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An Evaluation of the Impact of Novel Processing Technologies on the Phytochemical Composition of Fruits and Vegetables

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Abstract

Phytochemicals are highly beneficial in lowering the risk of several noncommunicable diseases. There is a need to provide novel technologies that can ensure the maintenance of desired phytochemicals in fruits and vegetables when compared to the traditional chemical or thermal treatments for the preservation of such crops. The development of physical nonthermal treatments such as pulsed electric field (PEF), pulsed light (PL), ultra sound (US), high pressure processing (HPP) and cold plasma (CP) techniques have been promising in maintaining the integrity of phytochemicals and the nutritional quality of fruits and vegetables. This chapter will focus on the effects such novel technologies can have on food quality and stability on phytochemicals in fruit and vegetable products.

Keywords: phytochemicals, novel processing technologies, nonthermal treatments, fruits and vegetables

1. Introduction

According to the Centers for Disease Prevention and Control (CDC), presently the most preventable and chronic health conditions are cardiovascular diseases, cancer, type 2 diabetes and obesity [1]. These diet related diseases account for an estimated number of 678,000 deaths annually [2]. Consumer demand for high quality, fresh and nutritious foods has increased over the years due to the need for a healthy diet and the associated consumption of fruits and vegetables, which is required for improved health. Organizations such as the World Health Organization (WHO),

the Food and Agriculture Organization (FAO), the United States Department of Agriculture (USDA) and the European Food Safety Authority (EFSA) have recommended the consumption of fruits and vegetables to lower the risk of cardiovascular diseases and cancer due to their high content of micronutrients and fibers [3]. Thus, the main contributor to the protective effect of fruits and vegetables against chronic diseases are largely due to their phytochemical content.

Phytochemicals are nonnutrient, biologically active compounds and are commonly found in vegetables, fruits, grains and other crop plants. The major groups of phytochemicals based on their chemical structure are polyphenols, terpenoids, sulfur compounds, and alkaloids [4]. In the fight against diseases, phytochemicals act as antioxidant, antibacterial, antifungals, antivirals, anti-inflammatory and cholesterol reducing agents [5]. Studies have shown that polyphenols found in potatoes have the ability to inhibit the enzymes responsible for Alzheimer's disease [6]. Consumption of blueberries containing high levels of phenolic acids, flavonols, anthocyanins and proanthocyanidins were associated with the prevention of degenerative and chronic diseases [7].

In developed countries, approximately 75% of all deaths are due to non-communicable diseases (NCDs) related to an unbalanced diet [8]. Developing countries are also overburdened due to over and under nutrition [8]. Associated with an increasing demand for fresh cut fruits and vegetables in developed countries, developing countries are now following suit due to an increased level of education and awareness for healthy food amongst consumers [3, 7]. The need for nutritious, ready to eat convenience foods has thus given rise to minimally processed fruits and vegetables (MPVFs) [7, 9], which are mildly processed such that they possess "fresh-like" attributes [9]. Some key attributes that ensure the marketability of MPVFs are the maintenance of nutritional value especially phytochemical content, flavor, color, texture, appearance and shelf life.

Some methods used to minimally process fruits and vegetables, negatively affect its phytochemical content and thus, the consumer does not benefit from the desired health benefits. Thermal processing allows for a longer shelf life by reducing microbial load and inhibiting enzymes that leads to deterioration, but it also decreases the level of phytochemicals in the fruits and vegetables [7, 10, 11]. Thus, this has prompted food scientists and researchers to find new ways to process fruits and vegetables without compromising the nutritional content and quality. Novel, nonthermal processing such as pulsed electric field (PEF), pulsed light (PL), ultra sound (US), high pressure processing (HPP) and cold plasma (CP) techniques have been promising in maintaining the integrity of phytochemicals and the nutritional quality of fruits and vegetables, inclusive of minimally processed ones [10]. Such technologies have the potential to be adapted in developing countries. This chapter will explore the use of non-thermal processing technologies and their effects on key phytochemicals such as carotenoids, flavonoids and phenolic acids in several fruits and vegetables with a focus on health benefits.

2. Sources of phytochemicals and functions

Scientific evidence has shown that phytochemicals are highly beneficial in lowering the risk of several noncommunicable diseases [10]. They are known to have the ability to treat diseases

such as stroke, cancer and metabolic syndromes. Phytochemicals are grouped based on their chemical structure and function. To date thousands of phytochemicals have been identified in fruits, vegetables and grains and the most important groups are phenolic compounds, nitrogen-containing compounds, alkaloids, organosulfur compounds, phytosterols, and carotenoids [11]. The most studied groups of dietary phytochemicals related to human health are carotenoids and phenolic acids [11].

2.1. Carotenoids

Carotenoids are the red, yellow and orange color plant pigments of fruits and vegetables. To date approximately 600 types of carotenoids have been identified. They are mostly present as fat soluble, colored pigments in plants [12]. They can be separated into two groups; carotenes and xanthophylls. The two primary forms of carotenoids are β -carotene and α -carotene [12]. Other essential carotenoids include zeaxanthin, lutein and lycopene. The health benefits of carotenoids are due mainly to their antioxidant effects and physiological functions as provitamins. However, post-harvest technologies and processing greatly affect the composition and bioavailability of carotenoids in fruits and vegetables. Fruits and vegetables such as papaya, mangoes, carrots, sweet potatoes, pumpkin and cantaloupes are rich in β -carotene, whilst tomatoes, pink grapefruits, and watermelons contains high levels of lycopene [10]. In a study by Leoung and Oey, it was found that the highest content of carotenoids was found in red peppers followed by carrots, apricots, plums and peaches, whilst cherries contained the lowest amount of carotenoids [13].

Since carotenoids are a precursor of vitamin A, they have been found to decrease the incidence of diseases such as cancer of the lungs, pancreas and gastrointestinal tracts, cardiovascular diseases and eye-related diseases [14]. According to Toniolo et al., a case-control study conducted in New York between the years 1985–1994, showed that the carotenoids lutein, zeaxanthin, lycopene, α carotene and β carotene were responsible for decreasing the risk of breast cancer [15]. In another study by Giovannucci, it was observed that a decrease in prostate cancer was associated with a consumption of tomatoes due to their high lycopene content [16]. With respect to cardiovascular diseases, studies showed that the blood plasma of patients suffering with coronary artery disease, contained lower levels of zeaxanthin, lycopene, β carotene and α carotene [17]. This is in agreement with a study conducted by Knekt et al. who showed that a higher intake of β carotene and several carotenoids, led to a lower risk of major coronary heart diseases [18].

2.2. Phenolic compounds

Phenolic compounds most commonly occur as antioxidants in fruits, and vegetables. Amongst the major classes of phenolic compounds with health benefits are flavonoids such as anthocyanins and non-flavonoids such as phenolic acids [19]. The many benefits of phenolic compounds include; antioxidant, anti-carcinogenic, antimutagenic and anti-inflammatory effects [20]. Amongst the most common phenolics are flavonoids. These are found in plant tissues and are often responsible along with carotenoids and chlorophylls for the blue, purple, yellow, orange and red colors in fruits and vegetables [20]. Within the group of flavonoids, are anthocyanins, which is responsible for reducing cardiovascular diseases. Anthocyanins are mainly found in red fruits like berries and grapes [21]. Non-flavonoid phenolic compounds, such as phenolic acids can be grouped into two major constituents; hydroxybenzoic acids

(HBAs) and hydroxycinnamic acids (HCAs). Phenolic acids are seldom found in mangoes, berries, citrus fruits, red wine and plums. Their main benefits to human health are the prevention of stroke, cancer and coronary heart diseases [22].

2.2.1. Anthocyanins

Anthocyanins belong to the widespread group of plant constituents called flavonoids. In fruits and vegetables, they are responsible for the orange, red, purple and blue colors. Such dietary antioxidants aid in preventing neuronal diseases, heart diseases, cancer, diabetes and inflammation [23]. According to a study by Zhao et al. various commercial extracts of anthocyanin rich grapes, bilberry and chokeberry were prepared. When investigated for their chemopreventive effects against colon cancer, it was found that all of the extracts inhibited the growth of HT-29 colon cancer cells [24]. In another study conducted by Wang and Mazza [25], the inhibitory effects of anthocyanins found in selected berries against nitric oxide (NO) were investigated. Since NO is associated with many chronic inflammatory diseases, the strong inhibition of anthocyanins on NO production indicated that anthocyanins can aid in the prevention of chronic inflammatory diseases [25].

2.2.2. Phenolic acids

Phenolic acids are a major source of dietary phenolics belonging to the non-flavonoid group of phytochemicals. Two major groups are HBAs and HCAs as noted above [25]. HCAs are found in many conjugated forms, with p-coumaric, caffeic, ferulic and sinapic acids being the most common and in HBAs; p-hydroxybenzoic, vanillic, syringic and protocatechuic are the most common. Phenolic acids are often found in berries such as strawberries, raspberries and blackberries [26]. Studies conducted on caffeic acid have shown that phenolic acids possess the ability to inhibit antitumor activity against colon carcinogenesis [27].

3. Advanced nonthermal technologies

Conventional thermal processing such as blanching and pasteurization can result in oxidation and other deleterious reactions that lower the levels of phytonutrients in processed foods [28–30]. For example, canned fruits and vegetables undergo retort processing temperatures in excess of 100°C to obtain commercial sterility. This can lead to significant losses in anthocyanin content, up to 70%, observed in the processing of strawberries into jam. Advanced nonthermal technologies are able to achieve preserving effects at sub-lethal temperatures (up to 40°C). These methods retain higher phytochemical content whilst minimally changing the sensorial properties of the food [29]. The stability of phytochemicals in thermally processed fruits and vegetables decreases exponentially with a linear increase in both the magnitude and duration of the heating process [30]. The use of nonthermal treatments at successfully lower temperatures and times provide real alternatives from traditional thermal processing through the production of additional health promoting-benefits and maintaining the desired "fresh-like" quality of foods for consumers [28, 29]. The present review will focus on the effects

of the following novel technologies: pulsed electric field (PEF), high pressure processing (HPP), pulsed light (PL), cold plasma (CP) and ultrasound (US) on food quality and stability of phytochemicals particularly in fruit and vegetable products. These findings are reported below and summarized in **Table 1**.

Technology and process conditions	Food matrix	Results	Source
Pulsed electric field (PEF)			
38 kV/cm, 15–24 μ s, 70–120 Hz	Mango nectar	High retention of carotene (94.2%), monoterpene (Z)-Ocimene; reduction in HMF; minimal changes in TSS, pH, acidity, color	Kumar et al. [33, 44]
35 kV/cm, 59 μ s, \approx 60°C	Orange juice	Less degradation of vitamin C, carotenoid, polyphenol, volatile aroma compounds	Cited in Buckow et al. [35]
5 kV/cm; 1.8 kJ/kg and 10 kV/cm; 6.7 kJ/kg	Grape skin	Total polyphenols index in PEF-treated wines was 13.7% higher (5 kV/cm treatment) and 29.0% higher (10 kV/cm treatment) with improved color	Cited in Ricci et al. [31]
1–3 kV/cm, 20 μ s, 20 Hz; mechanical pressing (1.32 bar/6 min)	Red raspberries	Increase bioaccessibility of total phenolics (up to 22%) and total anthocyanins (up to 26%); increased juice recovery (9–25%)	Lamanauskas et al. [36]
0.3–2.5 kV/cm, 20 μ s, 100 Hz	Sweet cherry	Enhanced production of desirable C6 aldehyde and alcohol volatiles	Sotelo et al. [37]
High pressure processing (HPP)			
Mild-temperature (300, 600 MPa/15 min)	Strawberry puree	Reduction in vitamin C, anthocyanin content of 20% and 5% higher at 600 MPa than at 300 MPa	Marszałek et al. [40]
Combination (300, 600, 900 MPa/60, 70, 80°C)	Pumpkin puree	Higher pressures effective in maintaining and/or increasing lutein, α -carotene, β -carotene	Garcia-Parra et al. [42]
Thermal-assisted (250 MPa/60°C/3 min)	Grapefruit juice	Reduction in PME, PPO activity; improvement in total carotenoid, anthocyanin, flavanol, flavonoid and antioxidant capacity	Aadil et al. [43]
Ultrasound (US)			
Combination (blanching 100°C/4 min + sonication 20 kHz/70%/2 min)	Carrot juice	Significant increase in total carotenoid, lycopene, lutein; improvement in retention of sucrose, fructose, glucose, chlorogenic acid, Na, K	Jabbar et al. [45]
25 kHz, 70%, 20°C, 30/60/90 min	Apple juice	Improved ascorbic acid, phenols, antioxidant capacity; no significant changes in TSS, pH, TA	Abid et al. [46]

Technology and process conditions	Food matrix	Results	Source
40 kHz, 0.5Wcm ⁻¹ , 20/40/60 min	Blueberry juice	Enhancement of viscosity, color; improvement in TSS, polyphenol, anthocyanin; increase in antioxidant scavenging activity	Zou, Hou [47]
19 kHz, 20–100%, 2–10 min	Soursop juice	Increasing sonication intensity resulted in lower phenolic content, ascorbic acid; minimal impact on overall color	Dias et al. [48]
200–500 W, 15–90 min	Blueberry extract	Degradation of cyanidin-3-glucoside and antioxidant activity with increasing sonication power and prolonged treatment time	Yao et al. [49]
Pulsed light (PL)			
17.5 J/cm, 0.5 μs, 0.5 Hz	Fresh-cut apple	Reduction in browning and slight retention in firmness during storage of irradiated samples	Manzocco et al. [54]
0.7 J/cm, 250 μs, 4 pulses per day	Fresh-cut mango	Reduced color and fresh mass loss; increase in total carotenoid and antioxidant activity.	Lopes et al. [55]
2.7, 7.8, 11.7, 15.6 J/cm at 9, 26, 39 and 52 pulses respectively	Fresh-cut cantaloupe	Retention in firmness, pH, TSS, TA, color; no significant effect on phenols; ascorbic acid content decreased significantly on stored samples subjected to higher-fluence	Koh et al. [56]
2–4 J/cm, 360 μs, 3 pulses	Uncut tomato and Annurca apple	Significant increase in total carotenoid, lycopene, phenolics and antioxidant activity noted in both fruits	Pataro et al. [57]
Cold plasma (CP)			
60 kV, 50 Hz, RH 42%	Strawberry	Minimal impact on color and firmness; significant reduction in microbial flora	Misra et al. [63]
30 kV, 50 Hz, RH 45%	Uncut cherry; uncut tomato	Insignificant changes on pH, color, firmness, weight loss in both varieties	Misra et al. [61]
7.5–15 kV, 30 s, RH 42%			Vukic et al. [64]
15 kV, RH 60%, 10/20/30 min for apple; 30/60 min for melon	Fresh-cut apple; and fresh-cut melon	Significant loss in "crunchiness" in apple texture, melons exhibited no significant texture impact; linear reduction in PPO and POD activity	Tappi et al. [65, 66]
15 kV, RH 60%, 1/5/10 min treatment	Fresh-cut kiwifruit	Slight initial reduction in chlorophyll and carotenoid but improved color retention during storage; slight reduction in phenols but no significant impact on antioxidant activity	Ramazinna et al. [67]

Table 1. Impact of nonthermal processes on food quality and phytochemical compounds.

3.1. Pulsed electric field (PEF)

Pulsed electric field (PEF) involves the direct application of short, high current voltage pulses that create an intense electric field, applied to a food matrix placed between two electrodes [31]. PEF has been used as an alternative nonthermal treatment in the pasteurization of liquid or pumpable foods. Fruit juices, milk, smoothies, yogurt, sauces, wine, and soup-based products contain large amounts of water and dipolar molecules making them more conductive for passage of electrical currents compared to solid type foods. The PEF system discharges a high voltage pulse uniformly throughout the food in a treatment chamber (see **Figure 1a**) [29, 32]. Typical field strengths varies from 0.1 to 80 kV/cm with the time duration of the pulse cycles ranging from μs to ms depending on the application of PEF. The mechanism of PEF is best explained using the “*electroporation*” model in which the strong electric fields generated induce either reversible or irreversible (depending on electric field intensity) perforation of the cytoplasmic membrane promoting cell leakage (see **Figure 1b**) [31]. This effect has shown inactivation of microorganisms and food spoilage enzymes, thereby enhancing food safety, quality and phytochemical yield and extraction.

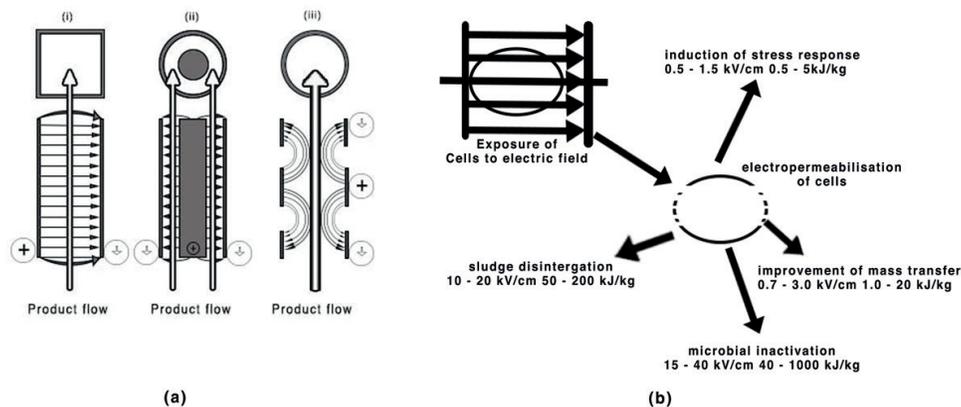


Figure 1. (a) Configuration of treatment chambers for continuous PEF processing: (i) parallel plate, (ii) coaxial, and (iii) co-linear; and (b) effects of exposure of biological cells at different electric field strengths and applications in food. Adapted from Toepfl et al. [32].

Kumar et al. on investigating the effect of PEF on carotenoids, microbial stability and different physicochemical changes on ready-to-drink (RTD) mango nectar, noted a high retention of carotene content (94.2%) and minimal changes in total soluble solids (TSS), pH acidity and color [33]. In a separate study [34], a higher retention of volatile monoterpene compounds, in particular (*Z*)-Ocimene, in mango nectar pasteurized at 96°C for 300 and 600 s was observed. Sensory scores conducted also found PEF samples to be insignificantly different from control samples owing to retention in volatile components and reduction in nonenzymatic 5-hydroxy methyl furfural (HMF) brown compounds. As cited in Buckow et al. several studies surveyed the effects of PEF on orange juice treated at $\leq 68^\circ\text{C}$, resulted in maintenance of vitamin C, carotenoid, polyphenol, and volatile aroma compounds compared to thermal pasteurization (95°C for 30 s) both after processing and refrigerated storage [35].

PEF is capable of extracting compounds such as pigments, antioxidants and flavors through the ability of the electric fields to induce cell membrane breakdown in plant tissue, increasing the

bioaccessibility of phytochemicals [29, 31]. As cited in Ricci et al. investigations using PEF assisted maceration on Tempranillo grape skin with treatments of 5 and 10 kV/cm increased the polyphenol and anthocyanin extraction in wine processing [31]. Results showed total polyphenols index in PEF treated wines was 13.7% higher (5 kV/cm treatment) and 29.0% higher (10 kV/cm treatment) with respect to the control after 96 h maceration; and at the end of fermentation color intensity also improved of 23.93 (control), 27.04 (5 kV/cm treatment), and 29.33 (10 kV/cm treatment). Increased juice recovery (9–25%) and higher amounts of total phenolics (up to 22%) and total anthocyanins (up to 26%) in PEF treated raspberries and press cakes extracts were reported [36]. With sweet cherries, PEF applied at low field strengths, increased production of volatiles, (aldehydes and alcohols) known to have desirable odors was reported by Sotelo et al. [37].

3.2. High pressure processing (HPP)

High pressure processing (HPP), also known as high-hydrostatic pressure (HHP) or ultra-high pressure (UHP), is capable of inactivating both pathogenic and vegetative spoilage microorganisms by using pressure rather than heat [38]. HPP mainly uses water as a medium to transmit pressure ranging from 100 to 800 MPa to foods [29]. The basic components of an HPP system include a pressurization vessel, a pressure transmitting fluid, a material handling unit, and supporting heating and cooling system components (see **Figure 2**) [39]. During HPP, food in flexible packages/containers is placed in a holding basket and lowered into the reaction chamber. High hydrostatic pressure is generated through the action of a piston or pump, which compresses the pressure-transmitting fluid allowing for uniform distribution throughout the product matrix [29]. Vitamins, flavor compounds and pigments survive the process while denaturation of proteins, gelation, hydrophobic reactions, lipid phase changes and ionization of molecules is able to modify the integrity of cell walls and membranes [38]. By optimizing HPP parameters of pressure (P), temperature (T) and duration time (t); important foodborne pathogens can be inactivated whilst preserving and/or enhancing the nutritional and organoleptic properties of food and vegetables [29].

On investigating the effects of mild temperature (50°C) and HPP (300 and 600 MPa) on the shelf life of strawberry purée, Marszałek et al. showed that higher pressure values resulted in prolonging shelf life from 4 to 28 weeks [40]. However, HPP was unable to preserve vitamin C and anthocyanin content in the treated purée, resulting in significant degradation of 20 and 5% higher at 600 than at 300 MPa respectively. The inactivation of endogenous enzymes such as β -glucosidase, polyphenol oxidase (PPO) and peroxidase (POD) are mainly responsible for anthocyanin degradation during storage. However, other factors such as temperature, light, pH, sugars, presence of oxygen, sulfites, ascorbic acid, metal ions and co-pigments may also destabilize anthocyanin compounds and accelerate its decomposition [41].

Garcia-Parra et al. investigated the effect of thermal assisted HPP to preserve pumpkin puree under varying combinations of pressure and temperature (300, 600, 900 MPa/60, 70, 80°C <71 min) and found that treatments at higher pressures were effective in maintaining and/or increasing the individual carotenoids (lutein, α -carotene and β -carotene) [42]. Similar studies on orange, carrot and tomato juices/purees also showed significant increases in carotenoid content and antioxidant activity [28]. It is believed that the mechanism of pressure-induced disruption of cell

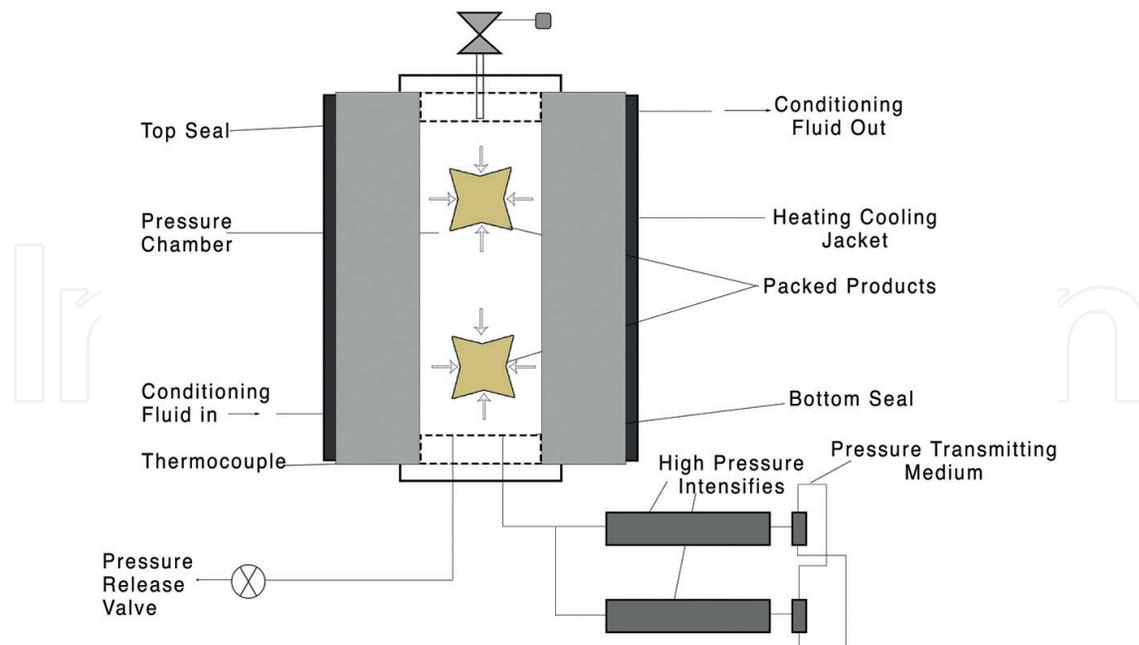


Figure 2. Schematic of a batch high pressure processing setup. Adapted from Chakraborty et al. [39].

walls and membranes, proteins and enzymes also facilitate the release and extraction of bound carotenoid from the cellular matrix, increasing its bioaccessibility [29]. Aadil et al. studied the effects of thermal-assisted HPP versus thermal processing of grapefruit juice and observed that processed juice at 250 MPa/60°C/3 min had an improvement in total carotenoid and anthocyanin content compared to control and thermally treated samples [43]. In the same study, ascorbic acid contents were reduced from 25.58 to 19.32 (mg/100 ml) in HPP and 17.28 (mg/100 ml) in thermal processed samples. While retention of vitamin C was higher under HPP compared to thermal processing, the elevated temperatures are most likely responsible for its depletion in both cases.

3.3. Ultrasound (US)

Ultrasound (US) employs mechanical sound waves at frequencies between 20 kHz and 500 MHz, and has emerged as an alternative technique, capable of inactivating microorganisms for food preservation [29, 44]. US systems are either batch or continuous type, that include sonication baths, ultrasonic probes and vibrating systems, and can be applied to liquid foods or solid type matrices embedded in a transmitting liquid medium (typically water) (see **Figure 3**) [45]. US mode of action is attributed to the “cavitation” phenomenon in which micro-bubbles generated in the transmitting medium by the sonication device, oscillate, grow in size and eventually collapse producing shock waves that induce a number of thermal, mechanical and chemical effects. As stated by Majid et al. the high temperatures, pressures, shear forces and free radicals generated in the cavitation zone affects cell walls and membranes for microbial inactivation, whilst retaining sensory, nutritional and functional characteristics of the food [44].

Jabbar et al. in evaluating the combined effects of blanching and sonication (frequency 20 kHz, amplitude level 70%) on carrot juice, reported improvements in the retention of chlorogenic acid, total carotenoids, lycopene and lutein content [45]. The increase in the bioavailability of these

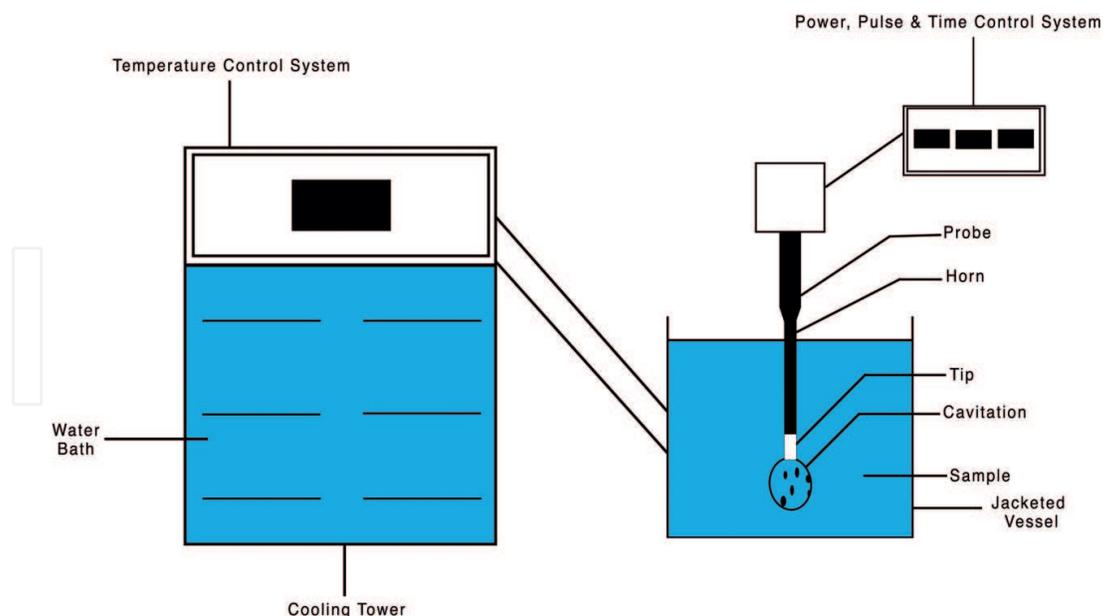


Figure 3. Schematic of a probe-type sonication system. Adapted from Jabbar et al. [45].

compounds might be attributed to the breakdown of cell walls and disruption of chromoplasts created by cavitation pressures allowing for release of membrane bound carotenoids. These results were similar to Abid et al. and Zou and Hou, when investigating US on different quality parameters of apple and blue berry juice respectively [46, 47]. Sonication showed increased levels of ascorbic acid, total phenolics, flavanols and flavonoids, and increased antioxidant activity due to the extraction and availability of these compounds. In a contrasting study by Dias et al. soursop juice subjected to varying levels of sonication energy, showed that increasing US intensity resulted in lower levels of phenols, ascorbic acid and higher levels of total color difference between sonicated and untreated samples [48]. The apparent decreases in overall phytonutrient content was attributed to increasing temperature and free radical formation that produced strong oxidizing effects during cavitation. Yao et al. investigating the effects of US on cyanidin-3-glucoside in blueberries, demonstrated that the pathway for degradation was the pyrolysis of water molecules creating $\cdot\text{OH}$ radicals involved in the opening of anthocyanin ring formation [49]. US-assisted extraction of various phytochemicals has grown in interest because of the potential industrial application to provide an efficient and energy saving extractive method.

3.4. Pulsed light (PL)

Pulsed light (PL) involves the use of intense, short duration pulses of light over a broad spectrum of wavelengths ranging from UV (180–380 nm), visible light (380–700 nm) to near-infrared (700–1100 nm); mainly used for decontamination of surface microorganisms on food and packaging [50, 51]. The basic components of a PL system incorporates three main parts: a lamp (xenon gas lamp), a power supply and a pulse configuration device (controller); configured in either batch or continuous flow design depending on the food material to process (see **Figure 4**) [52]. The mechanism of PL on microbial inactivation is attributed to both photochemical and photothermal effects. UV radiation is absorbed by carbon–carbon double bonds in

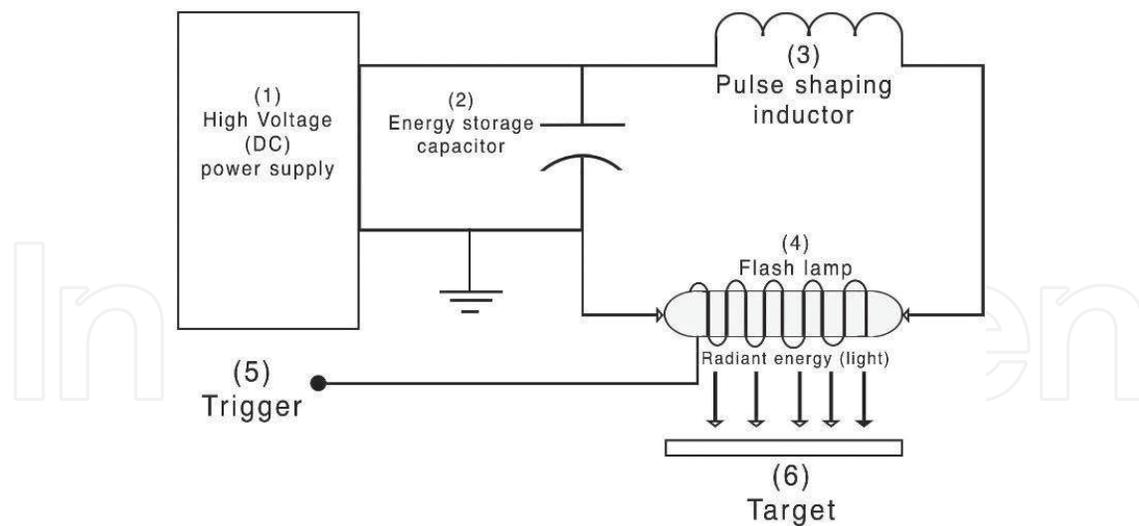


Figure 4. Schematic diagram of a high intensity pulsed-light system. Adapted from Abida et al. [52].

nucleic acids and proteins disrupting DNA and RNA structures, as well as rupturing bacterial cells due to localized overheating from absorption [50–52]. Similarly, the nonionizing effects of UV-C radiation at low doses has been the subject of numerous studies and documented by Maharaj et al. as having positive impacts on phytochemicals and sensory properties, either by preserving its content in fruits and vegetables or increasing it following treatment [53].

Manzocco et al. on studying the effect of PL on fresh-cut apple of increasing fluence ranges of 0, 8.8 and 17.5 J/cm² showed a significant decrease in browning of PL treated samples attributed to the modification of metabolic respiration and controlling the formation of brown polyphenols [54]. Similar studies on the effects of PL support this theory as observed by Lopes et al. On the effects of the exposure mode of light treatment on fresh-cut mangoes. PL treatments of 1 pulse (0.7 J/cm²), 4 pulses (2.8 J/cm²) and 1 pulse for 4 days (2.8 J/cm²) reduced the respiration rate with positive impacts on maintenance of yellow color and lower mass loss during storage [55]. Significant improvements in firmness were most likely associated with higher levels of UV-C, which either directly suppress cell wall hydrolase activity or indirectly via increase polyamine content that inhibit the enzyme. In the same study, there were marked increases in carotenoid and ascorbic acid content at the higher fluence intensity treatments. The authors noted the increase in the biosynthesis of these compounds with antioxidant activity could be an adapted photo-protective response to increasing oxidative stresses caused by UV-radiation. Koh et al. demonstrated that PL treatment on fresh-cut cantaloupe, a nonacidic fruit, resulted in the retention of phenolic and ascorbic acid content, albeit at much lower levels when compared to other studies on acidic types [56]. The study also highlighted that at much higher fluence treatments of 11.7 and 15.6 J/cm² there was a significant reduction in ascorbic acid content attributed to photothermal degradation of heat labile ascorbic acid at the higher intensities. At low PL dosage rates of 2 and 4 J/cm², Pataro et al. recorded significant increases in total carotenoids, lycopene and phenolics in whole, uncut tomatoes and Annurca apples [57]. Investigations on raspberries known to be high in antioxidant compounds showed that PL in combination with sanitizer washing was able to significantly increase the total phenolic and anthocyanin content both directly after treatment,

and retain higher levels after 3 months of frozen storage compared to untreated samples [58]. Both UV light and thermal stress created by PL induce the production of phenolic compounds through increased activity of phenylalanine ammonia lyase (PAL). However, increasing the duration of treatment (20–30 s) leads to over dosage of thermal stress producing severe damages to plant tissue, discoloration of the fruit skin and loss in bioactive content.

3.5. Cold plasma (CP)

Plasma is a quasi-neutral gas state, considered the "fourth" state of matter, and composed of a mixture of partially ionized gas molecules, ions, atoms and free electrons in their fundamental or excited state with an overall net neutral charge [59]. Plasma can be generated by using several types of energies to excite molecules. In the food industry, the general approach of producing plasma is to subject atmospheric air to an electric or electromagnetic field of constant or alternating amplitude, to induce electron collisions and generation of the ionized species [60]. The dielectric barrier discharge (DBD) and the plasma jet (see **Figure 5**) [59] are two common design types used to breakdown gas in a stationary electric field between electrodes to create the ionizing effect. The term cold plasma (CP) is considered a nonthermal technique from the fact that the temperature of electrons (T_e) is much higher than the temperature of the ions, neutrals and global gas (T_g) in the plasma ($T_e \gg T_g$) [61]. Thus the overall temperature of CP is at ambient temperature without raising the temperature of the surrounding medium. Under Atmospheric cold plasma (ACP), several reactive oxygen species (ROS); as well as reactive nitrogen species (RNS) are formed with high lethal effects, capable of inactivating a wide range of microorganisms [62]. The nonthermal nature of CP technology, coupled with its high antimicrobial effects, has provided an alternative treatment for the decontamination of fruits and vegetables whilst minimizing deleterious quality impacts.

Misra et al. studied the effects of ACP on fresh strawberries and demonstrated significant reductions of 2.4 and 3.3 log cycles for mesophiles and surface yeast and mold respectively, with minimal impact to color and firmness between treated and control samples [63]. This is in agreement with other studies conducted on whole cherry tomatoes where CP did not induce metabolic changes that adversely affect critical quality parameters of color, firmness, pH and weight loss [61, 64]. Studies conducted by Tappi et al. on the effect of CP on fresh-cut apples and melon had variable changes on texture. Whilst apples showed a significant loss in "crunchiness" in texture, melons exhibited no significant differences in the cut fruit [65, 66]. However,

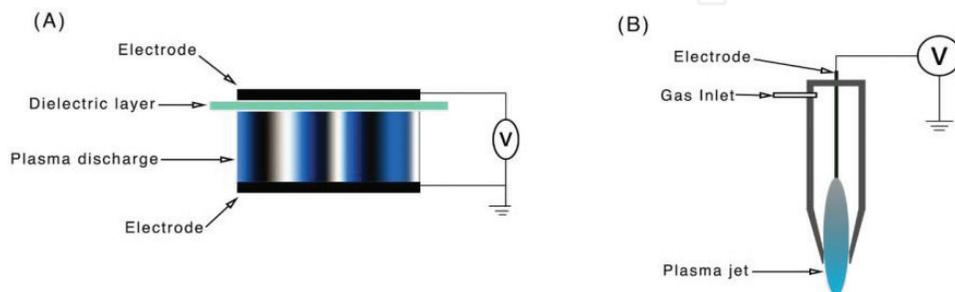


Figure 5. Schematic diagram of (A) dielectric barrier discharge; and (B) plasma jet system. Adapted from Pankaj et al. [59].

common to both cut apples and melons, was significant improvement in a reduction in brown color formed from enzymatic degradation products. By increasing CP treatment time, an observed linear reduction was noted for PPO and POD activity. The inhibitory effect of CP on enzyme activity was attributed to chemically reactive oxygen and nitrogen species modifying amino acids within the 3-D structure of proteins resulting in loss in enzyme function.

While the effects of CP on phytochemical composition is in its infant stage, Ramazzina et al. attempted to evaluate the effects of CP on bioactive compounds in minimally processed kiwifruit [67]. In the study, a significant reduction in chlorophyll and carotenoid content was observed in CP treated samples followed by better retention in these pigments during storage. This was attributed to the breakdown and oxidation of chlorophyll and carotenoids mediated by reactive species during the initial stage of treatment, followed by a slower rate of deterioration during storage due to partial protein denaturation and reduction in enzyme activity as previously described [65]. Analysis of health promoting ascorbic acid and phenolic compounds in the same study showed no significant changes in their content in the kiwifruit. While the investigators did note a slight initial decrease in total phenolic content, it did not significantly affect the overall antioxidant activity between CP and control treatments. It was noted that plasma induced oxidation of phenols at the initial stage of treatment, could be counteracted by tissue response/defense mechanisms that synthesize new phenolic compounds through increased activity of the enzyme (PAL) [67].

4. Conclusion

The recent global rise in consumer health awareness has prompted some food producers to utilize nonchemical preservation treatments to maintain and enhance the integrity of food products. Enhancing the competitiveness of the food industry requires technological innovation for improving quality, nutritious and safe ready to eat foods. Some studies have shown that unlike traditional thermal processing, nonthermal alternatives such as pulsed electric field (PEF), pulsed light (PL), ultra sound (US), high pressure processing (HPP) and cold plasma (CP) techniques have the ability to preserve and in some cases elicit increased phytochemical content of some fruits and vegetables. Such novel food preservation technologies have shown promising evidence in producing foods capable of reducing noncommunicable diseases with benefits to both domestic and export markets. In summary, the review has focused on both the application and impact of nonthermal technologies on the bioavailability of phytochemicals in fruits and vegetables which can positively impact the Food and Beverage industry.

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