

Chapter 2

High-Pressure Processing of Plant Products

HPT of plant products is gaining popularity in the food industry because of its ability to inactivate microorganisms and some enzymes near room temperature with little impact on flavor or nutritional attributes of the food.

2.1 Fruits

2.1.1 Apples

Apple cubes (var. Granny Smith and Pink Lady) in pineapple juice subject to HPT (600 MPa) resulted in no visible color change during 4 weeks of storage at 4 °C. The treatment significantly reduced residual PPO activity, while PME activity was not affected. Pineapple juice in combination with high pressure can be used as a preservation method for minimally processed apples (Perera et al. 2010). HPT (200–650 MPa) of apple cubes in acidified glucose solution (25.0 %) resulted in 6-log reduction of *Candida lipolytica* and *Escherichia coli* at 400 and 600 MPa, respectively. The microbiological shelf life of the product was extended from 15 days to 90 day during refrigerated storage (7 °C). The treatment had no significant effect on the hardness of the apple pieces, but addition of sodium metabisulfite helped to prevent browning during the entire storage period (Vercammen et al. 2012).

HPT (150 MPa) in presence of argon gas resulted in delayed browning and microbial growth as well as lower respiration rate, ethylene production, and total phenolics of fresh-cut apples in comparison with controls, when stored at 4 °C for 2 weeks. Dipping the sample into 0.5 %w/w ascorbic acid, 0.5 %w/w citric acid, and 0.5 %w/w calcium chloride for 5 min reduced the changes in color and firmness of apple wedges during high-pressure treatment and retained good sensory attributes (Wu et al. 2012).

Application of high pressure (500 MPa) preserves and even improves the availability of minerals and antioxidants. The bioaccessibility of calcium, iron, and zinc

was increased by 2.11–303 %, 4.63–10.93 %, and 8.68–28.93 %, respectively. At the same time, the dialyzability and solubility of these minerals was reduced and antioxidant activity was increased (Labarca et al. 2011). Husband et al. (2011); indicated that combining high pressure and thermal processing effectively reduces the allergenicity of apples. Kim et al. (2012) demonstrated that treatment of apple juice at 500 MPa, 25 °C, 3 min did not cause significant changes in vitamin C content, whereas total polyphenol content was increased. The product was microbiologically safe without physicochemical changes during 21 days of storage at 4 °C. Novotna et al. (1999) showed that the aroma of apple juice subjected to HPP was superior to that of pasteurized juice.

Buckow et al. (2009) developed a polynomial model to describe the rate of PPO inactivation in cloudy apple juice as a function of pressure and temperature and showed synergistic effects of pressure and temperature on the inactivation of apple PPO at pressures above 300 MPa and antagonistic effects at lower pressures. Landl et al. (2010) demonstrated that HPP (400 MPa) of apple puree resulted in no significant changes in total vitamin C and total phenolic content during 3 weeks of storage at 5 °C. However, treatment at 600 MPa led to a decrease in total phenolic content as did pasteurization treatment (75 °C, 10 min). Microbial counts were reduced below the detection limit (50 CFU/g) and storage revealed no further growth.

2.1.2 Apricots

High pressure (300–500 MPa, 5–20 min) applied to apricot nectar resulted in activation of PPO and POD, whereas PME was not changed. High-temperature short-time (HTST, 110 °C, for 8.6 s) treatment induced a complete inactivation of these enzymes. HPT increased total and individual phenolics in apricot nectars compared to HTST-treated apricot nectars. HPT also had no effect on total carotenoids and individual carotenes in apricot nectars except that treatment at 500 MPa, 20 min increased total carotenoids and β -carotene. Moreover, the color of high-pressure-treated apricot nectars was closer to the untreated apricot nectar (Huang et al. 2012).

2.1.3 Avocados

Lopez et al. (1998) pointed out that standard plate as well as yeast and mold counts of high-pressure-treated (345–689 MPa, 710–30 min) avocado puree was less than 10 CFU/g during 100 days of storage at 5 °C, 15 °C, or 25 °C. For treatment at pH 4.1 and 689 MPa, residual PPO activity was reduced to 24.7 %, 21.8 %, and 15.6 % for 10, 20, or 30 min of processing, respectively (Fig. 2.1a). Avocado puree with a residual PPO activity of less than 45 % maintained an acceptable color for 60 days during storage at 5 °C (Fig. 2.1b). Palou et al. (2000) indicated that HPT (689 MPa) resulted in complete inactivation of PPO and lipoxygenase (LOX) and reduction in standard plate count to less than 10 CFU/g without significantly affecting the

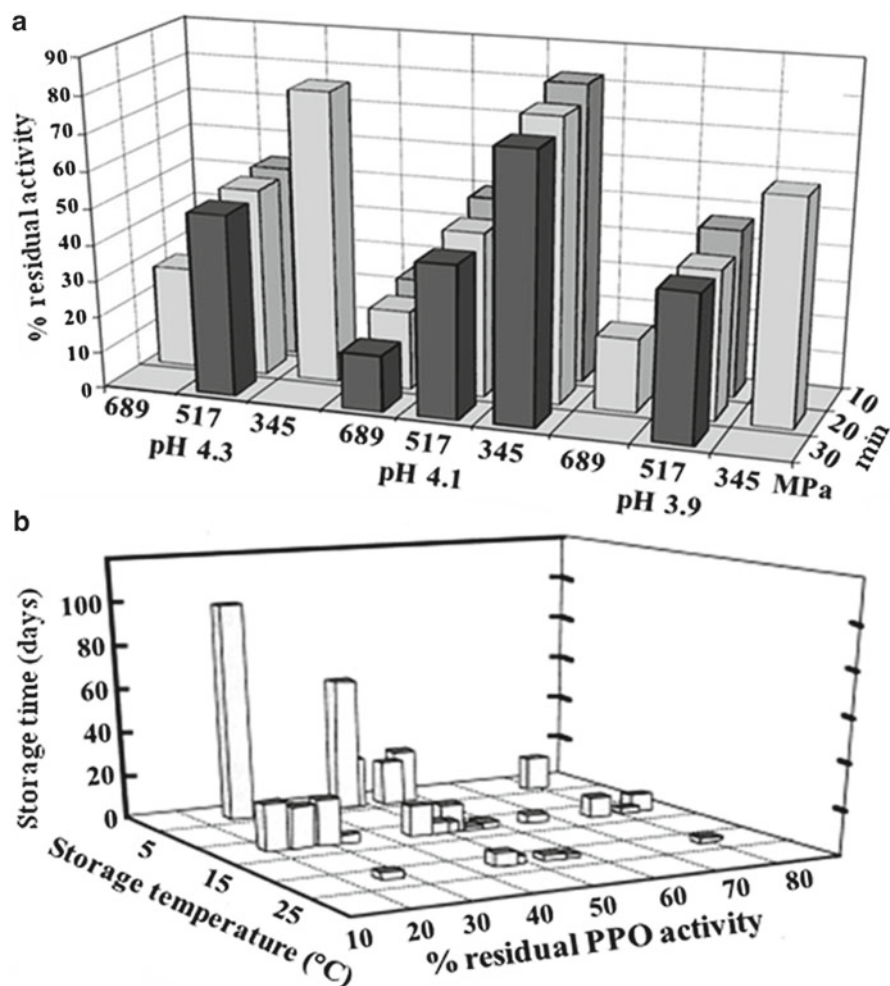
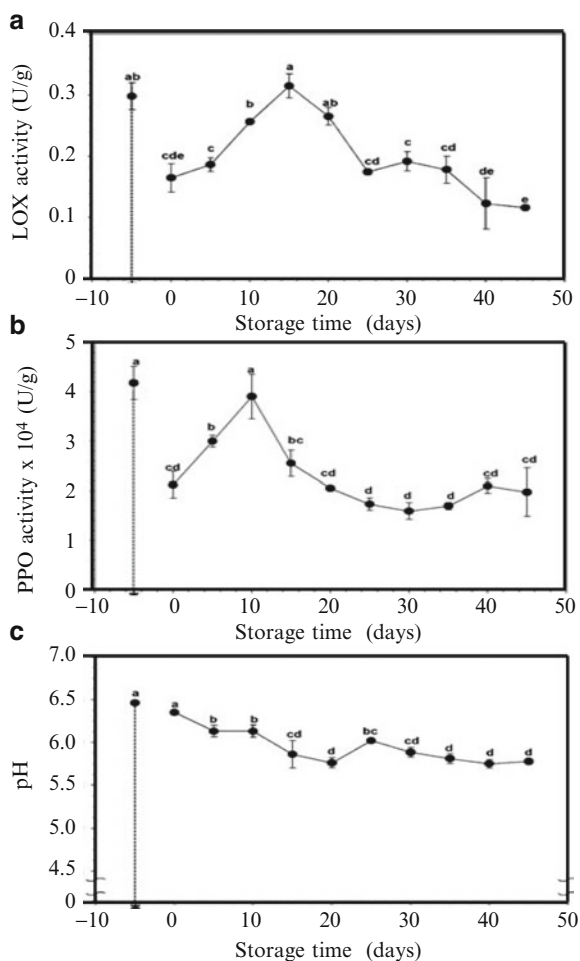


Fig. 2.1 (a) Effect of HPT and initial pH on residual polyphenoloxidase activity of avocado puree; (b) Effect of residual polyphenoloxidase activity and storage temperature on the storage time needed to lose the *green color* component in avocado puree (From Lopez, M.A., Palou, E., Barbosa-Cánovas, G.V., Welti-Chanes, J., and Swanson, B.G. 1998. *Food Res. Intl.* 31: 549–556. With permission)

sensory properties with extended shelf life. Later, Velazquez and Brenes (2010) showed that HPP (600 MPa and 3 min) of avocado paste resulted in a decrease in PPO and LOX activities, which were reactivated and reached the original values during 10–15 days of storage and then started to decline again until the end of the storage period (Fig. 2.2a, b). The pH of the pulp consistently declined during the first 20 days of storage (Fig. 2.2c). Enzyme reactivation, cell disruption, and a gradual migration of intracellular components such as organic acids were proposed as the main mechanisms for the deterioration of high-pressure-treated avocado paste during storage.

Fig. 2.2 Effect of HPT (600 MPa for 3 min) and storage (4 °C for 45 days) on (a) lipoxygenase (LOX), (b) PPO activity of avocado paste, (c) the pH of avocado paste. (Velazquez, D.A.J. and Brenes, C.H. 2010. *J. Food Sci.* 75: S264–S270. With permission)



Further, Velazquez and Brenes (2012) demonstrated that HPT (600 MPa, 3 min) induced a significant increase in individual carotenoids namely neoxanthin-b, α -cryptoxanthin, α -carotene, β -cryptoxanthin, β -carotene, and lutein concentrations as well as total extractable carotenoids. The carotenoid levels declined during storage (40 days, 4 °C), but at the end of the product's sensory shelf life were higher than those initially present in unprocessed avocado paste.

2.1.4 Berries

Terefe et al. (2009, 2010) found that HPT (600 MPa, 60 °C, 10 min) led to substantial inactivation of POD (58 %) in strawberries, whereas no significant reduction in PPO, total polyphenol, and total anthocyanin content was observed. Best quality

retention of strawberry products was obtained when HPP was combined with vacuum packaging in high-barrier packaging material and refrigerated storage. Patras et al. (2009a) demonstrated that HPT (400–600 MPa, 15 min, 10–30 °C) did not yield significant changes in ascorbic acid and anthocyanin content and antioxidant activities in strawberry and blackberry purees. The treatment retained the redness of purees as compared to thermally processed samples. Verbeyst et al. (2010) indicated that HPT (200–700 MPa, 80–130 °C) of strawberry paste resulted in first-order degradation kinetics of anthocyanins (pelargonidin-3-glucoside). At constant pressure, anthocyanin concentration decreased with an increase in treatment time and the degradation was accelerated at higher temperatures. At constant temperature, anthocyanins were more rapidly degraded as the pressure increased, but the effect of increasing pressure was smaller than the effect of increasing temperature. Cao et al. (2011) indicated that HPT (400–600 MPa) effectively retained monomeric anthocyanins, polymeric color and redness, phenolic compounds, and color of strawberry pulps. It partially inactivated food quality-related enzymes such as PPO, POD, and β -glucosidase (Fig. 2.3). Further, Cao et al. (2012) demonstrated that HPT (600 MPa) of cloudy and clear strawberry juices after 6 months of storage at 4 °C resulted in 39.41 %, 29.76 %, and 16.22 % decrease in ascorbic acid, anthocyanins, and total phenols, respectively in cloudy juices, whereas the corresponding values for clear juice were 48.91 %, 7.02 %, and 13.82 %, respectively. The decrease of these indices at 25 °C storage was almost doubled, while total difference color and browning degree were significantly higher.

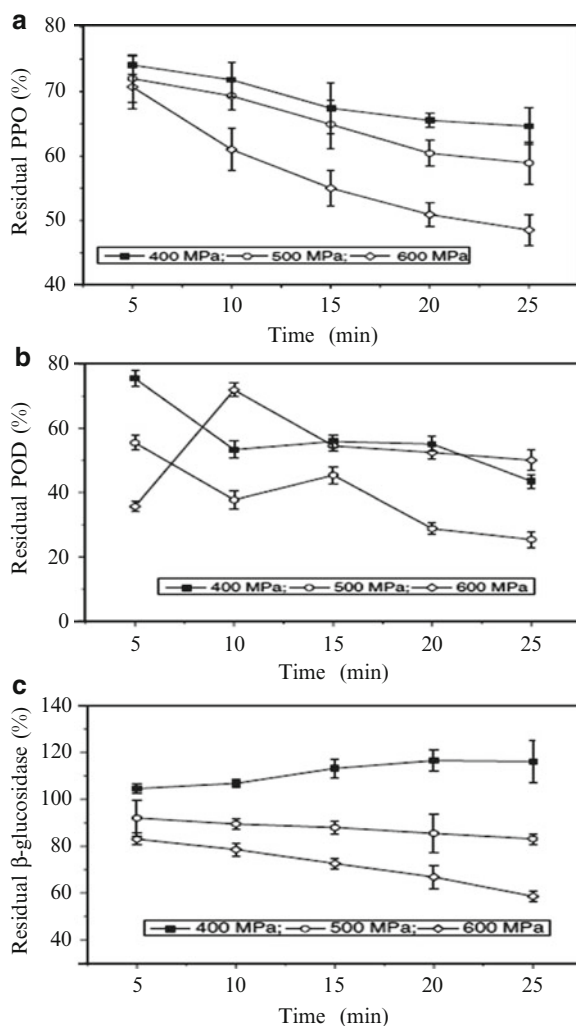
Bodelon et al. (2012) demonstrated that HPT (100–400 MPa, 20 °C and 50 °C, 15 min) resulted in no change in ascorbic acid and concentration of anthocyanins. PME activity decreased in the samples pressurized at 50 °C, but, a gel-network formation in the strawberry puree was not found; however, the latter was observed in the control and in the sample pressurized at 20 °C throughout cold storage. The temperature of processing had a significant effect on the color of strawberry puree, but no significant difference was observed after cold storage.

Lambert et al. (1999) demonstrated that strawberry aroma can be characterized by two main components (nerolidol and furaneol) and no major changes in strawberry aroma profiles were observed up to 500 MPa. But, higher pressure (800 MPa) induced significant changes in the aroma profiles due to the formation of new compounds namely 3,4-dimethoxy-2-methyl-furan and γ -lactone (Fig. 2.4).

Fraeye et al. (2010) studied infusion of PME and calcium prior to thermal, high-pressure, and combined high-pressure/thermal processing of strawberries. Processing of strawberries caused a decrease in firmness, which was reduced by infusion of PME and calcium chloride. PME was able to decrease the degree of methoxylation of pectin, accompanied by an increased cross-linking of the chains.

Hyperbaric storage (25–220 MPa, 15 days) at room temperature (20 °C) reduced the initial microbial load of the strawberry juice by more than 2 log units to levels below the limit of detection. Moreover, pressure was effective to attenuate viscosity and color losses in the samples stored at 20 °C. Stability of the samples after the hyperbaric storage was good when the samples were kept under refrigeration at atmospheric pressure for 15 additional days (Bravo et al. 2012).

Fig. 2.3 The effects of high hydrostatic pressure on (a) PPO, (b) POD, and (c) β -glucosidase activity in strawberry pulps (From Cao, X., Yan, Z., Fusheng, Z., Yongtao, W., Jianyong, Y., Xiaojun, L. 2011. *J. Sci. Food Agric.*, 91(5): 877–885. With permission)



Verbeyst et al. (2011) studied the combined effect of high temperature and high pressure on the degradation of cyanidin-3-glycosides in raspberries. Anthocyanin degradation was found to increase with increasing temperature as well as with increasing pressure. Cyanidin-3-glucorutinoside showed less degradation in comparison to the other cyanidins. Cyanidin-3-rutinoside experienced the smallest effect of temperature and the strongest effect of pressure.

2.1.5 Cashew Apples

HPT (350–400 MPa, 3 or 7 min) of cashew-apple juice reduced the aerobic mesophilic bacteria count to a level below the detection limit as well as resulted in

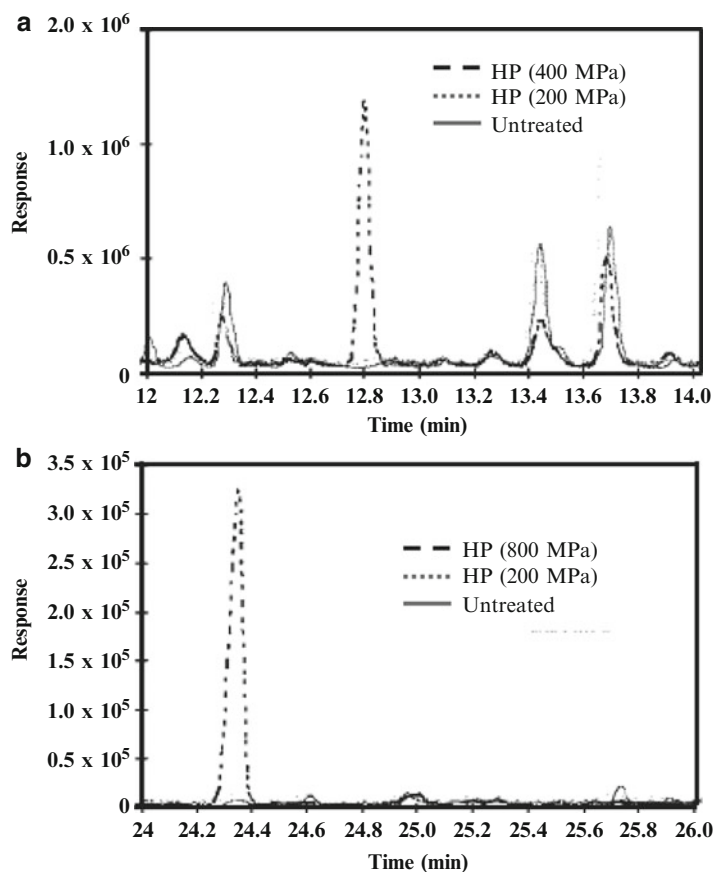


Fig. 2.4 Volatile compounds appearing after HPT (800 MPa, 20 min, 20 °C). Peaks are characterized by retention time of (a) 12.8 min attributed to 3,4-dimethoxy-2-methylfuran or 2-5-dimethyl-4-methoxyfuran-3, (b) 24.3 min attributed to a lactone volatile compound (From Lambert, Y., Demazeau, G., Largeteau, A., and Bouvier, J. M. 1999. *Food Chem.* 67: 7–16. With permission)

complete inactivation of yeast and filamentous fungi. The treated juice was stored for 8 weeks at 4 °C without any significant change in product quality (Lavinias et al. 2008).

2.1.6 Grapefruit

Naringin (a flavanone glycoside) is the dominant bitter principle in grapefruit juice. Application of high pressure was shown to enhance the reduction of naringin to naringenin (a tasteless compound) using naringinase immobilized on calcium alginate. Under atmospheric pressure, naringin reduction was only 35 % in a model system,

but it was found to be 75 % under high pressure (160 MPa, 37 °C, 20 min, Ferreira et al. 2008). Further, optimized conditions indicated that use of high pressure (205 MPa, 60 °C, 30 min) resulted in 81 % naringin reduction (Ribeiro et al. 2010).

Uckoo et al. (2012) demonstrated that HPT provided 'fresh-like' grapefruit juice without altering the levels of beneficial bioactive compounds. The retention of ascorbic acid was found to be significantly higher in HPP samples as compared to thermally treated samples. Further, these levels were gradually decreased during 0 and 7 days of storage. The levels of citric acid, flavonoids, limonoids, and furocoumarins in HPP samples did not change significantly, whereas the level of carotenoids was lower for both the treatments as well as for the control after 21 days of storage.

2.1.7 *Grapes*

Moio et al. (1994) demonstrated that HPT (500 MPa for 3 min) sterilized white grape 'must' with little changes in physicochemical properties, whereas red grape 'must' did not show higher stability due to the natural microflora present in it. Rastogi et al. (1999) studied the combined effects of HPT (100–600 MPa, 0–60 °C) on inactivation of endogenous enzymes in order to develop shelf-stable red grape juice. The lowest POD (55.75 %) and PPO (41.86 %) activities were found at 60 °C, with pressure at 600 and 100 MPa, respectively (Fig. 2.5). Corrales et al. (2008a, b) indicated that HPT (600 MPa) of red grape skins resulted in increased extraction of total phenolic content, which led to threefold higher antioxidant capacity along with the higher extraction of acylated anthocyanins. The maximum antioxidant capacity was achieved when the extraction was carried out at 70 °C, using 50 % ethanol concentration and pressures up to 600 MPa. In addition, the antioxidant capacity of the extracts increased with extraction time (Fig. 2.6). The highest levels of total anthocyanin monoglucosides were obtained at pressures of 200 MPa, whereas pressures of 600 MPa were optimal for the extraction of acylglucosides (Corrales et al. 2009). Addition of partially purified copigments such as rosemary and thyme polyphenolic extracts with muscadine grape juice during HPT (400 and 550 MPa, 15 min) increased color and antioxidant activity and reduced phytochemical losses during subsequent storage (Pozo et al. 2007). Casazza et al. (2012) demonstrated that use of high-pressure/high-temperature for the extraction resulted in higher total polyphenol and total flavonoid yield from grape skins. Chauhan et al. (2011) pointed out that the maximum retention of total antioxidant activity, phenolics, and flavonoids in the black grape juice were found at optimum level (550 MPa, 44 °C, 2 min).

2.1.8 *Guavas*

HPT (600 MPa, 15 min) of guava puree completely killed microbes and partially inactivated enzymes; the puree was stored up to 40 days at 4 °C without any

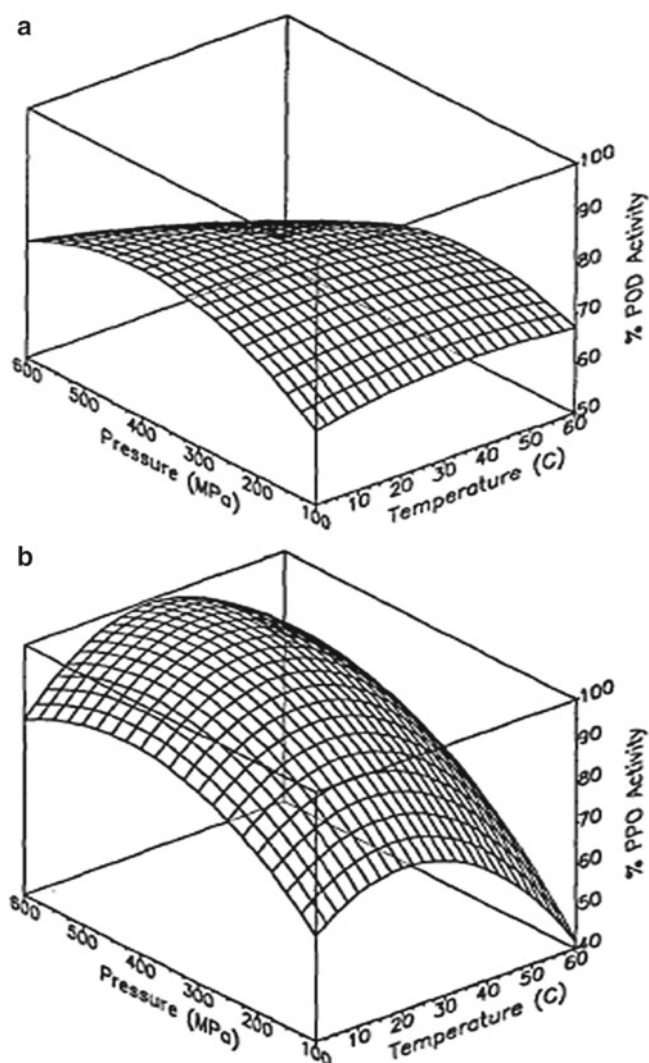


Fig. 2.5 Response surfaces showing effect of pressure and temperature on (a) % POD activity, (b) % PPO activity (From Rastogi, N.K., Eshtiaghi, M.N., and Knorr, D. 1999. *Food Biotechnol.* 13: 195–208. With permission)

change in color, cloudiness, ascorbic acid content, flavor distribution, and viscosity (Fig. 2.7, Gow and Hsin 1996). The treatment resulted in an increase in the levels of methanol, ethanol, and 2-ethylfuran throughout the entire storage period (Gow and Hsin 1999).

Fig. 2.6 (a) Effect of high pressure (600 MPa) at (a) different temperatures, (b) ethanol concentrations on the antioxidant capacity of Dornfelder *Vitis vinifera* L. grape skin extracts expressed as $\mu\text{mol TE/g DM}$ (Corrales, M., Fernandez, G.A., Butz, P., and Tauscher, B. 2009. *J. Food Eng.* 90: 415–421. With permission)

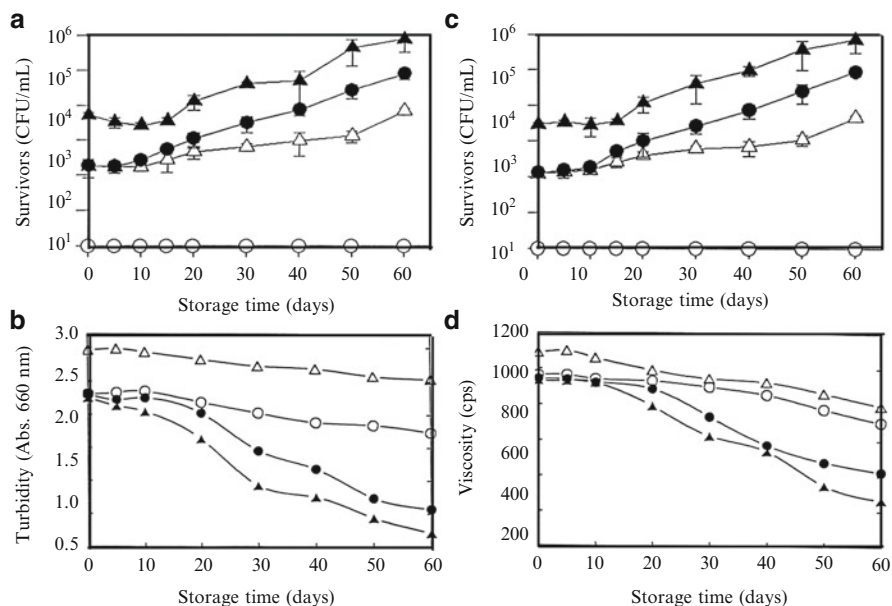
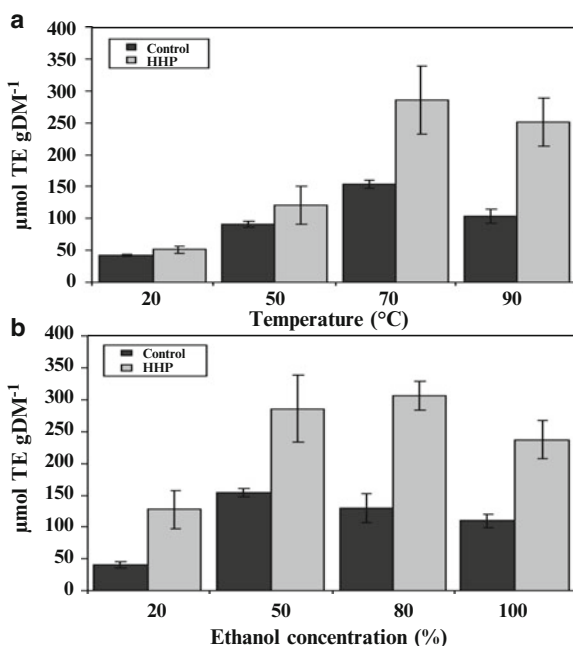


Fig. 2.7 Effects of high pressure treatment and thermal pasteurization on the changes in (a) total plate counts, (b) turbidity, (c) yeast and mould counts, and (d) viscosity of guava puree during storage at 4°C. (○) pressurized at 600 MPa; (●) pressurized at 400 MPa; (Δ) heated at 88–90°C; (▲) without treatment (From Gow, C.Y., and Hsin, T.L. 1996. *Intl. J. Food Sci. Technol.* 31: 205–213. With permission)

2.1.9 Kiwi Fruit

Actinidin is the sulfhydryl protease of the kiwi fruit and can be employed in place of other plant sulfhydryl proteases like papain and ficin as a milk clotting enzyme for traditional and novel dairy products, as meat tenderizer, and beer clarifier. Katsaros et al. (2009) demonstrated that high pressure resulted in controlled inactivation of actinidin and caused the desirable extent of clotting or tenderization. High pressure (200–800 MPa, 25–50 °C) induced inactivation allowed the selection of optimal high pressure process conditions for achieving desirable enzyme activity.

2.1.10 Lemons

High-pressure-processed (300 MPa) lemon juice was demonstrated to have a satisfactory shelf life with minor changes in its constituents and physicochemical properties. No fungi were detected in pressure-treated lemon juices, whereas control samples were spoiled by yeasts and fungi after 10 days (Donsi et al. 1998). High-pressure (100 and 200 MPa) induced enzymatic treatment (combination of cellulase and xylanase) resulted in higher pectin yield from dried lime peel than those using acid and aqueous extraction only weakly affecting the average molecular weight and intrinsic viscosity of pectin extracts (Naghshineh et al. 2013).

2.1.11 Lychee

The visual quality in both fresh and syrup-processed lychee fruit (*Litchi chinensis* Sonn.) after HPT (600 MPa at 60 °C for 20 min) was superior to that in the case of thermal processing. It led to extensive inactivation of POD and PPO in fresh lychees; these effects were less significant when the samples were processed in syrup (Fig. 2.8, Phunchaisri and Apichartsrangkoon 2005). Lychee fruit pericarp contains high amounts of flavonoids which are useful natural antioxidants. Prasad et al. (2009a, b) found that high-pressure extraction increases extraction yield (30 %) as compared to ultrasound-assisted extraction (24 %) and conventional extraction (1.83 %).

2.1.12 Longan

Yang et al. (2009) indicated that high-pressure extraction of longan fruit (*Dimocarpus longan* Lour.) pericarp resulted in decrease in the yield of water-soluble polysaccharides (lowest being 6.4 mg/g at 500 MPa), whereas the yield of alkali-soluble polysaccharides and cellulose did not change significantly as compare to conventional extraction. The lignin composition also was not affected by the application of high

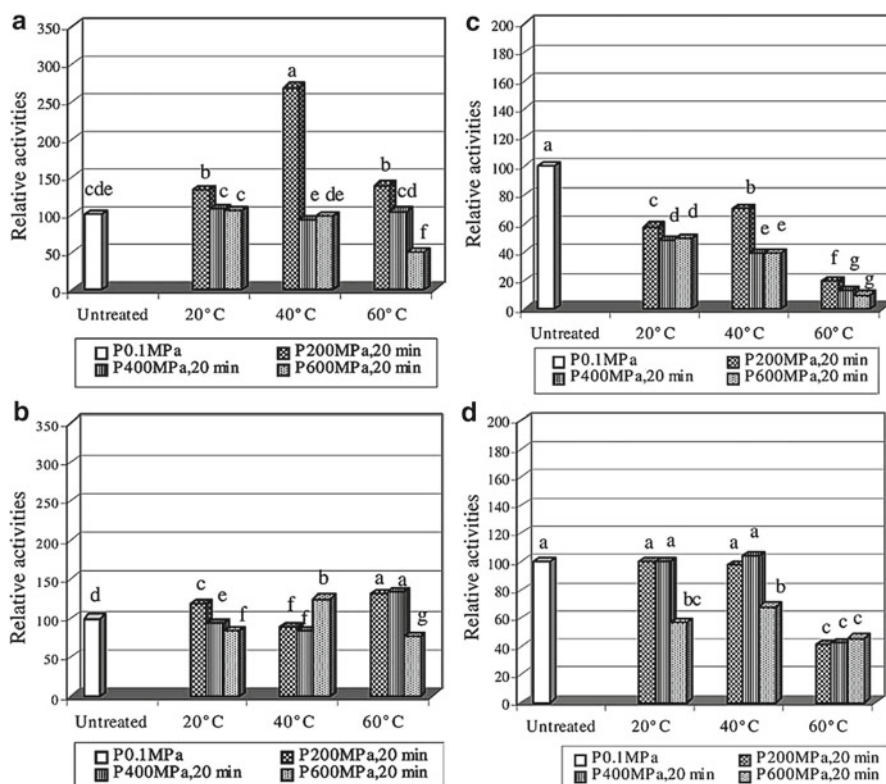


Fig. 2.8 Effect of combined UHP/temperature on (a) POD and (b) PPO activity of fresh lychee; (c) POD and (d) PPO activity of syrup lychee (Phunchaisri, C., and Apichartsrangkoon, A. 2005. *Food Chem.* 93: 57–64. With permission)

pressure during extraction. HPT resulted in higher extraction of phenolic antioxidant compounds and less extraction time as compared to conventional extraction. Corilagin concentrations were highest among the three phenolic compounds namely gallic acid, corilagin, and ellagic acid. The total phenolic content of the high-pressure-assisted extract was also higher as compared to the conventional extract (Prasad et al. 2009c, d) (Fig. 2.9).

2.1.13 Mangoes

HPT (300 or 600 MPa, 1 min) of pre-cut mangoes during storage at 3 °C led to slightly reduced fresh flavor, increased off-flavor and sweetness, as well as improved microbial status, but color, texture, and other sensory attributes changed only slightly (Boynton et al. 2002). In the case of high-pressure shift freezing, before pressure release the entire volume of mango sample reached the initial freezing

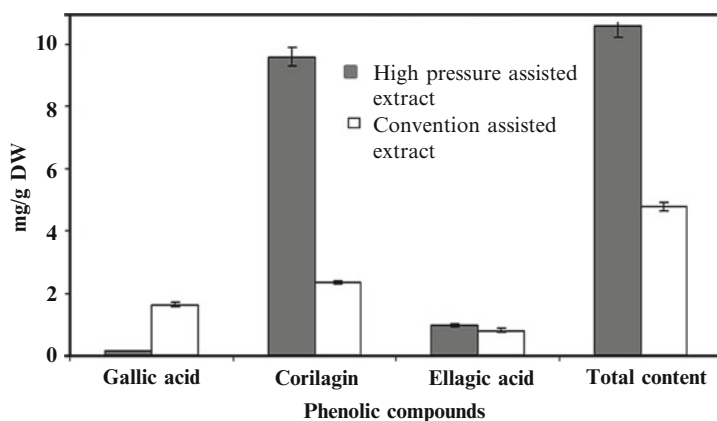


Fig. 2.9 Phenolic contents of longan fruit obtained by different extraction methods (Prasad, K.N., Jing, H., Shi, J., Ting, L., Jiang, L., Xiaoyi, W., Shengxiang, Q., Xue, S., Yueming, J. 2009c. *Innovat. Food Sci. Emerg. Technol.* 10: 413–419. With permission)

point at the same time, which led to high levels of supercooling resulting in uniform and rapid ice nucleation throughout the sample volume, resulting in maintenance of original tissue microstructure (Otero et al. 2000).

HPT (552 MPa, 5 min) of mango puree with added ascorbic acid and phosphoric acid (pH 3.5) resulted in reduced rates of browning during storage at 3 °C for 1 month without any microbial growth (Guerrero-Beltran et al. 2006). Flow behavior index for fresh and canned mango pulp was found to decrease and increase, respectively, with increase in pressure treatment. At the same time, the consistency index of fresh pulp increased with pressure level from 100 to 200 MPa, while a steady decrease was observed for canned pulp (Ahmed et al. 2005). Aguirre et al. (2011) showed that mesophiles in fresh mango nectar were inactivated up to 4 log during come-up time of pressure application. The treatment at 345 and 414 MPa for 2 and 1 min, respectively, inactivated all viable *Escherichia coli*. The highest inactivation of mesophiles (7 log) was reported at 414 MPa after 4 min. No significant reductions in PME activity were observed after treatment at 275 or 345 MPa, but it was found to increase after treatment at 414 MPa. Hiremath and Ramaswamy (2012) pointed out that HPT at 400 MPa for 5 and 10 min for *Listeria mesenteroides* and *Escherichia coli* resulted in complete destruction and 6-log reduction, respectively. Complete eradication of *Escherichia coli* was achieved when the juice was subjected to 500 MPa for 1 min.

2.1.14 Melons

Wolbang et al. (2008) found that HPT of melon (*Cucumis melo* L.) did not have any effect on total titratable acidity and total soluble solids; however, color, ferric ion-reducing capacity, and vitamin C levels were adversely affected, while the

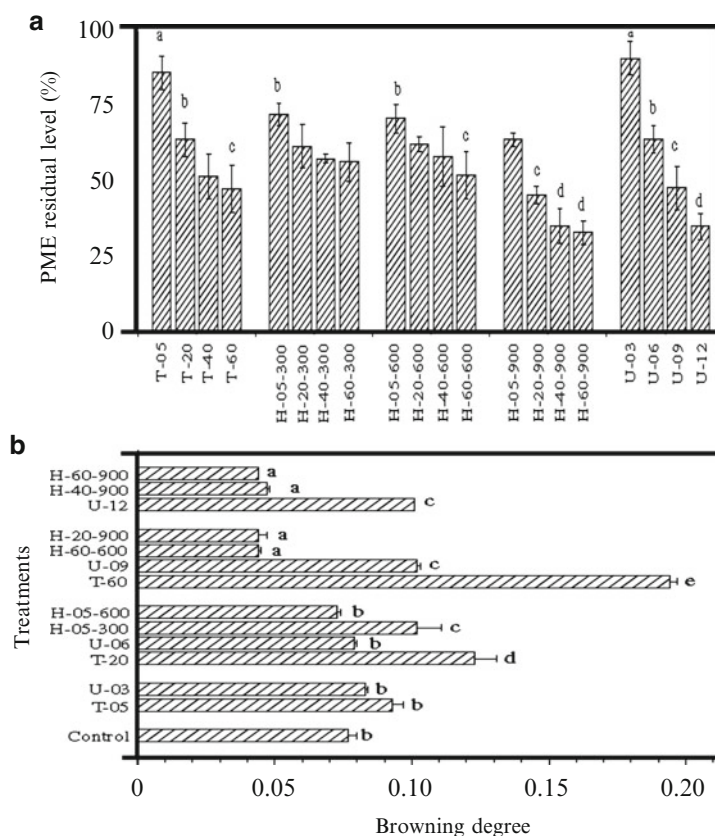


Fig. 2.10 (a) Effect of treatments on the PME residual level. The *a*, *b*, *c*, and *d* represent $(100 \pm 5)\%$, $(75 \pm 5)\%$, $(50 \pm 5)\%$, and $(35 \pm 5)\%$ of the PME residual level of the watermelon juice, respectively, after each treatment. (b) Effect of treatments on the browning degree of the watermelon juice. Data are means \pm standard deviation. Means with different letters represent a significant difference ($P < 0.05$) (Zhang, C., Trierweiler, B., Li, W., Butz, P., Xu, Y., Ruefer, C.E., Ma, Y., Zhao, X. 2011. *Food Chem.* 126: 254–260. With permission)

β -carotene level was significantly increased. Zhang et al. (2011) demonstrated that HPT (600–900 MPa) was effective in inactivating the PME of watermelon juice, while browning degree and dynamic viscosity of the treated juice was comparable to the controls (Fig. 2.10). Furthermore, HPT had a slight impact on the all-*trans*-lycopene, total *cis*-lycopene, and total lycopene concentration of the juice.

Cantaloupe (*Cucumis melo* L.) is a flavorful fruit with a unique aroma produced all around the world. However, because of lack of processing techniques, large amounts of cantaloupes rot away in farmlands every year. The fresh juice has a short shelf life and is highly heat sensitive. Ma et al. (2010) suggested that HPT may become a promising way to process cantaloupe juice. The microbial

count of juice after HPT (500 MPa, 20 min) was reduced to 100 CFU/100 ml and the activities of POD, PPO, and LOX were significantly lowered without change in sensory quality.

2.1.15 Oranges

Many researchers have reported extended shelf life of high-pressure-processed orange juice under refrigeration with increased flavor retention (Parish 1998a, b; Donsi et al. 1996; Strolham et al. 2000; Takahashi et al. 1998; Plaza et al. 2006a). HPT (800 MPa, 25 °C, 1 min) was shown to have a potential for stabilizing fresh orange juice yielding lowest levels of residual PME activity, good cloud stability, and less loss of ascorbic acid over a period of more than 2 months at 4 °C or 37 °C (Nienaber and Shellhammer, 2001). Later, Sampedro et al. (2008) demonstrated that HPT (700 MPa, 55 °C, 2 min) can result in complete inactivation of PME. High-pressure-processed (600 MPa, 1 min) juice from Valencia and navel oranges was shown to be safe for consumption and retained its freshness and nutritional values even after of 12 weeks at 4 °C (Sellaheewa 2002). In case of Navel and Valencia orange juices the population of aerobic bacteria, yeasts, and other fungi was reduced to below detectable levels. Inactivation of *Salmonella* up to 7 log cycles and marked reduction of PME was also observed. Color, browning index, viscosity, °Brix and titratable acidity, levels of alcohol insoluble acids, ascorbic acid, and β -carotene were unaffected when stored for 12 weeks at 4 or 10 °C (Bull et al. 2004). Katsaros et al. (2010b) studied the inactivation kinetics of PME and pressure-resistant species of spoilage lactic acid bacteria in freshly squeezed Valencia orange juice under high pressure combined with moderate temperature. Process conditions of 350 MPa at 35 °C for 2 min were proposed for the cold pasteurization Valencia orange juice. Donsi et al. (2010) demonstrated the use of pulsed high hydrostatic pressure with moderate temperature (250 MPa, 45 °C, 6 pulses) to achieve a desired lethality. At this optimum condition, the natural freshness (color, odor aroma) as well as nutritional quality of orange juice was found to be preserved for 21 days at a storage temperature of 4 °C (Fig. 2.11).

No significant difference in antioxidative capacity, sugar and carotene contents between high-pressure and thermally pasteurized orange juice was shown (Fernandez et al. 2001a). HPT (500 MPa, 5 min, 35 °C) of orange juice resulted in lower loss of ascorbic acid as well as higher retention of flavor, antioxidant capacity, shelf life, sensory scores, and viscosity as compared to conventionally pasteurized samples (Polydera et al. 2003, 2004, 2005). The odor and flavor (volatile content, 20 key aroma compounds) of the high-pressure-processed orange juice was acceptable to consumers even after storage for 12 weeks at lower temperatures of up to 10 °C (Baxter et al. 2005). Pan et al. (2011) demonstrated that limonene degradation in case of freshly squeezed navel orange juice increased with increasing processing pressure or temperature. The limonene degradation was found to result in significant increase of α -terpineol and carvone concentrations.

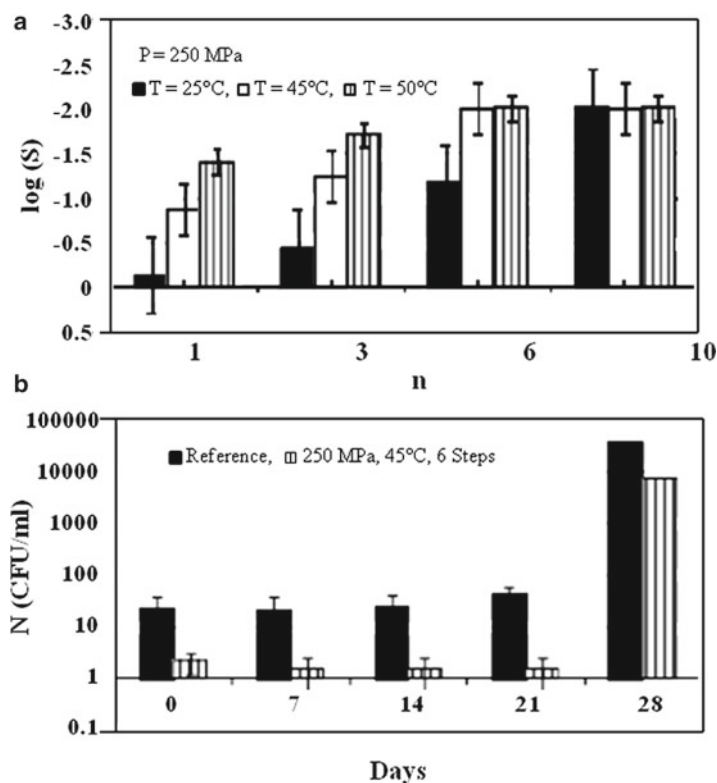


Fig. 2.11 Levels of inactivation of freshly squeezed orange juices processed in pulsed HPT at (a) different temperatures and constant pressure, 250 MPa and (b) number of surviving cells during the shelf life of untreated (reference) and processed in pulsed HPT at different storage times at 4 °C. (Pulse holding time=60 s, ramp rate=10.5 MPa/s) (From Donsi, G., Ferrari, G., Maresca, P. 2010. *J. Food Sci.*75: E169–E177. With permission)

Ancos et al. (2002) showed that HPT (350 MPa, 5 min, 30 °C) leads to an increased extraction of carotenoids as compared to controls. Moreover, Sanchez et al. (2003), Sanchez et al. (2005) demonstrated increased extraction of health-promoting compounds such as flavanones, vitamin C, carotenoids, and antioxidants in orange juice during storage at 4 °C. Butz et al. (2004) demonstrated that excess ascorbate resulted in no major loss in folate (hematopoietic vitamin) in freshly squeezed orange juice during HPT (600 MPa, 80 °C).

Vervoort et al. (2011) compared the impact of high pressure with that of a pulsed electric field processing and thermal processing. None of the methods were able to cause a complete inactivation of PME, although heat and high pressure were the most effective in limiting the residual activity, whereas POD was completely inactivated by heat treatment and was much less susceptible to the other two methods. Timmermans et al. (2011) also compared HPT with mild heat pasteurization and pulsed electric field processing and indicated that thermal pasteurization resulted in

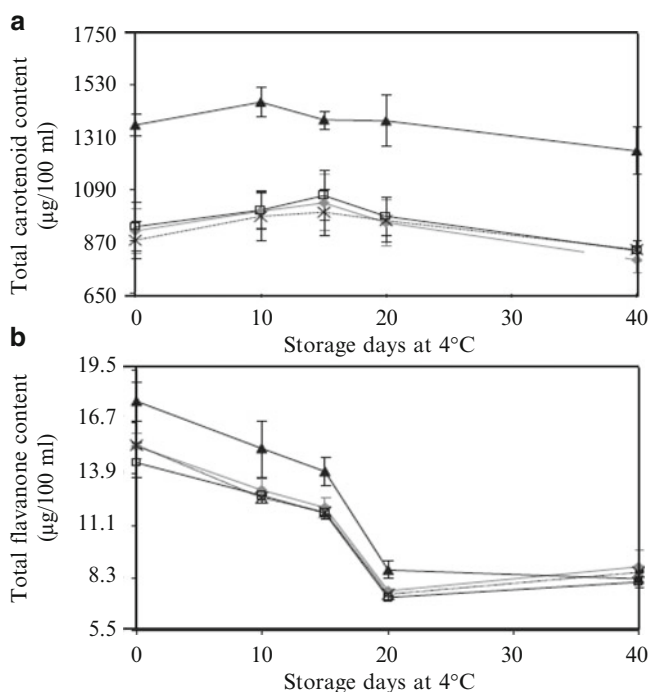


Fig. 2.12 Profile of (a) total carotenoid content (b) total flavanone content in orange juices during storage at 4 °C for each treatment assayed. *FS* freshly squeezed (without treatment) (♦), *LPT* low pasteurization (70 °C/30 s) (×), *HP* high pressure (400 MPa/40 °C/1 min) (▲), *PEF* pulsed electric fields (35 kV cm¹/750 ms) (□) (From Plaza, L., Moreno, C.S., Ancos, B.D., Martínez, P.E., Belloso, O.M., Cano, M.P. 2011. *Lebens. Wiss. Technol.* 44: 834–839. With permission)

most stable orange juice in terms of cloud stability due to inactivation of PME. However, a lower cloud degradation rate was found for high-pressure-processed juice as compared to pulsed-electric-processed juice. Plaza et al. (2011) indicated that high-pressure pasteurization was more effective in preserving bioactive compounds in orange juice during refrigerated storage as compared to pulsed electric field as well as thermal pasteurization. Immediately after treatment, high-pressure-processed juice showed a significant increase in vitamin A, as well as total carotenoid and flavanone content, whereas no significant changes were observed for the other two treatments. Flavanone content was found to decrease significantly during the first 20 days of storage at 4 °C for all treatments, while carotenoid content showed a moderate decrease that took place during the last 20 days (Fig. 2.12).

Torres et al. (2011) pointed out that retention of anthocyanins and ascorbic acid of high-pressure-processed blood orange juice during processing was more than 99 % and 94.5 %, respectively. However, degradation of these compounds was found to follow first-order kinetics during storage. During storage at 4 °C for 10 days, the retention of anthocyanins and ascorbic acid of high-pressure-treated

(600 MPa, 15 min) orange juice was found to be 93.4 % and 85.0 %, respectively. Gou et al. (2012) demonstrated that high pressure resulted in increased yield of pectin (20.44 %) as compared to yields obtained by traditional (15.47 %) or microwave (18.13 %) heating. The intrinsic viscosity and average molecular weight of pectin extracted by HPT was much higher than those extracted by traditional heating or microwave compared to commercial pectin.

2.1.16 *Passionfruit*

HPT (300 MPa, 5 min, 25 °C) was used to preserve yellow passion fruit pulp, which yielded a ready-to-drink juice with improved sensory quality free from cooked and artificial flavor attributes compared to commercial juices. HPT did not cause significant modifications in compounds responsible for the aroma, flavor, and consistency (Laboissiere et al. 2007).

2.1.17 *Peaches*

HPT (>300 MPa) in combination with citric acid (1–1.2 %w/w) could effectively be used for inactivation of peach PPO enzyme, which indicating that such treatment could be a potential alternative for conventional blanching. Furthermore, the use of citric acid as carrier fluid resulted in an increased rate of removal of moisture resulting from the formation of cracks in the upper layer by the acidic medium (Kingsly et al. 2009b).

The inactivation of endogenous PME of Greek commercial peach pulp under high pressure (100–800 MPa, 30–70 °C) followed first-order kinetics. High pressure and temperature acted synergistically on PME inactivation, except at 70 °C within the middle pressure range (100–600 MPa), whereas antagonistic effects of pressure and temperature were observed (Boulekou et al. 2010). The development of brown color (measured as browning index) in peach puree subjected to HPTs (400–600 MPa, 1–3 min) during 6 weeks of storage at 4 °C and 20 °C followed a zero-order kinetic (Khalil et al. 2011).

2.1.18 *Pears*

Beltran et al. (2011) demonstrated that HPT (0–241 MPa, 2 s, 0–15 min) reduced the initial counts in pear nectar inoculated with *Saccharomyces cerevisiae*, *Escherichia coli*, and *Listeria innocua* from 6.0×10^5 , 1.02×10^7 , and 2.4×10^7 CFU/ml to 2.4×10^5 , 6.3×10^5 , and 2.2×10^7 CFU/ml, respectively. The come-up time had an important microbial inactivation effect. The corresponding decimal reduction

time values were in the range of 2.0–35.3, 0.6–20.6, and 9.2–588.2 min, while Z_p values were 120.5, 92.6, and 75.2 MPa. Kou et al. (2012) showed that the volatile compounds in five pear cultivars differ considerably. The concentration of 1-methylcyclopropene could keep the levels of volatile compounds basically unchanged during storage and HPT changed the levels of volatiles significantly during the storage period.

2.1.19 Persimmons

Persimmon fruit are an important source of phenolic compounds, dietary fiber, and carotenoids. HPT (up to 400 MPa) of persimmon puree resulted in increased amount of extractable carotenoids, which was related to the increase in vitamin A value, but, this did not corroborate with the increase in antioxidant activity (Ancos et al. 2000). Gutierrez et al. (2011) showed that application of high pressure resulted in cell wall disruption and intracellular component dispersion throughout the tissue, together with some nutritionally active compounds namely tannins, fiber, and carotenoids.

Rojito Brillante is an astringent variety of persimmon fruit that needs a de-astringency treatment (95 % CO₂, 20 °C, 24 h) before commercialization to improve its sensorial quality. This fruit is a good source of bioactive compounds such as carotenoids. Plaza et al. (2012) studied the effect of HPT (200–400 MPa) on carotenoid content of astringent and nonastringent persimmon fruits at two maturity stages (III and V). HPT at 200 MPa resulted in an increase in extracted carotenoid content for astringent samples up to 86 % and 45 % at maturity stages III and V, respectively, whereas no significant differences or even a decrease was observed for nonastringent ones or those treated at 400 MPa (Fig. 2.13).

HPT (200–400 MPa, 1–6 min) of astringent and non-astringent persimmon ‘Rojito Brillante’ resulted in microstructural changes, which were related to the improvement in the diffusion and extractability of tannins and acid compounds. The application of high pressure resulted in decrease in flesh firmness and cohesiveness, while pH was increased in both astringent and non-astringent samples (Gutierrez et al. 2012).

2.1.20 Pineapple

Buzrul et al. (2008a) demonstrated that pineapple juice subjected to pulsed HPT (300 MPa, 20 °C, 60 s, 5 pulses) resulted in significant inactivation of *Escherichia coli* and *Listeria innocua* at lower pressure values than the ones used in commercial applications (>400 MPa). However, the pressure-treated juice stored at 4 °C, 20 °C and 37 °C up to 3 weeks led to an increase in the level of microbial inactivation and no injury recovery of the bacteria were detected. Ascospores of *Byssoschlamys nivea* are extremely heat-resistant and frequently associated with the deterioration of

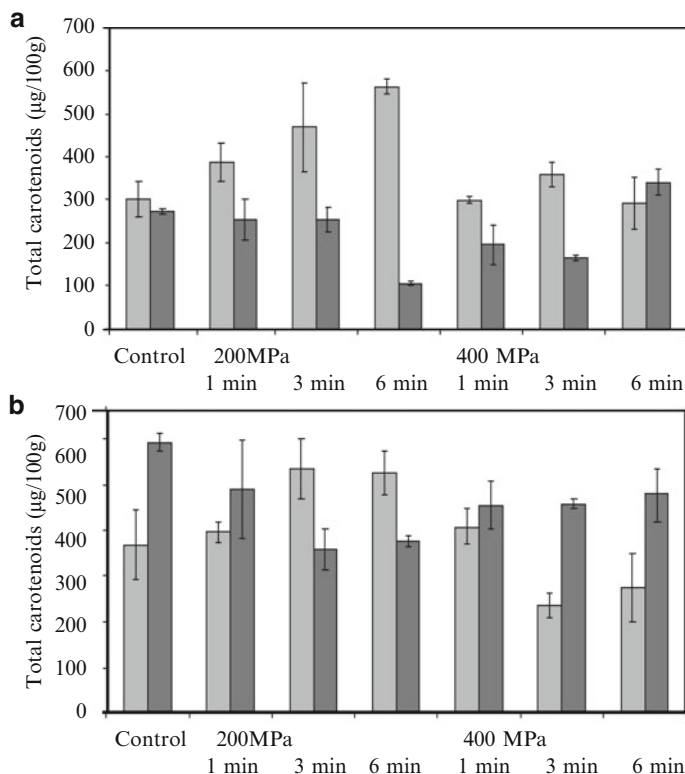
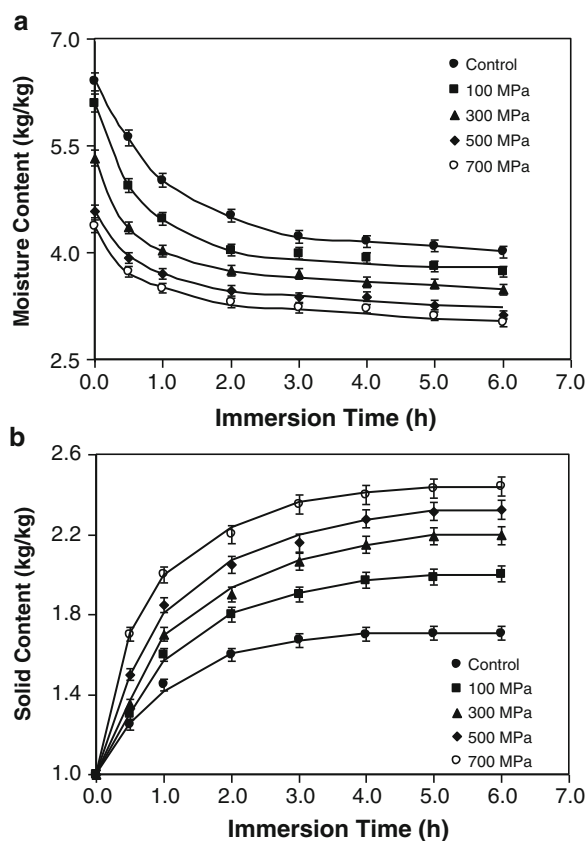


Fig. 2.13 Total carotenoid content of HP-treated (at 25 °C) astringent and nonastringent persimmon fruits. (a) Maturity stage III and (b) maturity stage V. (■) Astringent, (■) nonastringent (From Plaza, L., Colina, C., Ancos, B. de, Sanchez, M.C., Cano, M.P. 2012. *Food Chem.* 130: 591–597. With permission)

thermally treated fruit products. Ferreira et al. (2009) demonstrated that pressure cycles were more effective for inactivating *Byssochlamys nivea* ascospores in pineapple juice and nectar than the application of sustained high pressures. The ascospores were inactivated by applying sustained pressure of 600 MPa at 90 °C for 15 min and pressure cycles at 600 MPa and 80 °C for three cycles of 5 min or five cycles of 3 min could inactivate 10^5 – 10^6 CFU/ml of the ascospores in pineapple juice and nectar.

Application of HPT (100–800 MPa) was reported to enhance water removal as well as solute gain during osmotic dehydration of pineapple. Water as well as solute diffusivity values were reported to be increased by a factor of four and two, respectively. The compression and decompression steps during pressurization and release of pressure, respectively, caused the removal of a significant amount of water, which was attributed to cell wall rupture (Rastogi and Niranjana 1998, Fig. 2.14). Kingsly et al. (2009a) reported that application of high pressure reduced sample hardness, springiness, and chewiness, while it had no significant effect on cohesiveness of

Fig. 2.14 (a) Variation of moisture and (b) solid content (based on initial dry matter content) with time during osmotic dehydration (From Rastogi, N.K., and Niranjana, K. 1998. *J. Food Sci.* 63: 508–511. With permission)



pineapple. Moreover, the treatment reduced the drying time of pineapple slices. The effective moisture diffusivity was found to increase with an increase of pressure up to 500 MPa. Rastogi et al. (2000a) demonstrated that high-pressure-pretreated pineapple subjected to osmotic dehydration and then dehydration resulted in a dried product having less solid diffusion during rehydration, and so was the release of the cellular components. The reduction in loss of soluble solids during rehydration was due to formation of a gel-network between divalent ions and de-esterified pectin (Basak and Ramaswamy 1998; Eshtiaghi et al. 1994). It may prove to be a useful technique to reduce the loss of nutrients or color from dehydrated product during rehydration.

2.1.21 Pomegranate

Ferrari et al. (2010) demonstrated that HPT (400–600 MPa) of pomegranate juice at room temperature increased the intensity of red color of the fresh juice and preserved the natural anthocyanins content. The operating pressure, temperature, and

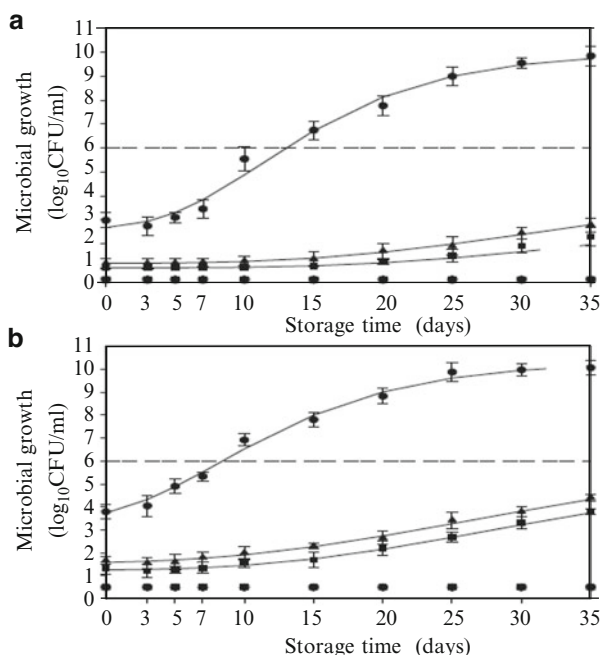


Fig. 2.15 Growth curve of (a) aerobic mesophilic and (b) molds and yeasts in untreated and high-pressure-treated pomegranate juice during storage at 4 °C for 35 days. Control (●), 350 MPa/30 s (▲), 350 MPa/90 s (■), 350 MPa/150 s (▼). The dotted line shows upper acceptable limit (Santos, E.V., Martinez, A.O., Munizaga, G.T., Reyes, J.E., Won, M.P., Labarca, V.B., Castro, J.M. 2012. *Innovat. Food Sci. Emerg. Technol.* 13: 13–22. With permission)

holding times were optimized with the aim of optimizing the processing condition in order to assure the microbiological stability, minimum degradation of the anthocyanins, as well as inactivation of PPO activity. Santos et al. (2012) indicated that pomegranate juice after HPT (>350 MPa, 150 s) resulted in a reduction of the microbial load around 4.0 log cycles, and the microbial populations (aerobic mesophilic bacteria as well as molds and yeasts) were below the detection limit during the entire storage period at 4 °C for more than 35 days (Fig. 2.15). The high-pressure-treated samples showed a slight reduction in antioxidant capacity during storage, while phenolic content increased. Total color difference (ΔE values) showed significant differences in color between untreated and treated samples. The pH, total soluble solids, and titratable acidity of high-pressure-treated samples did not significantly change during the first 15 days of storage.

Romero et al. (2012) demonstrated that HPT (350–550 MPa) of pomegranate arils was able to reduce the initial microbial load to less than 1.0 CFU/g and shelf life was extended for more than 35 days. During storage time, the total polyphenol content and antioxidant activity were found to decrease significantly compared to controls.

2.2 Vegetables

2.2.1 Bitter Melon

High-pressure extraction of momordicosides from fresh bitter melon (*Momordica charantia* L.) was found to be more efficient and rapid as compared to heat reflux extraction. The optimized parameters namely extraction pressure (423 MPa), extraction time (7 min), solvent to sample ratio (45.3:1 ml/g), and ethanol concentration of 70 % (vol./vol.) resulted in a maximum yield of 3.27 g Rgl equivalents/100 g bitter melon dry weight (Ji et al. 2010).

2.2.2 Broccoli

Glucosinolates present in broccoli can be hydrolyzed by endogenous myrosinase to isothiocyanates, the latter exerting anticarcinogenic activity. High pressure (100–500 MPa, 40 °C) was shown to have significant effect on glucosinolate degradation (Eylen et al. 2007, 2009; Barba et al. 2010). Verlinde et al. (2008) indicated that folylpoly- γ -glutamates present in broccoli were converted to folylmono- and folyldi- γ -glutamates by HPT (up to 600 MPa, 25–45 °C), which impairs dietary folate bioavailability (Fig. 2.16). HPT (500 MPa, 10 min) preserved nutritional substances in apple-broccoli juices such as sulforaphane and antimutagenic activity, apart from microbial inactivation (Houska et al. 2006).

Butz et al. (2002) showed that HPT did not have a significant impact on chlorophyll a and b in broccoli. The flavor of pressure-shift-frozen broccoli samples was

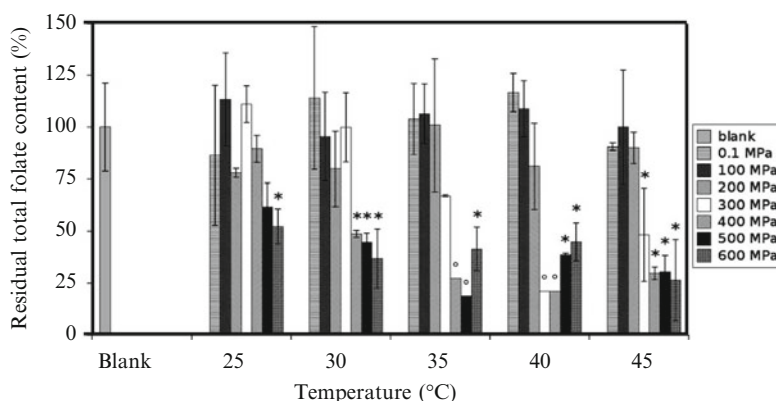


Fig. 2.16 Influence of thermal (25–45 °C, 0.1 MPa, 30 min) and isothermal-isobaric treatments (25–45 °C, 100–600 MPa, 25 min) on total folylpoly- γ -glutamate content in broccoli. *Indicates significant difference with blanks ($P < 0.05$) (From Verlinde, P., Oey, I., Hendrickx, M. and Loey, A. van. 2008. *Food Chem.* 111: 220–229. With permission)

not acceptable after 30 days of storage at -20°C , even though the texture remained quite firm. However, the sensory quality of samples blanched prior to high-pressure freezing (210 MPa, -20°C) was acceptable (Prestamo et al. 2004). Blanched and high-pressure-frozen broccoli presented less cell damage, lower drip losses, and better texture than frozen samples (Fernandez et al. 2006).

2.2.3 *Cabbage*

The application of high pressure (up to 500 MPa) to white cabbage resulted in reduction in the proportion of soluble fiber; total fiber content remained constant, which resulted in producing white cabbage with specific properties in terms of nutrition and function (Wennberg and Nyman 2004). HPT (600 MPa) was shown as an alternative preservation method for sour Chinese cabbage. The pressure level of 200 MPa had no significant impact on total aerobic bacteria, lactic acid bacteria, and yeasts in sour Chinese cabbage. The surviving total aerobic bacteria and lactic acid bacteria at 400 MPa equaled initial counts after 15-day storage at 27°C and 37°C , whereas they were inhibited at 4°C up to 60 days. The surviving total aerobic bacteria at 600 MPa did not grow. Yeasts at 400 and 600 MPa decreased below detectable levels after 2 days during storage (Li et al. 2010).

During storage of sauerkraut (obtained from white cabbage by natural or induced fermentation), a gradual rise of aerobic mesophilic bacteria and lactic acid bacteria was observed. HPT led to a reduction in microbial counts ($4\text{--}5 \log \text{CFU/g}$), which were further increased during storage. But the counts were always less than that of unpressurized sample stored for the same period (Penas et al. 2010). Koo et al. (2011) demonstrated that glucoraphanin present in red cabbage can be hydrolyzed by myrosinase to form sulforaphane, which has a cancer chemopreventive activity. The HPT at 400 MPa, followed by incubation at 60°C resulted in highest concentration of sulforaphane ($99.7 \mu\text{mol/kg}$ fresh wt). Ghawi et al. (2012) showed that the combined high-pressure (100–400 MPa) and temperature ($35\text{--}50^{\circ}\text{C}$) treatment followed first-order myrosinase inactivation kinetics. The results indicated that green cabbage myrosinase was stable up to 35°C and decay in activity occurred at higher temperatures, whereas it was stable up to 250 MPa and inactivation commenced from 300 MPa and above (Fig. 2.17).

2.2.4 *Carrots*

High pressure resulted in softening of carrot due to destruction of cell membrane and loss of soluble pectin along the cell liquor. PME resulted in de-esterification of pectin during depressurization and even after release of the pressure resulted in tissue hardening. High-pressure-processed carrot retained textural characteristics as compared to controls (Stute et al. 1996).

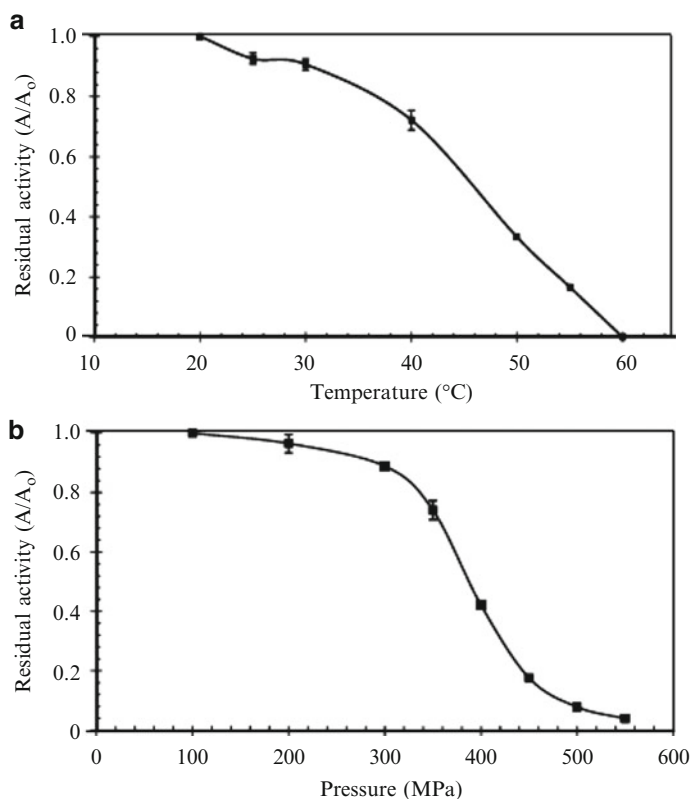


Fig. 2.17 Effect of (a) temperature and (b) pressure on residual activity of myrosinase (A/A_0) from green cabbage (From Ghawi, S.K., Methven, L., Rastall, R.A., Niranjana, K. 2012. *Food Chem.* 131: 1240–1247. With permission)

The instantaneous application of high pressure resulted in initial loss of texture followed by texture recovery as a result of pressure-hold. The extent of the initial loss of texture was more prominent at higher pressures and partial recovery of texture was higher at lower pressures. The texture reached original values at low pressure for long processing times (Basak and Ramaswamy 1998). The rapid loss of firmness of carrots was due to disruption of membranes, which reduces cell turgor pressure resulting in more deformable material or rubbery-like texture (Araya et al. 2007; Michel and Autio 2001). A combination of HPT with CaCl_2 infusion resulted in texture improvement during thermal processing. High-pressure pretreatment alone resulted in less loss of texture when the sample was treated at 100–125 $^{\circ}\text{C}$ (Sila et al. 2004, 2005).

Pressure-assisted thermal processing (PATP, 500–700 MPa, 95–105 $^{\circ}\text{C}$) resulted in less quality degradation (texture, color, and carotene content) as compared to thermally processed carrots (Nguyen et al. 2007) due to non-occurrence of

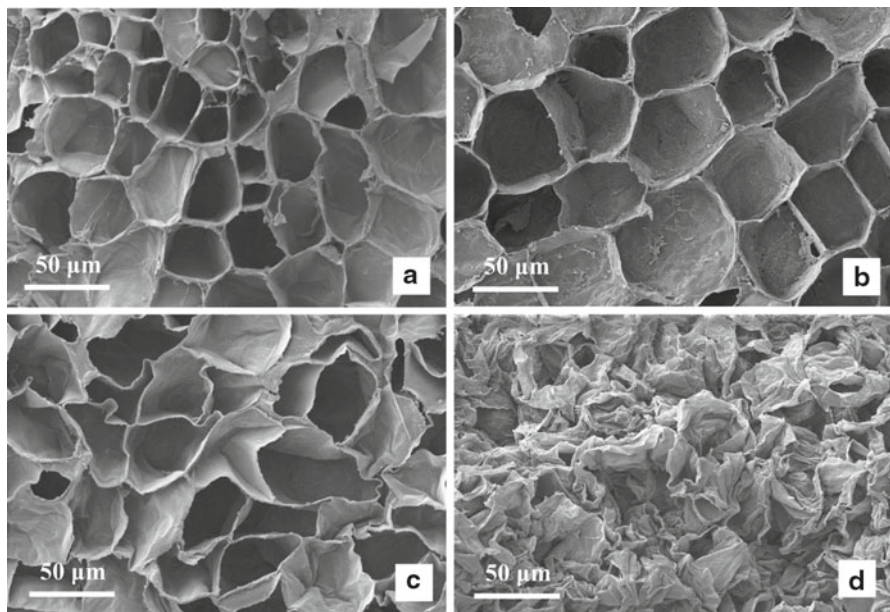


Fig. 2.18 Microstructures of (a) control, (b) pressure-treated (700 MPa, 25 °C, 5 min), (c) pressure-assisted thermal processed (700 MPa, 105 °C, 5 min), and (d) thermal-processed (105 °C, 0.1 MPa, 30 min) carrot samples (From Nguyen, L.T., Rastogi, N.K., and Balasubramaniam, V.M., *Journal of Food Science*, 72, E269, 2007. With permission)

β -elimination reaction and stimulation of demethoxylation of pectin (Roeck et al. 2008, 2009). Microstructures of cross-sections of raw, PATP (700 MPa, 105 °C, 5 min), and thermal processed (105 °C, 0.1 MPa, 30 min) carrot samples showed that the extent of structural damage was limited in the case of PATP, whereas thermal processing transformed intact cell structures of raw carrot to separated and ruptured cells with nondistinct middle lamellas because of degradation of pectinaceous material (Nguyen et al. 2007; Rastogi 2009b, Fig. 2.18).

Further, Roeck et al. (2009) demonstrated that combination of high pressure with high temperature (500–700 MPa, 90–115 °C) resulted in retardation or even stoppage of β -elimination reaction, whereas demethoxylation reaction was stimulated, this enhanced tissue strength by forming cross-links with divalent ions. Furthermore, hardness during pressure-assisted thermal processing could be further improved by a combined pretreatment involving calcium infusion (Rastogi et al. 2008a, b). The texture degradation in case of pressure-assisted thermally processed (600 MPa, 95–110 °C) sample was found to be tenfold slower in comparison to thermal treatment (Roeck et al. 2010).

The retention of total antioxidant activity, levels of ascorbic acid and carotenoids in carrot puree subjected to HPT (400–600 MPa, 15 min, 20 °C) were quite high as compared to thermal treatment (70 °C, 2 min). However, the color

parameters were significantly affected, whereas no significant change in phenolic content was observed by both of these processing techniques (Patras et al. 2009b). HPT (500–600 MPa) of carrot juice reduced the total counts by ~4 log cycles and only slight growth of the survivors was observed during storage at 4 °C up to 22 days. The total counts increased during storage of the product at 8 °C and 12 °C but it took significantly longer to reach maximum levels as compared to the untreated juice (Patterson et al. 2012).

The carrot sample did not freeze when subjected to high pressure (200–400 MPa) under freezing conditions (–30 °C); when pressure was reduced to atmospheric pressure, quick freezing was observed. These samples had better firmness, texture, and histological structure of frozen carrots than the ordinary frozen samples (Fuchigami et al. 1997a, b).

HP-processed (600 MPa, 2 min) carrots were found to be similar to sous-vide (90 °C, 5 min) carrots in terms of sweetness, green flavor, and crunchy texture. Furthermore, high-pressure carrots showed higher intensity perception of orange color and fibrousness and were shown to be better preserved for 14 days at 4 °C (Araya et al. 2009). A comparison of HPT with sous-vide-processed carrot disks indicated that HP-processed samples have higher retention of polyacetylenes. Falcarindiol-3-acetate and falcarindiol were found to be the most barosensitive and thermosensitive, respectively (Rawson et al. 2012).

2.2.5 *Cauliflower*

A considerable loss of turgor and structural collapse has been observed during HPT (400 MPa, 30 min, 5 °C) of cauliflower. The high pressure changes cell permeability and enables the movement of water from inside to outside the cell. As a result, treated tissue had a soaked or drenched appearance, however, after these changes, cauliflower maintained near-original, acceptable firmness and flavor (Prestamo and Arroyo 1998).

2.2.6 *Chestnut Kernels*

HPT at 300 and 500 MPa resulted in 61.3 % and 40.9 % retention of volatile compounds, respectively, in an instant chestnut product. The flavor profile of pressure-treated product indicated the appearance of new compounds and the disappearance of other compounds; but the characteristic flavor compounds were found to have high retention. The levels of aldehydes, ketones, and benzene compounds were decreased, but those of heterocyclic compounds and esters increased after pressure treatment (Zhiquing et al. 2011).

2.2.7 Eggplant

High-pressure-frozen eggplant samples had the highest firmness and the lowest rupture strain and drip loss compared to those of air-frozen samples. It was attributed to the formation of heavy ice polymorphs resulting from freezing of water under high pressure (100–700 MPa) leading to volume reduction (Otero et al. 1998). Microgram of still-air-frozen and air-blast-frozen eggplant with fresh sample indicated cell separation and disrupted cell wall, whereas, HP-assisted frozen sample had appearance similar to fresh sample and all the cells were positioned together and no cellular damage was evident (Fig. 2.19).

2.2.8 Garlic

HPT (600 MPa, 1 min) combined with citric or ascorbic acid (5 or 10 g/kg) treatment resulted in retarded browning of chopped garlic taken from dormant bulbs and stored under ambient conditions for 6 months. Also, the browning of germinated bulbs was reduced without inhibiting greening, which is a physiological disorder (Seok and Dong 2001). Ma et al. (2011) demonstrated the possibility of adjusting formation and degradation of the volatile compounds in garlic by pressurization to produce garlic products with different flavor. HPT at 200, 400, and 600 MPa for 20 min of intact garlic resulted in 29, 19, and 12 kinds of volatile compounds, respectively, where alkyl sulfides accounted for 61.04 %, 41.38 %, and 22.73 % in relative peak area. The flavor intensity of odor-active compounds decreased with an increase in pressure. The alliinase activity increased by 2.89 % after treatment of 200 MPa, but decreased by 37.19 % and 59.18 % after treatment of 400 and 600 MPa, respectively, leading to different flavor intensities of garlic.

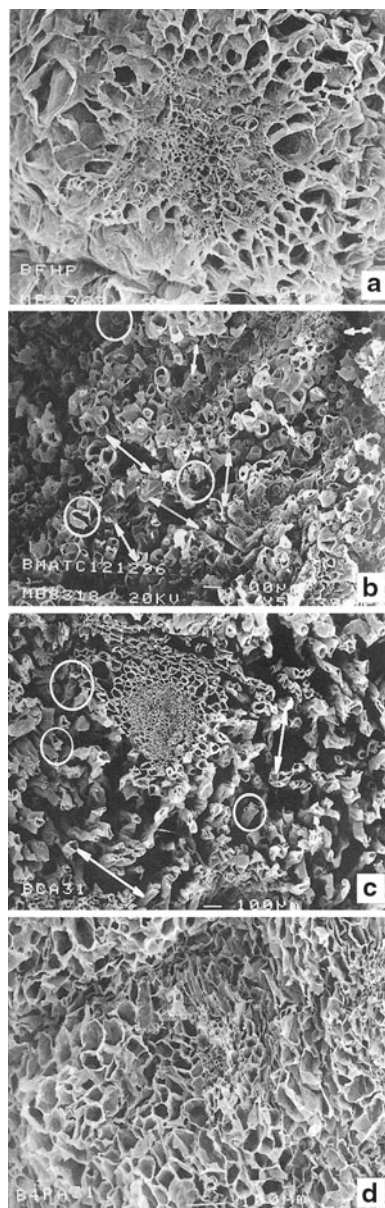
2.2.9 Ginger

Yamaguchi et al. (2010) pointed out that HPT (400 MPa, 5 min) of grated ginger resulted in the inactivation of quality-degrading enzymes such as geraniol dehydrogenase (less than 5 %) and PPO (37 %). On the other hand, heat treatment (100 °C, 10 min) reduced geraniol dehydrogenase and PPO activity to 43 % and 10 %, respectively. In case of HP-treated ginger, terpene and aldehydes disappeared without the formation of alcohols. Browning was not observed immediately after HPT, whereas it was complete in heat-treated samples.

2.2.10 Green Beans

HPT (500 MPa) and pulsed HPT (500 MPa, 2 pulses, 70 °C) resulted in improved texture, nutritional quality, and appearance of green beans and shelf life of beans

Fig. 2.19 Scanning electron micrographs of eggplant (a) fresh; (b) still-air frozen tissue (c) air-blast frozen tissue (d) HP-frozen tissue. Cell separation and disrupted cell walls are marked by arrows and circles, respectively (From Otero, L., Solas, M.T., Sanz, P.D., Elvira, C. de and Carrasco, J.A. *Euro. Food Res. Technol.* 206: 340–341, 1998. With permission)



was extended to at least 1 month at 6 °C or 20 °C storage temperature Krebbers et al. (2002). A comparison of HP sterilization of beans with the equivalent thermal processing showed that HP-sterilized green beans were darker and greener in appearance, and also twice as firm as the thermally processed samples (Leadley et al. 2008).

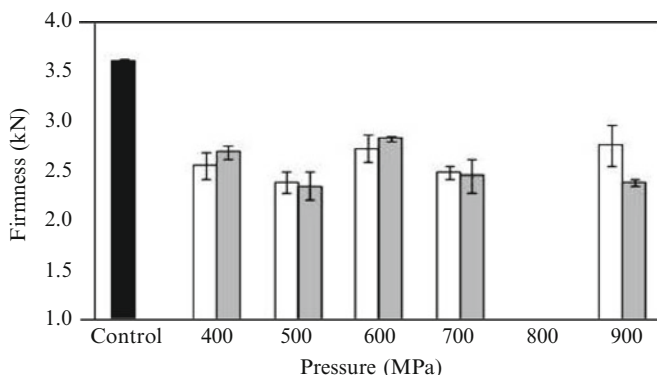


Fig. 2.20 Firmness of fresh and pressure-treated (5 or 10 min) green peas stored at -18°C for a week and thawed at room temperature (From Quaglia, G.B., Gravina, R., Paperi, R., and Paoletti, F. 1996. *Lebens. Wissen. Technol.* 29: 552. With permission)

2.2.11 Green Peas

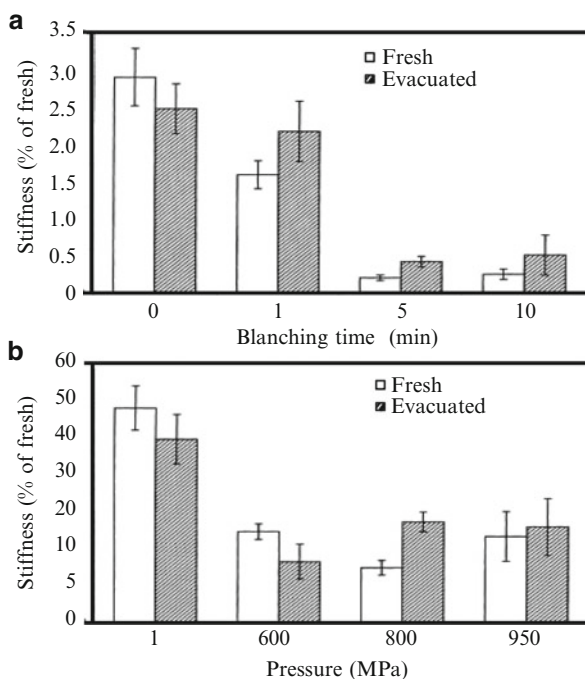
HPT (900 MPa) was demonstrated to be an alternative to thermal blanching of green peas. It resulted in a higher retention of ascorbic acid (82 %) in comparison with water (10 %) or microwave blanching (47 %). Although a significant softening resulted with respect to fresh frozen peas (Fig. 2.20). But, a combination of high pressure (400–900 MPa) with heat treatment (up to 60°C) did not cause any significant changes in firmness (Quaglia et al. 1996).

2.2.12 Mushrooms

HPT (600–900 MPa) resulted in less texture degradation of mushrooms compared to thermal blanching (Fig. 2.21). High pressure resulted in permeabilization of cell membranes due to crystallization of phospholipids within the cell membranes. The increased permeability resulted in contact of extracellularly located PPO with phenols leading to enhanced browning. However, product yield and color were comparable to thermally blanched products. The intensity of browning was further reduced by evacuating mushrooms before pressurization (Matser et al. 2000).

HPT at 1,400 and 1,600 MPa for 1 min reduced PPO activity by 90.4 % and 99.2 % in phosphate buffer; however, higher enzyme activity remained in the mushroom puree after the treatment. Circular dichroism and fluorescence spectra analysis showed that the secondary and tertiary structures of HP-treated PPO were changed (Fig. 2.22). Sulfhydryl group content on the surface of HP-treated mushroom PPO was found to increase, which indicated that the inactivation of mushroom PPO must have resulted from the synergistic effect of the pressure and the heat arising from pressurization (Yi et al. 2012).

Fig. 2.21 Stiffness of evacuated and fresh mushrooms after (a) blanching, (b) pressure treatment expressed as percentage of the stiffness of fresh mushrooms (From Matser, A.M., Knott, E.R., Teunissen, P.G.M., Bartels, P.V. 2000. *J. Food Eng.* 45: 11–16. With permission)



2.2.13 Olives

“Cornezuelo”-dressed olives are highly valued for their excellent organoleptic characteristics but have a low stability. HPT (400–600 MPa, 5 and 10 min) enhanced the shelf life of the olives prepared without preservatives. HP-treated olives showed higher stability and firmness but no significant differences were observed for color. The sample treated at 400 MPa for 5 min obtained higher score for sensory analysis after 120 days of storage (Pradas et al. 2012).

2.2.14 Onions

HPT (100 MPa) affected onion epidermis cells and cellular components, such as vacuoles. PPO oxidized phenol to orthoquinones, which upon polymerization formed brown pigment in diced onions. The rate of browning reaction was found to increase with an increase in pressure. Microscopic studies revealed that ability of sample to respond to sucrose was only affected to a minor degree for the samples treated at 100 MPa at 25 °C; however, severe damage to vacuoles of onion epidermis cells and cellular components was found for samples treated at 300 MPa (Butz et al. 1994). HPT (100 and 400 MPa, 5 °C) of onion led to better extraction of

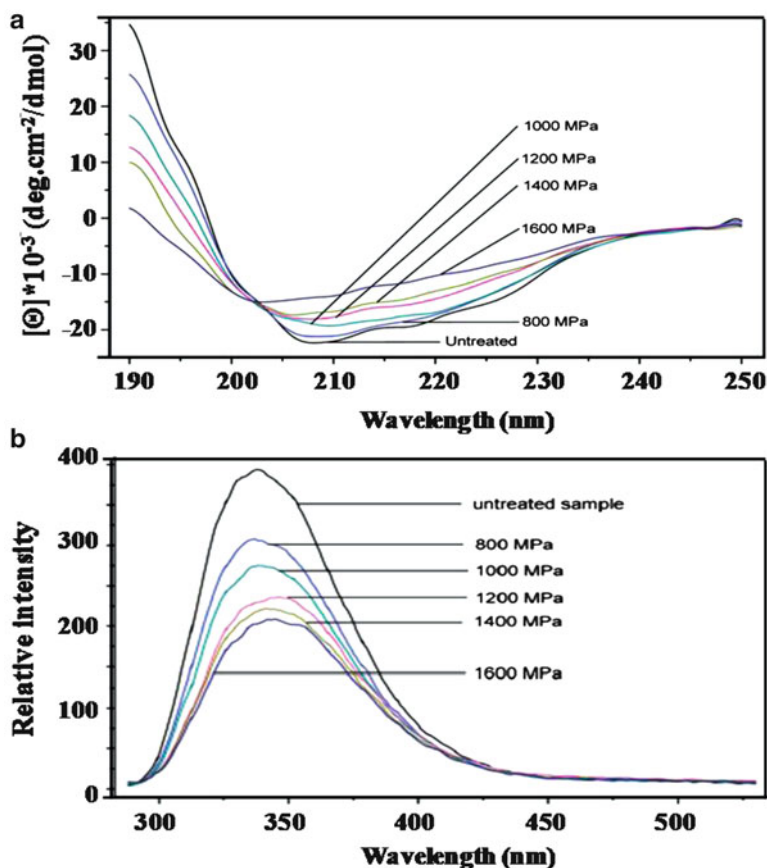


Fig. 2.22 (a) Far-UV CD spectra, (b) fluorescence emission spectra of high-pressure-treated mushroom PPO (From Yi, J., Bin J., Zhong, Z., Xiaojun, L., Yan, Z., Xiaosong, H. 2012. *J. Agric. Food Chem.* 60: 593–599. With permission)

flavonols (quercetin and quercetin glucosides) and increased antioxidant activity. At 400 MPa, the extraction of quercetin glucoside increased to 33 %, but there was no change in antioxidant activity (Roldan et al. 2009).

Gonzalez et al. (2010a) used proton nuclear magnetic resonance ($^1\text{H-NMR}$) relaxometry to study the effects of HP and thermal processing on membrane permeability and cell compartmentalization. Loss of membrane integrity was clearly shown by changes in transverse relaxation time in thermally processed sample. Gonzalez et al. (2010b) also determined changes in cell membrane permeability and/or integrity by measuring formation of pyruvate as a result of membrane permeabilization as well as leakage of electrolytes into solution.

Neetoo et al. (2011) indicated that HPT (250–500 MPa, 2 min) of green onions in unwetted, wetted (briefly dipped in water), or soaked (immersed in water for 30 min) conditions reduced the population of *Salmonella* and *Escherichia coli*

O157:H7 by 0.6 to more than 5 log CFU/g. The extent of pressure inactivation increased in the order of soaked>wetted>unwetted state. Furthermore, Neetoo et al. (2012) showed that green onions grown in soil contaminated with *Escherichia coli* O157:H7 and *Salmonella* take up the pathogens in their roots, bulbs, stems, and leaves, but that HPT (400–500 MPa, 2 min) eliminated both of these pathogens.

2.2.15 Bell Peppers and Red Pepper

HP-pretreated *Capsicum annuum* (400 MPa, 10 min) resulted in higher drying rates for red pepper during dehydration. The pretreatment can be used as an alternative to chemical (NaOH or HCl) pretreatments thereby minimizing environmental pollution from chemicals (Ade-Omowaye et al. 2001). The use of HPT (100–200 MPa, 10–20 min) as an alternative pretreatment in place of blanching resulted in producing frozen bell peppers with better nutritional (ascorbic acid) and texture (firmness) characteristics (Fig. 2.23, Castro et al. 2008).

2.2.16 Potatoes and Sweet Potatoes

High pressure (400 MPa, 15 min) in combination with citric acid (0.5 wt%) was shown as an alternative to hot water blanching. The treatment resulted in complete inactivation of PPO and reduction in microbial count by 4 log cycles (Eshtiaghi and Knorr 1993). HP-blached samples resulted in a significant increase in drying rates due to cell permeabilization by HPT (Eshtiaghi et al. 1994). HPT enhanced the rate of dehydration of potato during osmotic dehydration (Rastogi et al. 2000b,c). The variation in cell disintegration index (Z_p) of pressure-treated (200 and 400 MPa) and untreated potato samples with distance from the center of the material for different dehydration times indicated that the dehydration front moved faster within the pressure-treated sample (Fig. 2.24, Rastogi et al. 2003). Similarly, Sopanangkul et al. (2002) demonstrated the acceleration of osmotic dehydration of potato due to application of HPT up to 400 MPa. Further increase in pressure resulted in starch gelatinization leading to hindered diffusion. Yucel et al. (2010) indicated that high-pressure pretreatment (100–300 MPa) of carrots, green beans, and apple also resulted in higher drying rates during dehydration.

Abe et al. (2011) studied the effect of pretreatments such as heat treatment (100 °C, 5 min), heat treatment after HPT (200 MPa, 5 min), and HPT after heat treatment prior to drying of sweet potato on the rate of rehydration and quality. No significant difference in the color parameters or gelatinization rates of rehydrated sweet potato exposed to the three different pretreatments was observed. Heat treatment after HPT prior to drying was shown as an effective method for texture improvement.

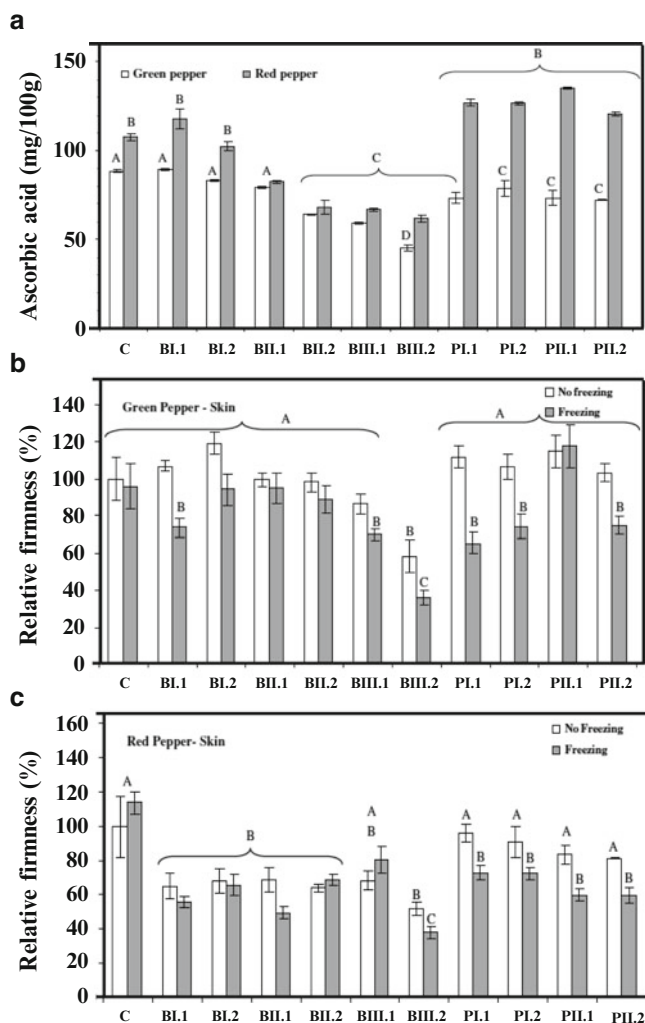
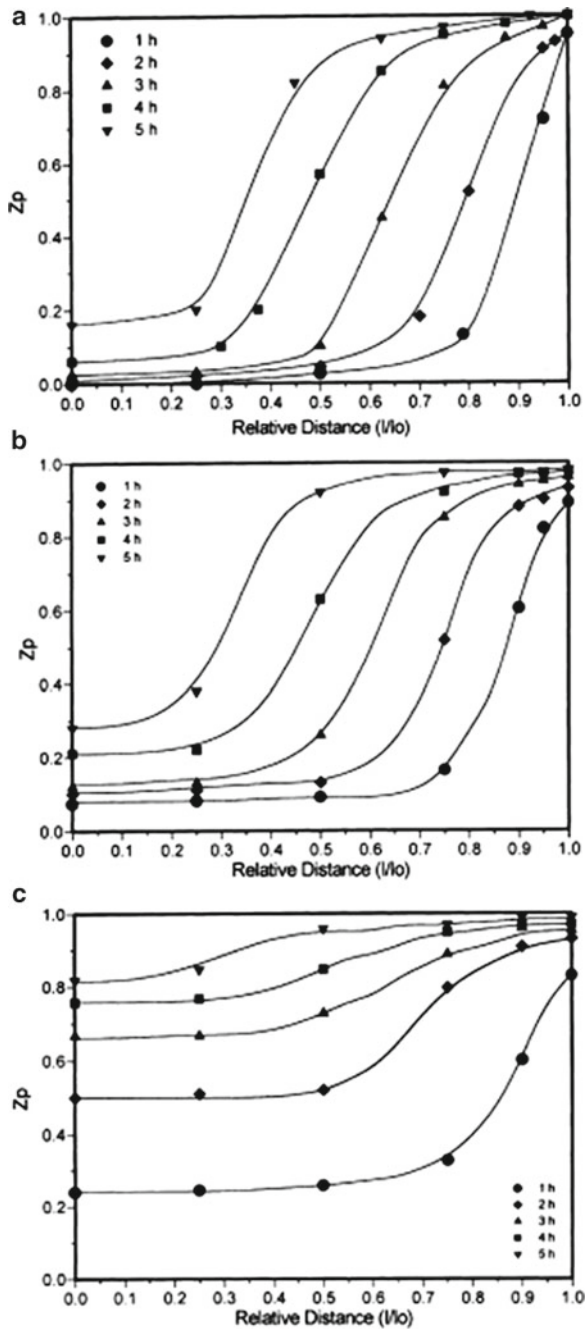


Fig. 2.23 Effect of thermal blanching and pressure treatments (a) on ascorbic acid content, (b, c) on the firmness of bell peppers. Different letters indicate cases of major effects. *C* refers to unprocessed sample, *BI.1* and *BI.2* refer to blanching at 70 °C for 1 min and 2.5 min, respectively, *BII.1* and *BII.2* refer to blanching at 80 °C for 1 and 2.5 min, respectively, *BIII.1* and *BIII.2* refer to blanching at 98 °C for 1 and 2.5 min, respectively, *PI.1* and *PI.2* refer to pressurization at 100 MPa for 10 and 20 min, respectively, *PII.1* and *PII.2* refer to pressurization at 200 MPa for 10 and 20 min, respectively (From Castro, S. M., Saraiva, J.A., Lopes Da Silva, J. A. et al. 2008. *Food Chem.* 107: 1436–1449. With permission)

Pressure-shift-freezing (400 MPa) resulted in preservation of textural properties even after freezing due to reduced membrane damage (Luscher et al. 2005). Optimization of the high-pressure/low-temperature process (freezing and thawing) for whole potato resulted in better quality and safety, improvement in color, and reduction in drip loss during thawing (Benet et al. 2006).

Fig. 2.24 Distribution of cell disintegration index with respect to distance from the center of the potato samples (thickness 10 mm) during osmotic dehydration of: (a) control sample; (b) pressure pretreated at 200 MPa, and (c) 400 MPa for 10 min (Rastogi, N.K., Angersbach, A., and Knorr, D. 2000c. *J. Food Eng.* 45: 25–31. With permission)



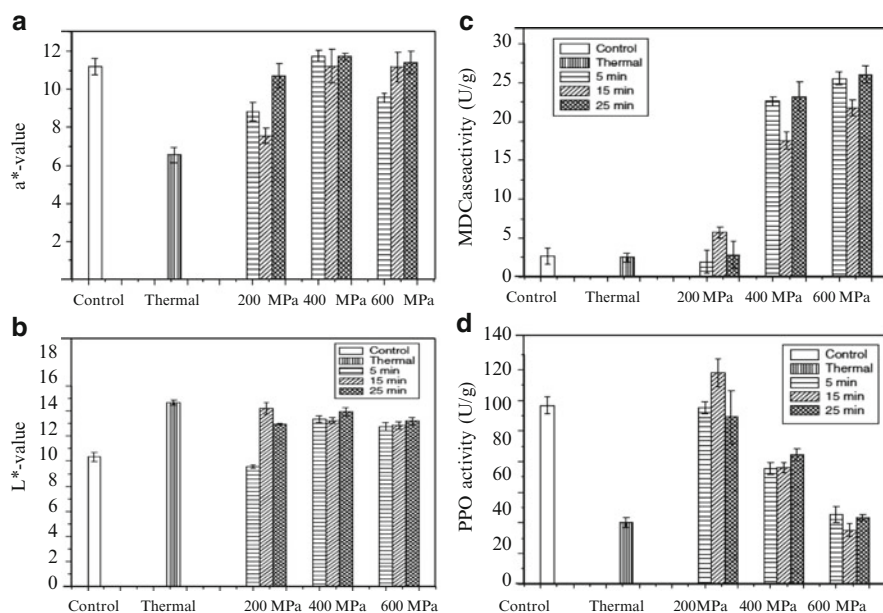


Fig. 2.25 Effects of high pressure on (a, b) instrumental color parameters, (c) MDCase activity, and (d) PPO activity of spinach puree (From Wang, R., Wang, T., Zheng, Q., Hu, X., Zhang, Y., Liao, X. 2012. *J. Sci. Food Agric.* 92: 1417–1423. With permission)

2.2.17 Spinach

HPT (400 MPa, 30 min, 5 °C) extensively effected the structure of spinach. The soft parenchyma cells of spinach leaves were completely destroyed by pressure treatment (Prestamo and Arroyo 1998), while the retention of visual green color and chlorophyll contents of HP-treated (200–600 MPa, 5–25 min) spinach puree was quite high. The activities of chlorophyllase (chlorophyll degradation enzyme) and PPO (responsible for enzymatic browning) were decreased by pressure treatment, while POD showed higher resistance to pressure. But the activity of Mg-dechelatase was dramatically increased after HPT (Fig. 2.25, Wang et al. 2012a, b).

2.2.18 Tomatoes

The exposure of whole cherry tomatoes to HPT up to 400 MPa resulted in decrease in hardness due to action of polygalacturonase (PG) enzyme, which hydrolyzed low methoxypectin to water-soluble galacturonic acid. Further, increase in pressure up to 500 or 600 MPa showed less decrease in hardness (or % cell rupture), and

tomatoes appeared similar to controls. The increase in firmness was attributed to the action of PME to produce low methoxypectin, which formed a gel network with divalent ions leading to tissue hardening (Tangwongchai et al. 2000). Kuo (2008) showed that HPT (200–500 MPa) of tomatoes retains color, extractable total carotenoids, lycopene content, and antioxidant activity. The residual activities of PME and PG were in the lower range of pressure (200 and 400 MPa for PME and PG, respectively), whereas these activities were higher for higher pressure (500 MPa). Viljanen et al. (2011) indicated that HPT (800 MPa, 20 °C) decreased the levels of certain volatiles, namely aldehydes, ketones, and alcohols present in tomatoes, whereas the levels of hexanal, heptanal, and octanal increased. Processing at 800 MPa and 60 °C could not preserve fresh tomato odor, but resulted in a marked increase in the intensity of cooked-tomato and tea-like odor.

Water-insoluble antioxidants, lycopene, and β -carotene did not change as a result of high pressure to tomato puree, but structural changes in tissue resulted in a decrease in recovery of carotenoids and increase in water-binding capacity. However, antioxidant levels of the water-soluble fraction increased after storage at 4 °C for 21 days (Fernandez et al. 2001b). HPT of tomatoes neither had a significant impact on β -carotene nor on antimutagenicity (Butz et al. 2002). High pressure (400 MPa) along with citric acid and NaCl are used for producing minimally processed tomato products with optimal sensory and microbiological characteristics, having resulted in 4-log reduction of total microbial counts along with a significant inactivation of PPO, POD, and PME (Plaza et al. 2003).

Sanchez et al. (2004, 2006) showed that HPT (200 MPa) affects the structure of cellular tomato matrix in such a way that various carotenes are released differently on the basis of their chemical features and chromoplast location. The treatment (400 MPa, 25 °C, 15 min) of tomato puree resulted in higher redness, carotenoids, and vitamin C than for the case of pasteurization at low temperature (70 °C, 30 s) or high temperature (90 °C, 1 min). McInerney et al. (2007) indicated that antioxidant capacity and total carotenoid content are not affected by HPT. Hsu et al. (2008) found that HPT (500 MPa) of tomato juice resulted in inactivation of microorganisms and pectolytic enzymes, improvement in the extractable carotenoids and lycopene contents, and retention of vitamin C compared with fresh juice.

Qiu et al. (2006) indicated that the highest stability of lycopene in tomato puree was obtained by HPT at 500 MPa and further storage at 4 °C. Varma et al. (2010) indicated that pressure can cause conformational change in lycopene from the all-trans to *cis* isomer form. HPT (320–620 MPa for 3 min) of lycopene isomers in both of the two systems tributyrin (model system) and tomato homogenate (real food system) showed an increase in *cis* isomer content compared to the control.

Krebbes et al. (2003) demonstrated that HPT (300–500 MPa, 20–90 °C) of tomato puree at ambient temperature is a suitable alternative to conventional processing techniques without causing marked losses in color and sensory properties at up to 8 weeks of storage at 4 °C. Rodrigo et al. (2007) found that combined thermal and HPT (300–700 MPa, 65 °C) did not result in visual color degradation of tomato puree. Dede et al. (2007) indicated that HPT (150–250 MPa) of tomato juices leads to higher retention of ascorbic acid, antioxidant activity, and minimum color loss at

up to 1 month of storage at 4 °C or 25 °C. Patras et al. (2009b) reported that high-pressure-processed (600 MPa) tomato puree results in retention of more than 90 % of ascorbic acid compared to thermally processed samples, but phenolic contents were unaffected by thermal or high-pressure treatments.

The combined pressure/temperature treatment was shown to be an attractive alternative to thermal sterilization for preserving tomato juice quality. Pressure-assisted thermal processing (600 MPa, 100 °C, 10 min) and HPT (700 MPa, 45 °C, 10 min) significantly improved the extractability of lycopene over thermal processing (100 °C, 35 min). Processed samples were stored at 4 °C, 25 °C, and 37 °C for up to 52 weeks. All-*trans* lycopene was found to be fairly stable to isomerization during processing, and the *cis* isomer content of the control and processed juice did not differ significantly (Gupta et al. 2010). Significant degradation of all-*trans* β -carotene occurred as a function of pressure, temperature, and time. Its retention in processed samples was found to vary between 60 and 95 %. The in-vitro bioaccessibility of carotenoids was not significantly different for all the treatments (Gupta et al. 2011).

2.2.19 Turnip

Ueno et al. (2009) reports that HPT (400 and 600 MPa) of turnips causes a unique green-blue color due to biochemical changes during storage for 7 days at 4 °C. The mechanism of green-blue compound formation apparently resulted from a biochemical pathway for green-blue pigment synthesis containing oxygen-dependent steps and possibly enzymatic reactions.

2.3 Other Plant Products

2.3.1 Aloe Vera

Galvez et al. (2011) indicated that high-pressure (300–500 MPa, 1–5 min), blanching, enzymatic, and microwave pretreatments increases the water diffusion coefficient compared to control samples during dehydration of Aloe vera gel. Microwaves followed by high pressure resulted in fastest drying rates and increased firmness. High pressure in combination with convective drying produced dried aloe with high antioxidant attributes. Further, Galvez et al. (2012) found that HPT (400 and 500 MPa) leads to undetectable levels of microorganism counts and higher antioxidant activities, as well as vitamin C and E levels. Navarrete et al. (2012) reported that HPT (300–500 MPa) of Aloe vera suspension during storage at 4 °C exhibits shear-thinning behavior. The treatment did not modify gel properties, but influenced the rheological properties.

2.3.2 Green Tea

High pressure extraction appears to have a great potential for extracting caffeine from green tea leaves. A comparison of ambient temperature extraction, ultrasonic extraction, and heat reflux extraction showed that high-pressure-assisted extraction resulted in higher yields, shorter extraction times, and lower energy consumption. The highest yield of caffeine (4.0 %) was obtained at 50 % ethanol concentration, liquid/solid ratio of 20:1, and 500 MPa pressure applied for 1 min (Fig 2.26a, b, Jun 2009). Later, Jun et al. (2011a) indicated that total phenolic contents and the antioxidant activities increase with an increase in applied pressure up to 450 MPa (Fig 2.26c). Further, Jun et al. (2011b), on examination of microstructure, revealed that high pressure could result in the disruption of leaf tissue, cellular walls, membranes, and organelles leading to enhanced transfer of solvents into the leaf material and the soluble constituents (active compounds) into the solvents.

2.3.3 Herbs and Roots

Pennywort herb juice is a nutraceutical drink considered to provide health benefits. Therefore, to preserve all of its aroma and active components, a nonthermal process such as ultra-high pressure was found to be more appropriate than pasteurization and sterilization. In comparison with heated juices, high-pressure-treated samples retained more volatile compounds such as linalool and geraniol similar to those present in fresh juice, whereas some volatiles such as α -terpinene and ketones were apparently formed by thermal treatment (Apichartsrangkoon et al. 2009).

High pressure extraction of salidroside from the herb *Sedum (Rhodiola) sachalinensis* at room temperature showed higher efficiency (0.40 % in 3 min) as compared to that of ultrasonic extraction (0.29 % in 30 min) and reflux extraction (0.30 % in 120 min) (Bi et al. 2009).

Clariana et al. (2011a) studied the effects of combined pressure/temperature treatments (200–600 MPa, 20 °C and 40 °C) on the color, texture, antioxidant activity, and glucosinolate profile of fresh-cut swede roots (*Brassica napus* var. *napobrassica*) as an alternative to traditional blanching techniques. All the studied treatments resulted in a loss of hardness, water binding capacity, and loss of antioxidant capacity. The strongest alteration of texture was observed at 400 MPa, while 600 MPa better preserved the texture properties. Blanching caused less total color changes than HPT.

Application of combined high pressure and microwave extraction of ginsenosides from *Panax ginseng* resulted in higher yields than other extraction methods, including soxhlet extraction, ultrasound-assisted extraction, and heat reflux extraction. The technique not only took a shorter time but also afforded higher extraction yields of ginsenosides (Yutang et al. 2008). High-pressure extraction of fresh and red ginseng was found to be more effective than thermal extraction (Lee et al. 2011).

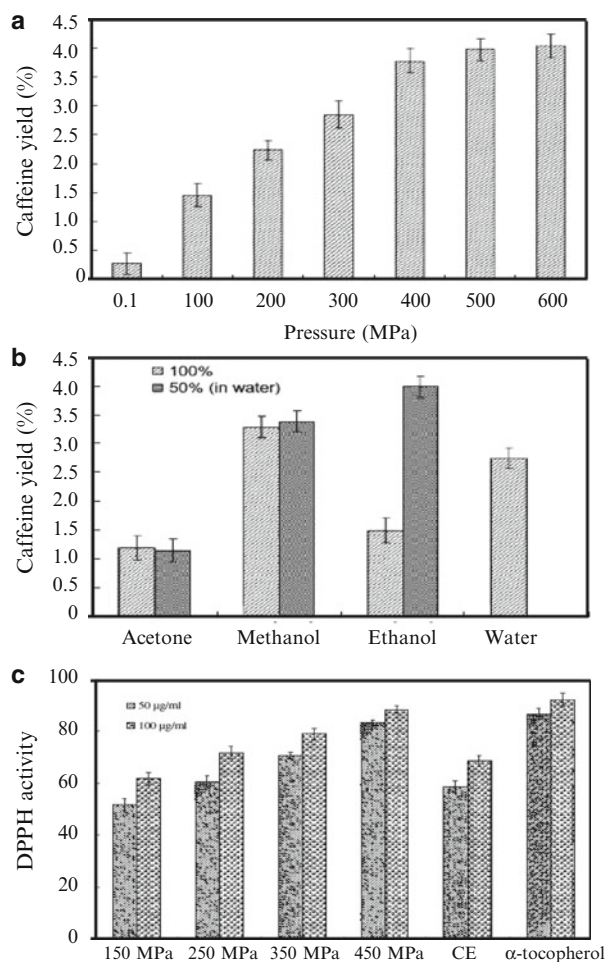


Fig. 2.26 Effect of (a) pressure, and (b) different solvents on the extraction yields of caffeine. (c) Comparison of DPPH activity of α -tocopherol and GTE collected by high-pressure extraction at two different concentrations (50 and 100 $\mu\text{g/ml}$). CE stands for conventional extraction (From Jun, X. 2009. *J. Food Eng.* 94(1): 105–109, Jun, X., Deji, S., Ye, L., Rui, Z. 2011a. *Food Res. Intl.* 44(9): 2783–2787. With permission)

2.3.4 Jam

Powdered sugar, pectin, citric acid, and freeze-concentrated strawberry juice was mixed, degassed, and then pressurized (400 MPa, 5 min) to form jam. The product had a bright red color and retained all the original flavor compounds (Watanabe et al. 1991). Kimura et al. (1994) have shown that pressure-treated jam had better

quality than heat-treated jam. The pressure-treated jam could be stored at refrigeration temperature up to 3 months. High-pressure-processed jam samples had better retention of anthocyanins (pelargonidin-3-rutinoside and pelargonidin-3-glucoside) (Gimenez et al. 2001). The increase in pectin concentration in high-pressure-processed (400 MPa, 5 min) strawberry jam resulted in increase in storage and loss moduli and decrease in absorbance intensity (Dervisi et al. 2001). A combined osmotic dehydration and HPT (550–700 MPa, 45–75 °C) process for grapefruit jam preservation resulted in only partial inactivation of PME and POD due to presence of pressure-stable fractions. The antioxidant capacity was not affected by the treatment (Igual et al. 2013).

2.3.5 Smoothies

Fruit smoothies have become popular with consumers and may significantly contribute to daily antioxidant intakes. HPT can help retain antioxidants in fruit smoothies offering a unique selling point for processors.

Keenan et al. (2010) demonstrated that compared to HPT (450 MPa, 1–5 min), thermal treatment ($P_{70} \geq 10$ min) resulted in significant reductions in antioxidant activity and phenolic content. The redness of HPP smoothies increased compared to the fresh one. Storage also had a significant effect on color variables but the effect was more pronounced in high-pressure-treated samples stored for 30 days. Keenan et al. (2012) compared thermally ($P_{70} \geq 10$ min) or high-pressure-processed (450 MPa/20 °C/5 min or 600 MPa/20 °C/10 min) fruit smoothie samples over a storage period of 10 h at 4 °C. The levels of total antioxidant, phenols, and anthocyanin content for the sample processed at 450 MPa were higher compared to the sample processed at 600 MPa. Ascorbic acid content degraded over the storage for all smoothies (Fig 2.27). Keenan et al. (2011) indicated that HPT (450 MPa) for 1 and 2 min resulted in higher levels of phenolic compounds (procyanidin B1 and hesperidin) than the sample processed for 5 min. Levels of flavanones and hydroxycinnamic acid were found to decrease after 30 days of storage at 2–4 °C.

2.3.6 Vegetable Beverages

The results indicated that the Mediterranean vegetable soup *gazpacho* subjected to treatment at 150 MPa led to better retention of carotenoids and antioxidative activity as compared to treatment at 300 MPa when stored at 4 °C for 40 days (Plaza et al. 2006b). Barba et al. (2010) indicated that HPT (100-MPa, 120–540 s) of vegetable beverage containing tomato, green pepper, green celery, onion, carrot, lemon, and olive oil retained more ascorbic acid compared to thermal treatment (90–98 °C, 15–21 s), whereas, color changes were less and no marked changes in total phenols for pressurized beverage compared to thermally treated samples was observed.

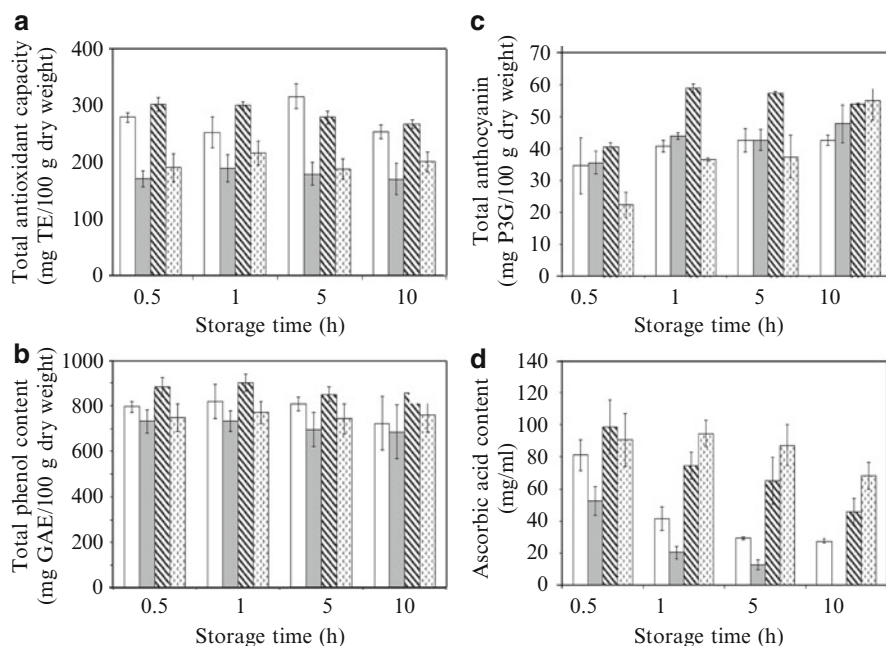


Fig. 2.27 (a) Antioxidant capacity, (b) phenolic content, (c) anthocyanin content, and (d) ascorbic acid content of fresh (□) fruit smoothies and their thermal (■) and 450 (▨) and 600 (▩) MPa high-pressure-treated counterparts over 10 h storage at 4 °C (Keenan, D.F., Roszle, C., Gormley, R., Butler, F., Brunton, N.P. 2012. *Lebensm. Wiss. Technol.* 45(1): 50–57. With permission)

Zhao et al. (2012) demonstrated that nisin (100 IU/ml) with HPT (400 MPa/4 min or 500 MPa/2 min) or thermal pasteurization (85 °C/15 s) had a synergistic effect on the inactivation of total aerobic bacteria. The retention of the quality attributes namely chlorophyll a and b, color, lipoxygenase activity, and key odorants in cucumber juice drinks was significantly better in the high-pressure-treated samples than in the thermally pasteurized samples during 50 days of storage at 4 °C. Besides, yeast and molds were completely inactivated by all treatments. It was indicated that HPT could be used to establish safety criteria for the commercial production of high-quality cucumber juice beverages.

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