxidant capacity with all combined treatments. Optimum levels were obtained with blue light (3 min) + UV-C (0.5 min).	[60]
Date palm mazafati (*Phoenix dactylifera* L.)	Gamma radiation; 0, 0.5, 1 and 2.5 kGy	Optimum concentration of total phenolic compounds and antioxidant capacity were observed with 2.5 kGy than control and other treatments.	[61]

Table 4.
Effect of radiation on phenolic composition of selected food systems.

physical state, time, pressure and temperature. Until now, research has provided data on HPCD with temperature ranges between 25 and 100°C, it is important to mention that pressure and temperature ranges of >28 MPa and > 60°C are recommended for food applications and fractionation of bioactive metabolites such as phenolics compounds [64]. Although previous authors have tried to explain the principle of HPCD, there still exist a non-well-defined theory. However, a common explanation among all reviewers is a reflection of the potential disintegration of structural cellular membranes and subsequent leakage of cytoplasmic composites during HPCD exposure [65]. Based on this explanation, it can be postulated that HPCD can modify phenolic composition of plant food systems through (1) cell wall and membrane deformation, thus enhancing the release of bound phenolic compounds from structural molecules (2) combination of CO_2 and low temperatures will help prevent oxidation of phenolic compounds through inactivation of polyphenol oxidase (PPO).

Gasperi et al. [66] investigated HPCD (10 MPa, 36°C and 10 min) effects on phenolic composition of carrot juice, with their results showing retention of phenolic compounds. In another study by Del Pozo-Insfran et al. [67], although phenolic composition of HPCD treated muscadine grape juice remained unchanged after processing, their antioxidant capacity was significantly increased after 1 week of storage whereas their control form exhibited reduced antioxidant capacity. This observation could be attributed to the groups of phenolic compounds released upon HPCD processing and the capacity of HPCD to inactivate endogenous PPO, than the control. Thus, helping retain the concentrations and bioactivity of native phenolic compounds in muscadine juice during HPCD processing. Ferrentino et al. [68] reported no

changes in total phenolic levels with HPCD treated red grapes. Similarly, apple juice subjected to high thermal processing and HPCD were evaluated for changes in phenolic compositions by Noci et al. [69]. According to the authors, high thermal treated apple juice showed significant reductions in concentrations of total phenolic compounds, whereas the HPCD treatments exhibited insignificant phenolic reductions compared to the control and thermal treatments. In synchrony with these studies are the works of Guo et al. [70] and Agcam et al. [34], which investigated the influence of ultra-high temperature and HPCD processing on phenolic compositions of lychee and litchi juices, respectively. According to the findings of Guo et al. [70], ultra-high temperature processing significantly reduced concentrations of caffeic acid, epicatechin, 4-methylcatechol and rutin in treated lychee juice, whereas HPCD retained concentrations of the aforementioned phenolic compounds after treatment. Comparable to their findings, HPCD treated litchi juice showed preserved concentrations of total phenolic content, rutin, (−)-epicatechin, chlorogenic acid, and antioxidant capacity, compared to the control whereas their ultra-high temperature treated counterparts exhibited significant losses of these investigated phenolic compounds [34].

Dearth research data is available on the influence of HPCD on phenolic composition of food products during processing. Thus, in-depth studies are crucial in order to stimulate their efficient applications in the food industry. However, available literature on HPCD processing seems to provide a trend of phenolics preservation rather than increments or degradation. This trend may be attributed to the low solubility of phenolic compounds in CO_2. Therefore, posing a challenge for their efficient extraction from food matrices.

4. Conclusion and future perspectives

Consumption of phenolic-dense foods has been attributed to positive health benefits such as antioxidative, anticancer and inflammatory effects. It is no doubt that, food processing conditions can either increase or decrease their phenolic compositions and subsequent bioactivities. The wide application of thermal techniques along plant food processing has been associated with high cost, reduced concentrations of phenolic compounds and their subsequent bioactivities. Thus, to encourage the food industry to produce phenolic-dense functional foods, there is an increasing demand to exploit alternative non-thermal processing techniques that can help enhance/maintain phenolic levels and bioactivities. In this quest, literature has identified pulsed electric field, high hydrostatic pressure (HHP) processing, ultrasound, radiation and high-pressure carbon dioxide (HPCD) processing as novel non-thermal techniques that can be exploited to enhance/retain bioactivities of food phenolic compounds. Arguably, these novel non-thermal processing methods will not only help enhance/retain food phenolic compositions but will also help the industry to improve food nutritional value, shelf-life and sensory attributes. However, in order to scale-up their applications, key technical queries such as (a) besides sustainability, will the non-thermal method oxidize phenolics and other bioactive compounds (b) what key parameters of the non-thermal technique should be optimized in order to maximize the yield and bioactivities of phenolic compounds, case by case (c) how does the bioactive composition of different food groups respond upon exposure to each non-thermal method case by case (d) are there any groups of hazardous compounds liberated during non-thermal processing? If yes, what are the health effects of these compounds and how do they influence the nutritional and sensory attributes of the treated food.

Author details

Josephine Ampofo[1*] and Michael Ngadi[2]

1 Department of Sciences, Université Sainte Anne, Pointe-de-l'Église, Nova Scotia, Canada

2 Department of Bioresource Engineering, MacDonald Campus, McGill University, Sainte Anne-de-Bellevue, Quebec, Canada

*Address all correspondence to: josephine.ampofo@mail.mcgill.ca

References

[1] Khan MK, Ahmad K, Hassan S, Imran M, Ahmad N, Xu, C. Effect of novel technologies on polyphenols during food processing. Innovative Food Science and Emerging Technologies. 2018;45:361-381.

[2] Ampofo JO, Ngadi M. Ultrasonic assisted phenolic elicitation and antioxidant potential of common bean (*Phaseolus vulgaris*) sprouts. Ultrasonics Sonochemistry. 2020;64:104974.

[3] Gan RY, Lui WY, Wu K, Chan CL, Dai SH, Sui ZQ, Corke H. Bioactive compounds and bioactivities of germinated edible seeds and sprouts: An updated review. Trends in Food Science and Technology. 2017;59:1-14.

[4] Akyol H, Riciputi Y, Capanoglu E, Caboni MF, Verardo, V. (2016). Phenolic compounds in the potato and its by-products: An overview. International Journal of Molecular Sciences. 2016;17:835.

[5] Anantharaju PG, Gowda PC, Vimalambike MG, Madhunapantula SV. An overview on the role of dietary phenolics for the treatment of cancers. Nutrition Journal. 2016;15:1-16.

[6] Aquino-Bolanõs EN, García-Díaz YD, Chavez-Servia JL, Carrillo-Rodríguez JC, Guzman AM, Heredia-García E. (2016). Anthocyanin, polyphenol, and flavonoid contents and antioxidant activity in Mexican common bean (*Phaseolus vulgaris* L.) landraces. Emirates Journal of Food and Agriculture. 2016;28:581-588.

[7] Moreira ASP, Nunes FM, Simoes C, Maciel E, Domingues P, Domingues MRM, Coimbra MA. Transglycosylation reactions, a main mechanism of phenolics incorporation in coffee melanoidins: inhibition by Maillard reaction. Food Chemistry. 2017;227:422-31.

[8] Pellegrini N, Chiavaro E, Gardana C, Mazzeo T, Contino D, Gallo M, Riso P, Fogliano V, Porrini M. Effect of Different Cooking Methods on Color, Phytochemical Concentration, and Antioxidant Capacity of Raw and Frozen Brassica Vegetables. Journal of Agricultural Food Chemistry. 2010;58:4310-4321.

[9] Versteeg K. Next generation of innovative food processing technologies. Benefits and Challenges. In: Kai K, Pablo J, Geoffrey S, editors. Innovative Food Processing Technologies. Extraction, separation, component modification and process intensification. Elsevier; 2016. p. 455-464.

[10] Toepfl S, Mathys A, Heinz V, Knorr D. Review: potential of high hydrostatic pressure and pulsed electric fields for energy efficient and environmentally friendly food processing. Food Review International. 2006;22:405-23.

[11] Li F, Chen G, Zhang B, Fu X. Current applications and new opportunities for the thermal and non-thermal processing technologies to generate berry product or extracts with high nutraceutical contents. Food Research International. 2017;100:19-30.

[12] Fellows P. Food Processing Technologies: Principles and Practices. 3rd ed. Boca Raton: Elsevier; 2009. 928 p.

[13] Barba FJ, Terefe NS, Buckow R, Knorr D, Orlien V. New opportunities and perspectives of high-pressure treatment to improve health and safety

attributes of foods. A review. Food Research International. 2015;77:725-42

[14] Heinz V, Buckow R. Food preservation by high pressure. Journal für Verbraucherschutz und Lebensmittelsicherheit. 2010;5:73-81.

[15] Patras A, Brunton NP, Da Pieve S, Butler F. Impact of high pressure processing on total antioxidant activity, phenolic, ascorbic acid, anthocyanin content and colour of strawberry and blackberry purées. Innovative Food Science and Emerging Technologies. 2009;10:308-313.

[16] Keenan DF, Rößle C, Gormley R, Butler F, Brunton NP. Effect of high hydrostatic pressure and thermal processing on the nutritional quality and enzyme activity of fruit smoothies. LWT-Food Science and Technology. 2012;45:50-57.

[17] Huang W, Bi X, Zhang X, Liao, X, Hu X, Wu J. Comparative study of enzymes, phenolics, carotenoids and color of apricot nectars treated by high hydrostatic pressure and high temperature short time. Innovative Food Science and Emerging Technologies. 2013;18:74-82.

[18] Fauzi AN, Farid MM. High pressure processed Manuka honey: change in nutritional and rheological properties over 1-year storage. Journal of Food Processing and Preservation. 2016;41:e13085–e13094.

[19] Shen J, Gou Q, Zhang Z, Wang M. Effects of high hydrostatic pressure on the quality and shelf-life of jujube (*Ziziphus jujuba* 4Mill.) pulp. Innovative Food Science and Emerging Technology. 2016;36:166-172.

[20] Kim MY, Lee SH, Jang GY, Li M, Lee YR, Lee J, Jeong HS. Changes of phenolic-acids and vitamin E profiles on germinated rough rice (*Oryza sativa* L.) treated by high hydrostatic pressure. Food Chemistry. 2017;217:106-111.

[21] Pérez-Rodríguez N, Torrado Agrasar A, Domínguez JM. High hydrostatic pressure as pretreatment and adjuvant for the enzymatic release of ferulic acid from corn cob. Process Biochemistry. 2017;58:204-210.

[22] Pinela J, Prieto MA, Barros L, Carvalho AM, Oliveira B, Saraiva JA, Ferreira ICFR. Cold extraction of phenolic compounds from watercress by high hydrostatic pressure: Process modelling and optimization. Separation and Purification Technology. 2018;192:501-512.

[23] Yuan B, Danao MGC, Stratton JE, Weier SA, Weller CL, Lu M. High pressure processing (HPP) of aronia berry purée: Effects on physicochemical properties, microbial counts, bioactive compounds, and antioxidant capacities. Innovative Food Science and Emerging Technologies. 2018;47:249-255.

[24] Picart L, Cheftel C. Pulsed electric fields. In: Zeuthen P, Bøgh-Sørensen L, editors. Food Preservation Techniques. Boca Raton: CRC Press; 2003. p.360-427.

[25] Hendrawan Y, Sabrinauly S, Hawa LC, Argo BD, Rachmawati M. Analysis of the phenol and flavonoid content from basil leaves (*Ocimum americanum* L) extract using pulsed electric field (PEF) pre-treatment. Agricultural Engineering International: CIGR Journal. 2019;21:149-158.

[26] Mañas P, Pagán R. Microbial inactivation by new technologies of food preservation. Journal of Applied Microbiology. 2005;98:1387-1399.

[27] Gachovska T, Cassada D, Subbiah J, Hanna M, Thippareddi H, Snow,D. Enhanced anthocyanin extraction from

red cabbage using pulsed electric field processing. Journal of Food Sciences. 2010;75:E323-3-E329.

[28] Luengo E, Álvarez I, Raso J. Improving the pressing extraction of polyphenols of orange peel by pulsed electric fields. Innovative Food Science and Emerging Technologies. 2013;17:79-84.

[29] Segovia J, Luengo E, Corral-Perez J, Raso J, Almajano M. Improvements in the aqueous extraction of polyphenols from borage (*Borago officinalis* L.) leaves by pulsed electric fields: Pulsed electric fields (PEF) applications. Industrial Crops Production. 2014;65:390-396.

[30] Liu C, Grimi N, Lebovka N, Vorobiev E (2018a) Effects of preliminary treatment by pulsed electric fields and convective air-drying on characteristics of fried potato. Innovative Food Science and Emerging Technologies. 2018a;47:454-460.

[31] Liu ZW, Zeng XA, Ngadi MO (2018b) Enhanced extraction of phenolic compounds from onion by pulsed electric field (PEF). Journal of Food Processing and Preservation. 2018b;42:1-8.

[32] El Kantar S, Boussetta N, Lebovka N, Foucart F, Rajha HN, Maroun RG, Louka N, Vorobiev E. Pulsed electric field treatment of citrus fruits: Improvement of juice and polyphenols extraction. Innovative Food Science and Emerging Technologies. 2018;46:153-161.

[33] Odriozola-Serrano I, Soliva-Fortuny R, MartÃn-Belloso O. Phenolic acids, flavonoids, vitamin C and antioxidant capacity of strawberry juices processed by high intensity pulsed electric fields or heat treatments. European Food Research and Technology. 2008;228:1-10.

[34] Agcam E, Akyıldız A, Evrendilek GA. Comparison of phenolic compounds of orange juice processed by pulsed electric fields (PEF) and conventional thermal pasteurization. Food Chemistry. 2014;143:354-361.

[35] Boussetta N, Vorobiev E, Le L, Cordin-Falcimaigne A, Lanoisellé JL. (2012). Application of electrical treatments in alcoholic solvent for polyphenols extraction from grape seeds. LWT - Food Science and Technology. 2012;46:127-134.

[36] Puertolas E, Lopez N, Condon S, Alvarez I, Raso J. Potential applications of PEF to improve red wine quality. Trends in Food Science and Technology. 2010;21:247-255.

[37] Delsart C, Cholet C, Ghidossi R, Grimi N, Gontier E, Gény, L, et al. (2014). Effects of pulsed electric fields on Cabernet Sauvignon grape berries and on the characteristics of wines. Food and Bioprocess Technology. 2014;7:424-436.

[38] Wiktor A, Sledz M, Nowacka M, Rybak K, Chudoba T, Lojkowski W, Witrowa-Rajchert D. The impact of pulsed electric field treatment on selected bioactive compound content and color of plant tissue. Innovative Food Science and Emerging Technologies. 2015;30:69-78

[39] Soliva-Fortuny R, Vendrell-Pacheco M, Martin-Belloso O, Elez–Martinez P. Effect of pulsed electric fields on the antioxidant potential of apples stored at different temperatures. Postharvest Biology and Technology. 2017;132:195-201.

[40] Aguilar-Rosas S, Ballinas-Casarrubias M, Nevarez-Moorillon G, Martin-Belloso O, Ortega-Rivas E. Thermal and pulsed electric fields pasteurization of apple juice: Effects on physicochemical properties and flavour

compounds. Journal of Food Engineering. 2007a;83:41-46.

[41] Aguilar-Rosas S, Ballinas-Casarrubias M, Nevarez-Moorillon G, Martin-Belloso O, Ortega-Rivas E. Thermal and pulsed electric fields pasteurization of apple juice: Effects on physicochemical properties and flavour compounds. Journal of Food Engineering. 2007a;83:41-46.

[42] Toma M, Vinatoru M, Paniwnyk L, Mason TJ (2001) Investigation of the effects of ultrasound on vegetal tissues during solvent extraction. Ultrasonics Sonochemistry. 2001;8:137142.

[43] Yu J, Engeseth NJ, Feng H. High intensity ultrasound as an abiotic elicitor-Effects on antioxidant capacity and overall quality of romaine lettuce. Food Bioprocessing Technology. 2016;9:262-273.

[44] Lu C, Ding J, Park HK, Feng H. High intensity ultrasound as a physical elicitor affects secondary metabolites and antioxidant capacity of tomato fruits. Food Control. 2020;113:1-8

[45] Oancea S, Ghincevici D, Ketney O. The effect of ultrasonic pretreatment and sample preparation on the extraction yield of antioxidant compounds and activity of black currant fruits. Acta Chimica Slovencia. 2014;62:242-248.

[46] Guerrouj K, Sánchez-Rubio M, Taboada-Rodríguez A, Cava-Roda RM, Marín-Iniesta F. Sonication at mild temperatures enhances bioactive compounds and microbiological quality of orange juice. Food and Bioproducts Processing. 2016;99:20-28.

[47] Moghimi M, Farzaneh V, Bakhshabadi H. The effect of ultrasound pretreatment on some selected physicochemical properties of black cumin (*Nigella sativa*). Nutrire. 2018;43:1-8.

[48] Lieu LN, Le VVM. (2010). Application of ultrasound in grape mash treatment in juice processing. Ultrasonics Sonochemistry. 2010:17:273-279.

[49] Khan MK, Abert-Vian M, Fabiano-Tixier AS, Dangles O, Chemat F. (2010). Ultrasound assisted extraction of polyphenols (flavanone glycosides) from orange (*Citrus sinensis* L.) peel. Food Chemistry. 2010;119:851-858.

[50] Alvarado AM, Aguirre-Becerra H, Vázquez-Hernández MC, Magaña-Lopez E, Parola-Contreras I, Caicedo-Lopez LH, Contreras-Medina LM, Garcia-Trejo JF, Guevara-Gonzalez RG, Feregrino-Perez AA (2019) Influence of elicitors and eustressors on the production of plant secondary metabolites. In: Natural bio-active compounds. Springer, pp 333-388

[51] Bantis F, Smirnakou S, Ouzounis T, Koukounaras A, Ntagkas N, Radoglou K. Current status and recent achievements in the field of horticulture with the use of light-emitting diodes (LEDs). Scientia Horticulturae. 2018;235:437-451

[52] Qian H, Liu T, Deng M, Miao H, Cai C, Shen W, Wang Q. Effects of light quality on main health-promoting compounds and antioxidant capacity of Chinese kale sprouts. Food Chemistry. 2016;196:1232-1238.

[53] Aguirre-Becerra H, Vazquez-Hernandez MC, de la O, DS, Alvarado-Mariana A, Guevara-Gonzalez RG, Garcia-Trejo JF, Feregrino-Perez AA. Role of Stress and Defense in Plant Secondary Metabolites Production. In: Pal D, Nayak AK, editors. Bioactive Natural Products for Pharmaceutical Applications.1st ed.

Switzerland: Springer Nature; 2021. p. 151-195.

[54] Alothman M, Bhat R, Karim A. (2009a). Effects of radiation processing on phytochemicals and antioxidants in plant produce. Trends in Food Science and Technology. 2009a;20:201-212.

[55] González-Aguilar GA, Villegas-Ochoa MA, Martínez-Téllez M, Gardea A, Ayala- Zavala JF. Improving antioxidant capacity of fresh-cut mangoes treated with UV-C. Journal of Food Science. 2007;72:S197–S202.

[56] Shao Y, Tang F, Xu F, Wang Y, Bao, J. Effects of γ-irradiation on phenolics content, antioxidant activity and physicochemical properties of whole grain rice. Radiation Physics and Chemistry. 2013;85:227-233.

[57] Azad MOK, Kim WW, Park CH, Cho DH. Effect of artificial LED light and far infrared irradiation on phenolic compound, isoflavones and antioxidant capacity in soybean (*Glycine max* L.) sprout. Foods. 2018;7:1-10.

[58] Routray W, Orsat V, Lefsrud M. Effect of postharvest LED application on phenolic and antioxidant components of blueberry leaves. Chemical Engineering. 2018;2:1-9.

[59] Dou H, Niu G, Gu M (2019) Pre-harvest UV-B radiation and photosynthetic photon flux density interactively affect plant photosynthesis, growth, and secondary metabolites accumulation in basil (*Ocimum basilicum*) plants. Agronomy. 2019;9:434

[60] Pérez-Ambrocio A, Guerrero-Beltrán J, Aparicio-Fernández X, Ávila-Sosa R, Hernández-Carranza P, Cid-Pérez S, Ochoa-Velasco C. Effect of blue and ultraviolet-C light irradiation on bioactive compounds and antioxidant capacity of habanero pepper (*Capsicum chinense*) during refrigeration storage. Postharvest Biology and Technology. 2018;135:19-26.

[61] Ghadi FE, Ghara AR, Ghanbari T. (2015). Effect of gamma irradiation on the total phenolic content and free radical-scavenging activity of Iranian date palm Mazafati (*Phoenix dactylifera* L.). International Journal of Latest Research in Science and Technology. 2015;4:149-153.

[62] Alfaia A, Alfaia CM, Patarata L, Fernandes MJ, Fernandes MH, Elias M, Ribeiroa MH, Fraquezabet MJ. Binomial effects of high isostatic pressure and time on the microbiological, sensory characteristics and lipid composition stability of vacuum packed dry fermented sausages "chouriço". Innovative Food Science and Emerging Technologies. 2015;32:37-44.

[63] Briongos H, Illera AE, Sanz MT, Melgosa R, Beltrán S, Solaesa AG. (2016). Effect of high pressure carbon dioxide processing on pectin methyl esterase activity and other orange juice properties. LWT - Food Science and Technology. 2016;74: 411-419.

[64] Rock C, Guner S, Yang W, Gu L, Percival S, Salcido E. Enhanced antioxidant capacity of fresh blueberries by pulsed light treatment. Journal of Food Research. 2015;4:89-97

[65] Sevenich R, Mathys A. Continuous versus discontinuous ultra-high-pressure systems for food sterilization with focus on ultra-high-pressure homogenization and high-pressure thermal sterilization: A review. Comprehensive Review in Food Science and Food Safety. 2018;17:646-62.

[66] Gasperi F, Aprea E, Biasioli F, Carlin S, Endrizzi I, Pirretti G,

Spilimbergo S. Effects of supercritical CO_2 and N_2O pasteurization on the quality of fresh apple juice. Food Chemistry. 2009;115:129-136.

[67] Del Pozo-Insfran D, Balaban MO, Talcott ST. Microbial stability, phytochemical retention, and organoleptic attributes of dense phase CO_2 processed muscadine grape juice. Journal of Agricultural and Food Chemistry. 2006;54:5468-5473.

[68] Ferrentino G, Plaza M, Ramirez-Rodrigues M, Ferrari G, Balaban M. Effects of dense phase carbon dioxide pasteurization on the physical and quality attributes of a red grapefruit juice. Journal of Food Science. 2009;74:E333-E341.

[69] Noci F, Riener J, Walkling-Ribeiro M, Cronin D, Morgan D, Lyng J. Ultraviolet irradiation and pulsed electric fields (PEF) in a hurdle strategy for the preservation of fresh apple juice. Journal of Food Engineering. 2008;85:141-146.

[70] Guo M, Wu J, Xu Y, Xiao G, Zhang M, Chen Y. (2011). Effects on microbial inactivation and quality attributes in frozen lychee juice treated by supercritical carbon dioxide. European Food Research and Technology. 2011;232:803-811.