Chapter 4
Impact of High-Pressure Processing on Food Quality

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4.1 Introduction

High-Pressure Processing (HPP) application is increasing at food industries as a possible alternative to heat treatments for food preservation and processing. It is being mainly applied to inactivate microorganisms and enzymes, with lower degradation of flavors and nutrients, minimizing the losses of beneficial ingredients, resulting in distinctive organoleptic properties of foods (Huppertz, Kelly, & Fox, 2002; Pasha, Saeed, Sultan, Khan, & Rohi, 2014). Since HPP acts on volume compression, due to the low change in volume on low-molecular compounds, such as vitamins and other functional compounds, the effects of this technology are expected to be minimum on these compounds unlike thermal treatment (Wang, Huang, Hsu, & Yang, 2016). Alike, HPP has also a lower effect on flavor and color compounds of food products, compared to the color changes and formation of off-flavors caused by thermal pasteurization (Wang, Huang, et al. 2016).

As the overall nutritional properties of foods can be better preserved by HPP, food texture can also be better maintained by this technology, affecting to a lesser extent the quality and acceptance of the products by the consumer, unlike thermal treatments that are more prone to affect texture and structure (i.e., due to loss of instrumental firmness by membrane disruption on vegetable/fruit products).

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Thus, in this chapter, HPP application on different food products will be addressed, i.e., fruits, vegetables, fish and meat products, milk and cheese, and its effects on the nutritional, textural and sensorial properties will be discussed. In each sub-section, tables are presented to summarize the most important studies; being highlighted in the text the most pertinent results therein.

4.2 Advantageous and Challenges of Using High-Pressure Processing on Food Quality

4.2.1 Nutritional Properties

4.2.1.1 Fruits and Vegetables

Fruits

Fruit is normally associated with great nutritional properties due to its high content of vitamins, carotenoids or polyphenols. HPP has appeared as a promising tool to process fruit products retaining most of its nutrients. For instance, both ascorbic acid (Tewari, Sehrawat, Nema, & Kaur, 2017) and phenolic compounds (Zhao, Zhang, & Zhang, 2017) have been shown to present higher stability after HPP and during storage of many fruit products, comparatively to those processed by traditional heat treatments. It is generally accepted that HPP has small effects on low molecular weight compounds such as vitamins C. In general, vitamin C is unaffected by HPP as most studies reported a retention above 80% after processing (Barrett & Lloyd, 2012), which can be maintained during 1–3 months at refrigerated storage (Tewari et al., 2017). For example, pressures between 350 and 600 MPa almost did not affect the vitamin C content of strawberry, blackberry (Patras, Brunton, Da Pieve, & Butler, 2009), tomato purées (Patras, Brunton, Da Pieve, Butler, & Downey, 2009), and orange juice (Sánchez-Moreno, Plaza, De Ancos, & Cano, 2003). However, there are still some exceptions, particularly at more severe conditions, both after processing and during storage. For instance, Landl, Abadias, Sárraga, Viñas, and Picouet (2010) reported higher losses of vitamin C at 600 MPa comparatively to 400 MPa after processing, and Valdramidis et al. (2009) reported losses during storage up to 36 days. There may be several reasons for different degradation rates, such as type of cultivar (Wolbang, Fitos, & Treeby, 2008), packaging and storage conditions, oxygen present and enzymatic activity (Valdramidis et al., 2009), however the most probable reason is due to oxidation (Oey, Van der Plancken, Van Loey, & Hendrickx, 2008). There are fewer studies regarding other vitamins, mainly vitamin B group, which are very stable under pressure and no major losses are reported after HPP (Barrett & Lloyd, 2012).

Similar to vitamins, carotenoids in fruits are not much affected by HPP and sometimes their availability even increases most likely due to the rupture of the cells of the fruit and leaking its content to the extracellular medium (Chen et al., 2013;

Sánchez-Moreno, de Ancos, Plaza, Elez-Martínez, & Cano, 2009). This effect was reported in several fruit products, for instance in tomato purée (600 MPa/15 min) (Patras, Brunton, Da Pieve, Butler, & Downey, 2009) and orange juice (400 MPa/1 min) (Plaza et al., 2011). In another study, Sánchez-Moreno et al. (2005) reported an increase in the availability of both total and individual carotenoids (β-cryptoxanthin, zeaxanthin, lutein, β-carotene and α-carotene). Nonetheless, there are some few contradictory results, such as those reported by Gupta, Kopec, Schwartz, and Balasubramaniam (2011), where a decrease of 25% in the availability of carotenoids in tomato juice after HPP was reported.

Similarly to vitamins and carotenoids, phenolic compounds on fruit products are minimally affected by HPP (Marszałek, Woźniak, Kruszewski, & Skąpska, 2017; Zhao et al., 2017). For instance, Chen et al. (2013) found that the availability of total phenols present in pomegranate juice increased after HPP, however the content of anthocyanins decreased from 68.54 mg/100 g before processing to 61.11 mg/100 g after processing. However, the impact was smaller than the traditional thermal processing, which decreased the content of anthocyanins to 59.51 mg/100 g of pomegranate juice. Similar results were obtained by Patras, Brunton, Da Pieve, and Butler (2009) in blackberry and strawberry purées. The authors reported an increase in the total phenols with increasing pressure (400–500 MPa) and an increase in anthocyanins at different HPP conditions except in the strawberry purée samples treated at 400 MPa. Overall, the general nutritional content of fruit-based products is well preserved by HPP and, in some cases, even improved.

Vegetables

HPP is mainly used to inactivate microorganisms and enzymes without degrading flavors/nutrients and minimizing the losses of beneficial ingredients in fruit and vegetable commodities (Pasha et al., 2014). Since HPP acts on volume compression, due to the low change in volume on low-molecular compounds, such as vitamins and functional content, the effects of this technology are expected to be minimum in these compounds (Wang, Huang, et al. 2016). The secondary metabolites produced by horticultural crops when they are subjected to environmental stresses are commonly known as bioactive compounds due to their health-promoting properties (Jacobo-Velázquez et al., 2017). When these stresses are applied during the postharvest phase, the biosynthesis and accumulation of these compounds can be enhanced by using HPP treatment (Dörnenburg & Knorr, 1998). HPP can also act as an extraction technique, enhancing the extractability of important compounds. For example, Paciulli, Medina-Meza, Chiavaro, and Barbosa-Cánovas (2016) have demonstrated that HPP applied at 650 MPa and room temperature (Table 4.1) can effectively increase the content of total phenolic compounds of beetroot, obtaining higher yields after longer extraction times (from 3 to 30 min), when compared to the raw vegetable. Similar results were obtained for red sweet pepper, another example of a nutritious food, being demonstrated that high pressures (above 500 MPa) can enhance the extractability of fiber (Hernández-Carrión et al., 2014). Analogous

Table 4.1 Examples of the main effects of HPP on the nutritional properties of vegetables

Vegetable products	HPP conditions	Nutritional effects	Reference
Beetroot slices	650 MPa/3–30 min/RT	Good retention of ascorbic acid after HPP when compared to thermal treatment. Higher extractability of total phenolic compounds after HPP treatment	Paciulli et al. (2016)
Spinach leaves	100, 250, 500, and 600 MPa/5 min/RT	HPP maintained the content of chlorophylls *a* and *b*	Wang, Ding et al. (2016)
Spinach, parsley, dill, kale	200, 400, 600 MPa/5, 10, 40 min/RT	HPP did not reduce the content in xanthophylls and chlorophylls; HPP allowed a higher extractability of these compounds in spinach purée	Arnold, Schwarzenbolz, and Böhm (2014)
Carrot, tomato, red pepper, broccoli, spinach, green pepper	625 MPa/5 min HPP: 20 °C HPHT: 70, 117 °C	While HPP treatment did not cause degradation on carotenoids and chlorophylls, HPHT process led to both chlorophylls' degradation	Sánchez, Baranda, and Martínez de Marañón (2014)
Onion, potato, pumpkin, red beet	600 MPa/15 min/117 °C	HPHT seems to reduce the formation of Maillard reaction and Strecker degradation products and enhance oxidative reaction products	Kebede et al. (2014)
Red sweet pepper	100–500 MPa/15 min/RT	Higher extractability of dietary fiber after HPP treatment at 500 MPa	Hernández-Carrión, Hernando, and Quiles (2014)
Carrot and spinach	100–500 MPa/20 min/20 °C	Good retention of ascorbic acid after HPP when compared to thermal treatment for both vegetables. Higher extractability of total phenols and flavonoids after HPP treatment	Jung, Lee, Kim, and Ahn (2013)

results were found after HPP treatment of carrot and spinach (Jung et al., 2013) since the total phenolic contents and flavonoids were the highest in HPP treated samples at 500 MPa, followed by thermal processing and HPP treated samples at 300 MPa, respectively. Total phenol and flavonoid contents were enhanced by increasing the pressure levels, which may be due to the enhanced membrane permeability (Jung et al., 2013).

Chlorophylls and chlorophyll-protein complexes are key factor quality in vegetable products. Wang, Ding, Hu, Liao, and Zhang (2016) showed that HPP under 100, 250 and 500 MPa (for 5 min at room temperature) allowed better retention of chlorophylls *a* and *b* of spinach leaves (Table 4.1), and the treatment at 100 MPa was reported to be most effective. Contrasting results were obtained for the thermal-treated samples at 100 °C for 60 s, where was found a significant ($p < 0.05$) decrease of the chlorophylls content, since the high temperature induced the disruption of the thylakoid membrane, while HPP was able to maintain a compact and stacked structure, similar to the untreated samples (Wang, Ding et al. 2016). Similar results were found by Arnold et al. (2014) who studied the effect of HPP at 200, 400, and 600 MPa, for 5, 10, and 40 min at room temperature on the bioactive compounds of spinach, parsley, dill, and kale (Table 4.1), and concluded that HPP maintained the concentration of xanthophylls (e.g. lutein and zeaxanthin) and carotenoids, compared to the samples subjected to heat for 5–20 min at 121 °C. In addition, HPP led to a significant higher extractability of these compounds regardless of the pressure level or the holding time, when compared to untreated spinach purée (Arnold et al., 2014).

Ascorbic acid is known for being easily degraded at high temperatures. After thermal treatment of carrot and spinach, it was found a decrease of 15% and 24% of ascorbic acid compared to the controls, respectively (Jung et al., 2013). Nevertheless, when the samples were treated by HPP (100–500 MPa, 20 min, 20 °C), good retention of ascorbic acid was reported when compared to the thermal treatment and control for both samples (Jung et al., 2013). Similar results were obtained by Paciulli et al. (2016), who reported better retention of ascorbic acid using HPP (650 MPa at room temperature) compared to thermal blanching.

4.2.1.2 Meat Products

Fish and Fish-Based Products

Fish has high nutritional value, especially high biological value proteins and lipids, being marketed and consumed worldwide. Additionally, fatty fish has a high concentration of n-3 fatty acids, which is often recognized by consumers as beneficial for human health (Ruxton, Calder, Reed, & Simpson, 2005). The effects of HPP on the fatty acid profile of HPP-treated fish were evaluated and no changes in the composition of this lipid fraction in turbot (Chevalier, Le Bail, & Ghoul, 2001) and coho salmon muscles (Ortea, Rodríguez, Tabilo-Munizaga, Pérez-Won, & Aubourg, 2010) were reported (Table 4.2). In another study, salmon processed by pressure resulted in the stable saturated, monounsaturated and polyunsaturated fatty acids, only with a decrease of n-6 fatty acids in samples treated at 300 MPa/15 min and consequent reduction of the n-6/n-3 ratio (Yagiz et al., 2009). On the other hand, Sequeira-Munoz et al. (2006) reported an increase of the free fatty acids content in carp muscle when compared to the untreated samples, using a pressure level between 140 and 200 MPa (for 15–30 min at 4 °C). In contrast, the formation of free fatty acids after processing was reduced at 150–450 MPa at 20 °C for 0–5 min (Aubourg et al., 2013). Furthermore, HPP seems to not induce any effect on lipase enzyme, being observed a similar activity to untreated samples in most of the HPP-treated samples (Teixeira et al., 2013).

Table 4.2 Some publications with the main effects of HPP on free fatty acids of fish

Fish products	HPP conditions	Nutritional effects	Reference
Atlantic salmon	150 and 300 MPa/ 15 min/room temperature	Stable total saturated, monounsaturated, and n-3 and n-6 polyunsaturated fatty acids profiles	Yagiz et al. (2009)
Carp	140–200 MPa/ 15–30 min/4 °C	Increase in free fatty acids levels	Sequeira-Munoz, Chevalier, LeBail, Ramaswamy, and Simpson (2006)
Coho salmon	135–200 MPa/ 30 s/15 °C	No significant changes	Ortea et al. (2010)
Mackerel	150–450 MPa/ 0–5 min/20 °C	Reduction of the formation of free fatty acids	Aubourg, Torres, Saraiva, Guerra-Rodríguez, and Vázquez (2013)
Turbot	100–200 MPa/ 15–30 min/4 °C	No significant changes	Chevalier et al. (2001)

Medina-Meza, Barnaba, and Barbosa-Cánovas (2014) observed a stronger catalytic oxidation power using pressure levels up to 300 MPa, although higher oxidation levels were observed in other studies at lower pressures between 150 and 300 MPa (Amanatidou et al., 2000; Lakshmanan, Patterson, & Piggott, 2005; Sequeira-Munoz et al., 2006; Teixeira et al., 2014). However, the effects of HPP on lipid oxidation of fish muscles also varied significantly depending on many factors, such as applied pressure level/pressure holding time, fish species and the type of muscle (dark or white). For example, a treatment lower than 400 MPa for 20 min at room temperature showed a slight effect on lipid oxidation in cod muscle compared to untreated muscle (Angsupanich & Ledward, 1998), whereas carp and turbot muscles were more susceptible to lipid oxidation after HPP-treatment of 100 MPa for 30 min at 4 °C (Sequeira-Munoz et al., 2006) and 100 MPa for 15 min at 4 °C (Chevalier et al., 2001), respectively.

There are a few research studies evaluating the cholesterol oxide formation in fish after HPP treatment. Although the cholesterol concentration did not change in mackerel and herring muscles after HPP treatment at 600 MPa for 10 min, higher cholesterol oxidation was observed in mackerel muscles (Figueirêdo, Bragagnolo, Skibsted, & Orlien, 2015). The cholesterol oxidation might be due to the breakage of cell structures and exposure of phospholipids membrane (Medina-Meza et al., 2014).

Meat and Meat-Based Products

HPP has been described as a powerful tool for the development of new/improved food products (Huang, Wu, Lu, Shyu, & Wang, 2017). However, some issues have been found on fresh meat products when processed by high pressure. One of the concerns, behind color losses, is the possible nutritional value decrease of the products processed by this technology.

It is known that a pressure level between 300 and 600 MPa led to the lipid oxidation of several meat products, being its lipid content and fatty acid composition of phospholipids and free fatty acids modified (Sazonova, Galoburda, & Gramatina, 2017). As the minimization of saturated fat intake with a concomitant increase of polyunsaturated fats is currently recommended, the oxidation of the unsaturated fatty acids may lead to a decrease in the nutritional value of the product (Ma & Ledward, 2004). Thus, some researchers have applied antioxidant active packaging and/or used different antioxidants to inhibit lipid oxidation (Sazonova et al., 2017).

Several studies have reported the possible fresh meat nutritional changes promoted by HPP and the oxidation process. In fact, in McArdle, Marcos, Kerry, and Mullen (2010) work, some differences were observed in specific fatty acids of bovine (*M. pectoralis profundus*) meat, not being found an overall HPP effect on polyunsaturated/saturated fatty acids (PUFA/SFA) or omega 6/omega 3 (n-6/n-3) ratio; however, the processing temperature influenced the sum of SFA, monounsaturated (MUFA) and PUFA fatty acids, being 40 °C the processing temperature that led to a higher SFA and PUFA and lower MUFA compared to HPP at 20 °C.

Nonetheless, in He et al. (2012) work, the authors found that a pressure level above 350 MPa in pork muscle caused marked lipolysis of the intramuscular phospholipids with a corresponding increase in free fatty acids. Over storage (at 4 °C) on HPP samples (350 and 500 MPa), the phospholipid breakdown increased with time with an increase of the free fatty acids and TBAR values. Thus, when the fatty acid composition of phospholipids was studied it was verified that SFA and MUFA increased with time, the result of palmitic and oleic acid contents while the PUFA content decreased, mainly due to losses of linoleic, linolenic and arachidonic acids (He et al., 2012). In what concerns HPP effect on fatty acid composition of intramuscular total lipids, some minor but not significant differences in fatty acid composition were observed between non-treated and treated samples, and for fatty acid composition of triglycerides, no significant differences in the percentage of every single fatty acid or SFA, MUFA and PUFA between non-treated and pressurized samples were observed, with the exception of linoleic acid (C18:2) (He et al., 2012). In another study performed by Wang et al. (2013), a loss of PUFA on HPP samples of yak body fat was detected, resulting in less favorable fatty acid profiles over storage. In this case, cold storage (20 days) of samples treated at 400 and 600 MPa led to an increase of TBAR values and a decrease in the sensory quality with a decrease in the PUFA/SFA and n-6/n-3 ratios.

In what concerns ultrastructure and *in vitro* protein digestion, Kaur et al. (2016) studied it on bovine *longissimus dorsi* muscle meat and verified that HPP meats (pepsin-digested, 60 min) presented fewer proteins or peptides of high molecular weight than on untreated meat, probably due to the breakdown proteins, mainly at 600 MPa pressure.

Nonetheless, some concerns regarding migration of compounds from plastic packages into the meat product have been addressed since HPP is applied to the final product already packaged. As an example, the study of Rivas-Cañedo, Fernández-García, and Nuñez (2009) allowed to observe both HPP and plastic packaging material effects on fresh meats, being concluded that as most of the compounds in the plastic were lipophilic, the migration of compounds into the meat could occur, being potentially harmful for the human health. In Table 4.3 are listed some works where the HPP effect on meat-based products was studied concerning its nutritional properties.

4.2.1.3 Dairy Products

Milk

High-pressure processing (HPP), as a cold alternative process to thermal pasteurization, has been applied in dairy food with mainly the advantage of shelf-life extension (2–3 times) relativity to non-pasteurized products (Dhineshkumar, Ramasamy, & Siddharth, 2016).

In dairy food, HPP has been applied in milk, fresh cheese, ripened cheese, whey cheese, yogurt, ice cream, and butter. However, the application on milk for subsequent cheese making and the application directly to the pressed curd and/or during cheese ripening have been the main areas in a study conducted by Martínez-Rodríguez et al. (2012). The effects of HPP are related to the pressure intensity, the holding time under pressure and the ripening stage when applied in cheese.

Table 4.3 Examples of HPP effects on the nutritional properties of different meat-based products

Meat products	HPP conditions	Nutritional effects	Reference
Cooked ham	100, 300 and 600 MPa/ 5 min/RT	45% salt reduction on cooked ham (salt content reduced to a level of 1.1% NaCl by the replacement of 0.2% of NaCl with KCl and combined HPP at 100 MPa after tumbling)	Tamm, Bolumar, Bajovic, and Toepfl (2016)
Serrano ham	600 MPa/6 min/21 °C	Only 8 volatile compounds presented to be HPP affected (higher levels of methanethiol and sulfur dioxide in HPP-treated samples and higher levels of ethyl acetate, ethyl butanoate, ethyl 2-methylbutanoate, ethyl 3-methylbutanoate, dimethyl disulfide and dimethyl trisulfide in untreated samples)	Martínez-Onandi et al. (2017)
Sliced skin vacuum packed dry-cured ham	600 MPa/6 min/15–32 °C	HPP did not produce changes in fatty acids content, protein content nor antioxidant enzyme activities HPP did not inhibit lipases and phospholipases action over storage (50 days with light) since treated and non-treated samples presented losses of fatty acids from phospholipid fraction while fatty acids increased from the free fatty acid fraction	Clariana et al. (2011)

The use of HPP in the food industry has been of great interest as a possible alternative to heat treatments for food preservation and processing. HPP eliminates or reduces the use of heating, and so avoiding thermal degradation of food components, and the retention of natural flavors, colors, and nutritional value (Huppertz et al., 2002). HPP has been applied to various food products, and several studies have been conducted for better knowledge on dairy foods, such as milk, cheese and yogurt (Ye, Anema, & Singh, 2004).

It has been reported that, among other effects, the application of high pressures to milk reduces its light-scattering properties, leading to a change in its appearance, and this was attributed to casein micelles disintegration into smaller structures (López-Fandiño, Fuente, Ramos, & Olano, 1998). In this study where bovine, caprine and ewe's milk were processed using 100–400 MPa for 5–30 min (Table 4.4),

Table 4.4 Examples of the main effects of HPP on the nutritional properties of milk

Dairy products	HPP conditions	Nutritional properties	Reference
Milk (bovine)	100, 200, 300 and 400 MPa/5–30 min/20 °C	Ca, P and Mg solubilization increased with pressurization up to 300 MPa, and then decreased slightly to 400 MPa. Maximum micelle dissociation was observed in milk treated at 300 MPa	López-Fandiño et al. (1998)
Milk (ovine)	100, 200, 300 and 400 MPa/5–30 min/20 °C	Soluble Ca, P and Mg increased with pressure but were smaller than those found in bovine milk. Milk dissociation increased with pressure up to 400 MPa	
Milk (caprine)	100, 200, 300 and 400 MPa/5–30 min/20 °C	Soluble Ca, P and Mg increment were more pronounced than those in the milk from the other two species. Micelle dissociation was observed at a maximum at 300 MPa	
Milk (bovine)	100–800 MPa/Up to 60 min/20 °C	A slight increase in fat globule size was observed with increasing pressure up to 700 MPa Association of β-LG with the milk fat globule occurred at pressures >100 MPa, while associations of α-LA and κ-casein occurred only at pressures ≥700 and 500 MPa, respectively	Ye et al. (2004)
Milk (ovine)	100–500 MPa/10 and 30 min/25 and 50 °C	Pressurization showed a tendency to increase milk fat globules in the range 1–2 μm	Gervilla, Ferragut, and Guamis (2001)
Milk (human)	400, 500, and 600 MPa/5 min/12 °C	HPP allowed better maintenance of the vitamin C and the same levels of preservation of fatty acid proportions and tocopherols when compared to thermal pasteurization	Moltó-Puigmartí, Permanyer, Castellote, and López-Sabater (2011)

the release of micellar Ca, P, and Mg into the serum was observed (López-Fandiño et al., 1998). Changes in the content of soluble Ca, P, and Mg were more pronounced in ewe's milk processed by HP when compared to bovine and caprine milk. Unlike bovine and caprine milk, pressurization at 400 MPa increased the levels of these three elements in the serum over the treatment at 300 MPa. In the case of bovine and caprine milk, solubilization increased with pressurization up to 300 MPa and then decreased slightly to 400 MPa. This can be related to micelle dissociation, since in the case of bovine and caprine milk, maximum dissociation from the micelle was found in milk treated at 300 MPa, while in ewes' milk, dissociation increased with pressure up to 400 MPa (López-Fandiño et al., 1998). Ye et al. (2004) observed that, in general, micelle size is not affected by treatments at 100 or 200 MPa for 20 min at 20 °C, while treatment at 250 MPa increases micellar size by 20%, and higher pressures (300–800 MPa) decrease it by 50%. The associations of α-LA and κ-casein occurred at pressures ≥700 MPa and 500 MPa, respectively, but the amounts are lower than that observed for β-LG. *α*-LA has a more rigid molecular structure, being much more resistant than β-LG to denaturation during high-pressure treatment.

Moltó-Puigmartí et al. (2011) suggested the possibility to process human milk using HPP, since fatty acid proportions in milk, δ-, γ-, and α-tocopherols, total vitamin C and ascorbic acid levels where preserved, while on the other hand, thermal pasteurization lead to a reduction in the nutritional content of human milk.

Fresh Cheese

Fresh cheese is a dairy product that has a short shelf life due to its pH near to neutral (no starter is added), high moisture and high-water activity (>0.99), which allows a fast growth of spoilage microorganisms. HPP could be a solution for minimal processing this highly nutritious and perishable food product while restraining microbial growth.

Overall, HPP resulted in fresh cheeses whey loss, which contributed to a reduction in moisture content (Table 4.5). For example, Evert-Arriagada et al. (2012) reported a reduction on microbial growth and no changes in fat and total protein contents or pH values, but significant whey loss occurred at 400 MPa for 5 min. Similar results were observed by the same authors using a higher pressure (500 MPa for 5 min), with a significant increase ($p < 0.05$) in whey loss from day 14 and the highest measure of free whey at day 21, with the highest amount of total solids observed at the same sampling day (Evert-Arriagada et al., 2014). On the other hand, Okpala et al. (2010) reported that moisture content did not vary from treatments using pressure up to 150 MPa, but dropped more when the pressure increased over 150 MPa.

Table 4.5 Examples of the main effects of HPP on the nutritional properties of fresh cheese

Dairy products	HPP conditions	Nutritional properties	References
Fresh Cheese (cow)	200, 400, and 600 MPa/3–20 min/20 and 40 °C	A small decrease in the protein content HPP resulted in moisture content reduction, as pressure increased (up to 2%)	Van Hekken, Tunick, Farkye, and Tomasula (2013)
Fresh Cheese (cow)	500 MPa/5 min/16 °C	The total solids content increased ($p < 0.05$) within the last 7 days of storage for pressurized samples No statistical variations were observed on whey loss after pressurization	Evert-Arriagada, Hernández-Herrero, Guamis, and Trujillo (2014) and Van Hekken et al. (2013)
Fresh Cheese (cow)	400 MPa/20 min/20 °C	HP cheese presented pH values higher than the control cheese	Sandra, Stanford, and Goddik (2004)
Fresh Cheese (cow)	300 or 400 MPa/5 min/6 °C	The total solid content of HP cheeses was higher than control cheeses, with no changes on fat and total protein contents, or pH values Significant whey loss was observed on cheeses treated at 400 MPa	Evert-Arriagada, Hernández-Herrero, Juan, Guamis, and Trujillo (2012)
Fresh Cheese (cow)	9, 50, 150, 250, and 291 MPa/1, 5, 15, 25, and 29 min/25 °C	Treatments over 150 MPa resulted in a more significant reduction in moisture content, and an increment of fat content The protein content of HPP fresh cheese in all treatments remained lower than the control pH and TBA value (lipid oxidation) decreased with increasing pressure	Okpala, Piggott, and Schaschke (2010)
Fresh Cheese (goat)	500 MPa/5, 15 and 30 min/10 or 25 °C	Non-protein nitrogen of pressurized cheeses was lower than that of control cheeses Pressure-treated cheeses expelled significantly more whey than control cheeses	Capellas, Mor-Mur, Sendra, and Guamis (2001)

Cheese

HPP has been applied to cheese in order to increase the preservation and/or the modification of the ripening process (deceleration/acceleration) (Martínez-Rodríguez et al., 2012; O'Reilly, Kelly, Murphy, & Beresford, 2001; Trujillo, Capellas, Saldo, Gervilla, & Guamis, 2002). However, in any HPP application, it is important to analyze the effect on nutritional properties. As shown in Table 4.6, HPP may cause or not lower effect on moisture, protein and fat content when applied in cheese with some days of ripening (Calzada, del Olmo, Picon, Gaya, & Nuñez, 2014a; Delgado et al., 2012, 2015; Voigt et al., 2010). When the treatment was applied in cheese curd (Calzada, del Olmo, Picon, Gaya, et al., 2014b, c; Delgado et al., 2012; Saldo et al., 2002; Voigt et al., 2010), major differences in nutritional composition occurred after HPP and during its ripening. In cheese, a relevant nutritional property is a proteolysis, which indicates the age of the cheese. In general, some studies revealed proteolysis acceleration when cheeses were treated by HPP with few days of ripening (Garde et al., 2007; Saldo et al., 2003; Voigt et al., 2010). Other researchers observed a deceleration or same proteolytic indexes of ripened cheeses treated by HPP (Calzada, del Olmo, Picon, Gaya, & Nuñez, 2014a; Garde et al., 2007). The lipolysis of short-chain (SC-), medium chain (MC-) and long-chain free fatty acids (LC-FFA) showed no significant changes after HPP treatment (Calzada et al., 2015; Calzada, del Olmo, Picon, Gaya, et al., 2014c; Voigt et al., 2010).

4.2.2 Textural Properties

4.2.2.1 Fruits and Vegetables

Fruits

The texture of fruit products is of paramount importance for the consumer acceptability. In a general way, HPP may decrease the hardness and chewiness in fruits. An example is the work of Denoya, Vaudagna, and Polenta (2015) who studied vacuum packed fresh-cut peaches subjected to HPP (500 MPa/5 min/20 °C) and their texture profile, that was analyzed for hardness, cohesiveness, and chewiness. The authors reported a decrease in hardness and chewiness after HPP. Furthermore, according to Miguel-Pintado et al. (2013), the intensity of HPP is also significant in what concerns texture modification, since nectarine halves subjected to 200–300 MPa presented fewer firmness changes than those subjected to 600 MPa. Likewise, hardness was reduced in a number of fruits following HPP, such as persimmons (Vázquez-Gutiérrez, Quiles, Hernando, & Pérez-Munuera, 2011), pumpkin (Zhou et al., 2014), and strawberry (Gao et al., 2016). The observed changes in the textural properties reported in these studies are most likely the result of the effects of HPP on the microstructure of fruits, namely the destruction of cell walls

Table 4.6 Effect of HPP on nutritional properties of different cheeses

Dairy products	HPP conditions	Textural effects	Reference
Casar Cheese (raw ewe milk)	200 or 600 MPa/5 or 20 min/10 °C	Moisture content: HPP causing no changes (at 60 days of ripening)	Delgado, Rodríguez-Pinilla, Márquez, Roa, and Ramírez (2015)
Ibores Cheese (raw goat milk)	400 or 600 MPa/7 min/10 °C	Fat content: HPP causing no changes (at 2 and 31 days of ripening) Protein content: HPP causing no changes (at 2 and 31 days of ripening), except to HPP at 600 MPa/7 min treated cheeses (at 50 days of ripening) with lower content	Delgado, González-Crespo, Cava, and Ramírez (2012)
Garrotxa cheese (pasteurized goat milk)	400 MPa/5 min/14 °C	Moisture content: higher for HHP cheeses (at 4 days of ripening)	Saldo, McSweeney, Sendra, Kelly, and Guamis (2002)
		Proteolytic indexes: higher for HPP cheeses (at 4 days of ripening)	Saldo et al. (2003)
Brie cheese (pasteurized cow milk)	400 or 600 MPa/5 min/9–14 °C	Moisture content: did not vary immediately after HPP (at 21 days of ripening)	Calzada, del Olmo, Picon, Gaya, et al. (2014b)
		SC.FFA: higher on HPP MC- and LC-FFA: HPP cheeses showed equal content when treated at 14 days and higher content were treated at 21 days	Calzada, del Olmo, Picon, and Nuñez (2014c)
NA (raw cow milk)	400 or 600 MPa/5 min/14 °C	SC-, MC-, LC-FFA: HPP cheeses showed similar concentration to control cheeses (21 days or ripening)	Calzada, del Olmo, Picon, and Nuñez (2015)
La Serena (raw ewe milk)	300 or 400 MPa/10 min/10 °C	Proteolysis: higher when HHP treatments were applied at 400 MPa on d 2 compared to other treatments	Garde, Arqués, Gaya, Medina, and Nuñez (2007)
Irish blue-veined cheese	400 or 600 MPa/10 min/20 °C	Moisture, fat and protein content: small differences between HPP and control cheeses Proteolytic indexes: higher for HHP cheeses treated Lipolysis/FAA: no significant effect of HPP (at 42 days of ripening)	Voigt, Chevalier, Qian, and Kelly (2010)

and the dispersion of intracellular component throughout the tissue (Vázquez-Gutiérrez et al., 2011), as well as due to the activity of the pectin methylesterase, facilitated by the release of the cell-wall-bonded enzyme and the contact with its substrate, which causes the de-esterification of pectin thus changing the fruit texture (Basak & Ramaswamy, 1998). Therefore, it is expected a decrease in hardness during storage due to enzymatic and non-enzymatic depolymerization of pectins, as seen, for example, in the work of Gao et al. (2016), and Zhou et al. (2014), who reported a decrease in hardness after storage at 4 °C for 45 and 60 days, respectively. Still, HPP retains textural properties at acceptable levels.

Zhang et al. (2012) reported that the hardness of yellow peach was preserved by 69.5% after 3 months of refrigerated storage after HPP (600 MPa/5 min). Furthermore, HPP seems to better retain textural properties than thermal processing. Gao et al. (2016) described a higher hardness of the flesh of strawberries after HHP (400 MPa/5 min) than after thermal processing (75 °C/20 min). Similar results were described in yellow peaches, most likely due to the higher structural damages caused by thermal processing comparatively to HPP Zhang et al. (2012).

Vegetables

Food texture can change after processing and affect the quality and acceptance of the product by the consumer. Thermal treatment is known to affect vegetable texture and structure, mainly due to loss of instrumental firmness by membrane disruption.

After HPP treatment (650 MPa at room temperature, for 3–30 min) of beetroot, it was demonstrated that high pressure allowed maintaining the vegetable's cut hardness similar to the raw untreated samples after 30 min of processing (Paciulli et al. 2016). It was also noteworthy that after long processing times, a higher recovery of consistency was found compared to short-time processed samples, being these results explained by the possible tissue recovery during the holding time by fortification of intercellular adhesion, since formation of new ionic linkages occurs in cell wall pectic polysaccharides (Paciulli et al., 2016; Trejo Araya et al., 2007). Other parameters such as hardness, chewiness, and cohesiveness were studied, being the results consistent with the previous, since the samples pressurized for 15 and 30 min presented similar characteristics to the raw sample, while the beetroot processed for 3 and 7 min presented lower values (Paciulli et al., 2016). Similar results were presented by Hernández-Carrión et al. (2014) who showed that the higher the pressure used (100–500 MPa, for 15 min, at room temperature), the least impact on the microstructure was found on red sweet pepper tissue (Table 4.7).

Turgor is an important textural characteristic since it has a direct impact on the fresh appearance of the vegetables. The effect of HPP on cell turgor of red cabbage was studied by Rux et al. (2017) at pressures between 150 and 250 MPa, for 5–20 min, at 35–55 °C (Table 4.7). The main results focused on the fact that cell turgor can be recovered within hours if the pressure treatment was not too strong (150 MPa up to 10 min). Nonetheless, when the pressure level was above 175 MPa, and the temperature above 45 °C, the cells were irreversibly damaged (Rux et al., 2017).

Table 4.7 Examples of the main effects of HPP on the textural properties of vegetables

Vegetable products	HPP conditions	Textural effects	Reference
Red cabbage leaves	150–250 MPa/5–20 min/35–55 °C	Cell turgor affected by HPP above 150 MPa and temperature above 45 °C. Above these thresholds occur irreversible turgor losses	Rux, Schlüter, Geyer, and Herppich (2017)
Beetroot slices	650 MPa/3–30 min/RT	Higher cut hardness, recovery of consistency, chewiness, and cohesiveness for the samples treated by HPP for longer times (15 and 30 min)	Paciulli et al. (2016)
Asparagus spears	10–600 MPa/0.5–30 min/RT	HPP resulted in a decreased firmness	Yi et al. (2016)
Cocoyam, carrot, sweet potato	600 MPa/5, 30 min/RT	Reduced maximum cutting force and lower rigidity for HPP samples	de Oliveira, Tribst, Leite Júnior, de Oliveira, and Cristianini (de Oliveira, Tribst, Leite, de Oliveira, & Cristianini, 2015)
Red sweet pepper	100–500 MPa/15 min/RT	Low effect on cell's microstructure after HPP treatment at 500 MPa	Hernández-Carrión et al. (2014)

Contrasting results were reported by de Oliveira et al. (2015) after HPP processing of cocoyam, Peruvian carrot, and sweet potato. These authors reported that HPP has reduced the maximum cutting force and lower rigidity (up to 25%) compared to the control sample, when high pressures (600 MPa) and longer holding periods (up to 30 min) were used, being these results attributed to the partial starch gelatinization that occurs in these vegetables (de Oliveira et al., 2015).

4.2.2.2 Meat Products

Fish and Fish-Based Products

In fish texture profile analysis, the hardness, and springiness were mainly investigated, but cohesiveness, gumminess, adhesiveness, and chewiness were also studied. Table 4.8 presents some publications with the main results of the HPP application in fish texture.

An increase of muscle hardness was observed in HPP-treated cod (Montiel et al., 2012), trout and mahi-mahi (Yagiz et al., 2007), salmon (Yagiz et al., 2009), and tuna (Ramirez-Suarez & Morrissey, 2006). Despite HPP-treated sea bass (100 and 300 MPa for 5 min at 10 °C) exhibits lower hardness than the control, similar values were observed when the samples were subjected to 400 and 500 MPa for 5 min at 10 °C (Chéret et al., 2005).

Table 4.8 Some publications with the main effects of HPP on the texture properties of fish

Fish products	HPP conditions	Textural effects	Reference
Cod	400–600 MPa/5 and 10 min	The increase in hardness and shear strength	Montiel, De Alba, Bravo, Gaya, and Medina (2012)
Mahi mahi	150–600 MPa/ 15 min/RT	The lowest hardness was observed on control samples The increase of chewiness and gumminess with the increase of pressure	Yagiz, Kristinsson, Balaban, and Marshall (2007)
Rainbow trout	150–600 MPa/ 15 min/RT	The increase of hardness at 450 and 600 MPa, compared to 0.1 and 150 MPa The increase of cohesiveness after HPP	Yagiz et al. (2007)
Salmon	150 and 300 MPa/ 15 min	The increase of hardness, gumminess, and chewiness, and a decrease in adhesiveness	Yagiz et al. (2009)
	100–200 MPa/ 10–60 min/ 1 and 5 °C	The increase of cutting strength at 150 and 200 MPa for 30 min or 200 MPa for 60 min	Amanatidou et al. (2000)
Sea bass	100–500 MPa/5 min/10 °C	The decrease of hardness at 100–300 MPa, and no changes at 400 and 500 MPa No changes of cohesiveness, springiness, and resilience The decrease of gumminess and chewiness at 100–300 MPa and the increase at 400 and 500 MPa	Chéret, Chapleau, Delbarre-Ladrat, Verrez-Bagnis, and de Lamballerie (2005)
Tuna	275 and 310 MPa/ 2, 4 and 6 min	The increase of hardness with pressure and holding time increase	Ramirez-Suarez and Morrissey (2006)

Several possible explanations were suggested for the increase in fish muscles hardness under HPP. According to Angsupanich and Ledward (1998), the unfolding of actin and sarcoplasmic proteins and the formation of new hydrogen-bonded networks could contribute to the increase in hardness and springiness of pressurized fish muscles.

These changes in fish texture under HPP are linked with protein modifications, mainly the interactions between actin and myosin, the release of α-actinin, and the denaturation of myofibrillar proteins. Collagen is very stable at high pressure (Guyon, Meynier, & de Lamballerie, 2016).

Meat and Meat-Based Products

Although HPP could be an interesting food processing technology for food preservation, in what concerns to meat products it is capable to modify its properties, for instance, changing meat texture as a free-additive and physical process to tenderize and soften meat and meat products. In fact, although dependent on pressure level, temperature, pH, and ionic strength, HPP effect on sarcoplasmic proteins (mainly enzymes and heme pigments) can lead to the denaturation (mainly pressures above 200 MPa) promoting changes on water holding capacity, color, and myofibrillar proteins, being the latter's strongly related to the meat structure, and unfolded above 300 MPa (Marcos, Kerry, & Mullen, 2010; Sazonova et al., 2017; Sun & Holley, 2010). On the other hand, as the triple helix of collagen is predominantly stabilized by hydrogen bonds, it is expected to be inert to pressure in normal conditions, being this crucial for meat texture since connective tissue (mainly collagen) and contractile systems (mainly actomyosin) play an important role (Ma & Ledward, 2013).

Several studies have been carried out concerning the effect of HPP on meat texture, for instance, Morton et al. (2017) concluded that when two levels of pressure were applied (to *longissimus thoracis* (strip loin) steaks) within 1 h of slaughter and chilled for 1 day before freezing, HPP allowed to obtain meat after 1 day of storage with 60% lower shear force and higher sensory eating quality scores when compared to the non-processed product. It was also observed that HPP increased the final pH and decreased cooking loss (Morton et al., 2017).

In fact, since 1973, HPP (<138 MPa) is reported as a technology capable to produce substantial improvements in pre-rigor meat tenderness (Macfarlane, 1973). Since then, several works allowed to conclude, for instance, that pressure could cause a shortening of ≥30% but on cooking little further shortening occurred compared to unprocessed samples, weep and cooking losses could be similar but when HPP samples were cooked presented slightly higher moisture contents, cooked HPP samples were significantly more tender than unprocessed samples as judged by taste panels and Warner Bratzler Shear values, and taste panels rated pressure-treated samples more acceptable than the untreated ones (Ma & Ledward, 2013).

Although HPP effect on pre-rigor is highly dependent on several conditions, as muscle temperature, pressure level, processing time, among others, it can be used to improve water holding capacity of meat (and meat-based products) replacing the need to use additives (salt/phosphates) or non-meat ingredients (polysaccharides/non meat proteins) (Ma & Ledward, 2013). For instance, in Souza et al. (2011) study regarding HPP of pork pre-rigor carcasses, it was concluded that this technology partially inhibited the post-mortem metabolism leading to better water-holding capacity parameters (drip loss and cook loss), being observed that HPP improved pork palatability parameters, where Warner-Bratlzer shear force values indicated an increase of mechanical tenderness (also confirmed by sensory evaluation of tenderness), and also no changes promoted by HPP on collagen were detected (Souza et al., 2011).

In what concerns to post rigor fresh meat, it was already observed that a pressure treatment (20 min) at room temperature promoted myofibrillar proteins denaturation, leading to the toughness of the meat, mainly up to 400 MPa. However, when HPP was applied at 60–70 °C up to 200 MPa, significant decreases in hardness, gumminess, and chewiness were detected (Ma & Ledward, 2004). In this study, as expected, collagen showed an inert behavior to pressure (unfolded only at temperatures of 60–70 °C), and myosin revealed to be easily unfolded by both pressure and temperature, being formed new and modified structures of low thermal stability when pressure denature the initial structures (Ma & Ledward, 2004).

It has to be noted that enzymes are also important on meat texture properties, and for so, HPP effect on enzymes activity must be carefully analyzed since it can be catalyzed or inhibited by pressure in the majority of cases with its denaturation (Ma & Ledward, 2013). In their work, Ma and Ledward (2004) suggested that probably the application of 200 MPa at high temperature accelerated proteolysis, being this fact the major cause for the hardness decrease. Other studies performed at moderate pressure and high temperatures revealed similar results on meat hardness (Beilken, Macfarlane, & Jones, 1990; Zamri, Ledward, & Frazier, 2006). One possible explanation for this behavior could be explained by the temperature increase up to the set temperature (including the adiabatic heating induced by HPP) where enzymes still active and the pressure combined with slowly rising temperature could increase their reaction rate, inducing protein structure modification, so that marked proteolysis can occur (Ma & Ledward, 2013).

Concerning specific enzymes, it was also shown that HPP can increase cathepsin activity and decrease calpastatin, an important inhibitor of calpains, being also the calpains pressure sensitive and their activity decreased, for instance at 250 MPa (over 10 min at room temperature) (Sikes, Tornberg, & Tume, 2010; Sikes & Warner, 2016). Regarding cathepsins (pressure resistant up to 500 MPa), as they are located in the lysosomes, and these rupture around 200 MPa, they are released into the cytoplasm at these pressures (Homma, Ikeuchi, & Suzuki, 1994). Thus, Sikes et al. (2010) suggested that the catheptic degradation at the Z-line (where the actin has been depolymerized) is a necessary precursor for the establishment of a strengthened but brittle myofibrillar network on meat. Some works regarding the effect of HPP on textural properties of meat-based products are presented in Table 4.9.

Table 4.9 Examples of HPP effects on the textural properties of different meat-based products

Meat products	HPP conditions	Textural effects	Reference
Meat batters and reduced-fat sausages	200 MPa/ 2 min/10 °C	Textural and rheological properties improvement. HPP sausages with 20% fat presented similar cooking losses and texture results when compared to AP sausages with 30% of fat	Yang et al. (2016)
Pork sausages containing carrot dietary fiber	500 and 600 MPa/ 1 s, 3, 6, and 9 min/ 40, 50, and 60 °C	Young's Modulus increased with HPP treatments and affected Hencky strain values. HPP and carrot dietary fiber improved emulsion strength resulting in firm sausages	Grossi, Søltoft-Jensen, Knudsen, Christensen, and Orlien (2011)
Low-acid fermented sausages	400 MPa/ 10 min/17 °C	No differences were detected between non-treated and HPP treated sausages with the exception of an increase in textural properties (higher cohesiveness, chewiness, and springiness)	Marcos, Aymerich, Dolors Guardia, and Garriga (2007)

4.2.2.3 Dairy Products

Milk

HPP of milk resulted in some cases in the increase of milk viscosity as pressure increases (Harte, Luedecke, Swanson, & Barbosa-Cánovas, 2003; Huppertz et al., 2002; Trujillo et al., 2007) as detailed in Table 4.10. Increase in the viscosity could be related to the disintegration of the casein micelles into smaller structures and the denaturation of β-LG, which could produce large protein aggregates leading to increasing the milk viscosity (Trujillo et al., 2007). Also, changes in viscosity could be related to the liberation of colloidal calcium phosphate and individual caseins concentrating in the serum in which submicelles are suspended (Harte et al., 2003).

Fresh Cheese

Fresh cheeses processed by HPP resulted in several textural changes, which were pressure intensity dependent (Table 4.11). Van Hekken et al. (2013) reported that heating fresh cheese prior to HPP affected fresh cheese texture (40 °C/400 MPa for 20 min or at 600 MPa for 5, 10, or 20 min) resulting in the highest fracture rigidity ($p < 0.05$), while fresh cheeses processed at 20 °C had less variation among treatments and were closest to the non-processed ones. Evert-Arriagada et al. (2012) observed that HPP fresh cheeses were significantly firmer than the control ones, and it could be related to lower water content compared to control cheeses. Similar results were described in other studies, where pressurized cheeses were more resistant to deformation (higher modulus values), and less fracturable and deformable than the control cheeses (Capellas et al., 2001; Evert-Arriagada et al., 2012; Sandra et al., 2004).

Table 4.10 Examples of the main effects of HPP on the textural properties of fresh milk

Dairy products	HPP conditions	Textural effects	Reference
Milk (bovine)	100 to 600 MPa/Up to 60 min/20 °C	The viscosity of skimmed milk increased with, up to a value of 2.5 as pressure and treatment time increased	Huppertz et al. (2002)
Milk (bovine)	310 MPa/0.3 s	Continuous high-pressure throttling increased the viscosity	Adapa, Schmidt, and Toledo (1997)
Colostrum (caprine)	400 and 500 MPa/10 min/20 °C	Samples processed with 500 MPa, presented higher visual viscosity	Trujillo et al. (2007)
Milk (bovine)	300, 400, 500, and 676 MPa/5 min/4 °C	An increase in milk viscosity after HPP was observed	Harte et al. (2003)

Table 4.11 Examples of the main effects of HPP on the textural properties of fresh cheese

Dairy products	HPP conditions	Textural effects	Reference
Fresh Cheese (cow)	200, 400, 600 MPa/3–20 min/20 and 40 °C	HPP cheeses tended to present higher values for hardness, chewiness, cohesiveness, fracture stress, and fracture rigidity	Van Hekken et al. (2013)
Fresh Cheese (cow)	500 MPa/5 min/16 °C	Pressurized cheeses were more resistant to deformation, less fracturable and deformable, than control cheeses	Evert-Arriagada et al. (2014)
Fresh Cheese (cow)	400 MPa/20 min/20 °C	HP cheese had higher firmness, gumminess, and chewiness than the control ones	Sandra et al. (2004)
Fresh Cheese (cow)	300 or 400 MPa/5 min/6 °C	In general, HP cheeses were significantly firmer than control cheeses	Evert-Arriagada et al. (2012)
Fresh Cheese (cow)	9, 50, 150, 250, and 291 MPa/1, 5, 15, 25 and 29 min/25 °C	Increased pressures led to increased hardness, but decreased adhesiveness of the HP-treated fresh cheese	Okpala et al. (2010)
Fresh Cheese (goat)	500 MPa/5, 15 and 30 min/10 or 25 °C	Fracture stress values were significantly higher when compared to control cheeses	Capellas et al. (2001)

Cheese

In general, HPP ripened cheeses revealed lower values of hardness, adhesiveness, firmness, elasticity, gumminess, and chewiness compared to control cheeses (Calzada, del Olmo, Picon, Gaya, et al., 2014b; Calzada, del Olmo, Picon, & Nuñez, 2014c; Delgado et al., 2012). However, after some days of storage, HPP cheeses recovered the textural properties to values closer to control cheeses (Calzada, del Olmo, Picon, Gaya, et al., 2014b) (Table 4.12).

4.2.3 Sensorial Properties

4.2.3.1 Fruits and Vegetables

Fruits

The nutritional compounds mentioned above play an important role in the general sensorial properties of food products, and since most of these compounds are minimally affected by HPP, also the sensorial properties are minimally affected.

One of the most studied sensorial parameters is the color; usually using the CIE 1976 ($L*$, $a*$, $b*$) color space parameters. Overall the color of fruit products is not

Table 4.12 Effect of HPP on textural properties of different cheeses

Dairy products	HPP conditions	Textural effects	Reference
Casar Cheese (raw ewe milk)	400 or 600 MPa/ 5 min/14 °C	Firmness and elasticity: higher values for the 600 MPa cheese and lower values for the 400 MPa cheeses in comparison to control cheeses (at 35 days of ripening)	Calzada, del Olmo, Picon, and Nuñez (2014a)
Brie cheese (pasteurized cow milk)	400 or 600 MPa/ 5 min/9–14 °C	Fracturability, elasticity, and firmness: decreased immediately after HPP (at 21 days of ripening), then HPP cheese revealed similar or higher texture characteristics than control	Calzada, del Olmo, Picon, Gaya, et al. (2014b)
Ibores Cheese (raw goat milk)	400 or 600 MPa/ 7 min/10 °C	Hardness, adhesiveness, gumminess, and chewiness: decreased after HPP (at 1, 30 and 50 days of ripening) Cohesiveness and springiness: was kept after HPP (at 1 and 30 days of ripening)	Delgado et al. (2012)
Commercial cheese (pasteurized ewe milk)	300 MPa/10 min	Fracture stress: increased immediately after HPP at 1 day of ripening and decreased when treated after 25 d of ripening Fracture strain: increased immediately after HPP	Juan, Ferragut, Guamis, and Trujillo (2008)

much affected by HPP rendering Δ*E* values generally below 4 (Koutchma, Popović, Ros-Polski, & Popielarz, 2016). Some recent examples are: i) the work of Chang, Wu, Chen, Huang, and Wang (2017) with grape juice where HPP, using 300 and 600 MPa for 3 min at 20 °C, resulted in a Δ*E* below 1 after treatment and up to 20 days of storage; ii) the work of Yi et al. (2017) that studied apple juice from 3 varieties and where HPP (600 MPa/3 min/10 °C) resulted in Δ*E* values below 2.5 (Pink Lady = 2; Granny Smith = 0.8; Jonagold = 2.5). Still, there are some cases in which the color changes were more noticeable. Among them, some studies standout, for example, studies with blood orange, watermelon, and orange juices, with Δ*E* values of 4.5, 8.0 and 9.3, respectively. It is noteworthy to mention that these juices were processed at severe conditions (600 MPa), particularly the watermelon juice that was processed at more extreme conditions than most fruit products usually are, namely 900 MPa for 60 min at 60 °C (Hartyáni et al., 2011; Torres et al., 2011; Zhang et al., 2011).

HPP has proven to also maintain other sensorial properties, considering several descriptors for acceptability such as odor and taste. Picouet et al. (2016) studied the effects of 350 MPa for 5 min on a multi-fruit smoothie containing apples, strawberries, oranges, and bananas. The authors compared the effect of HPP and thermal processing on odor, general appearance, and mouthfeel, and concluded that the HPP samples were similar in the overall sensory analysis to the untreated smoothies. However, the HPP-treated juices presented lower stability during storage, most likely due to the inefficacy of the process to considerably reduce the activity of oxidative enzymes. In another study with red fruit-based smoothies, similar results were obtained. Several parameters were evaluated, namely appearance, odor, flavor, and mouthfeel. According to the authors, moderate HPP conditions (350 MPa/10 °C/5 min) resulted in “fresh-like” smoothies, both after processing and during storage at 4 °C up to 14 days, presenting a non-altered sensory quality (Hurtado et al., 2017). Baxter, Easton, Schneebeli, and Whitfield (2005) studied several sensory properties of navel orange juice processed by HPP (600 MPa/1 min/20 °C) and its general consumer acceptability. The authors reported that the HPP juice had an odor and flavor that was acceptable by consumers, both after processing and up to 12 weeks of storage. Furthermore, the 20 key aroma components were analyzed by gas chromatography-mass spectrometry and it was concluded that the results of the HPP juice were similar to the untreated juice. Most studies available in the literature point to HPP as a good alternative for the stabilization of fruit-based products, since it is an effective technology maintaining good sensory qualities.

Vegetables

As HPP has a limited effect on the covalent bonds of low molecular weight compounds, such as flavor and color compounds of food products, it is expected that this technology will help to minimize the color changes and formation of off-flavors caused by thermal pasteurization (Wang, Huang et al. 2016).

A study on the color changes on cocoyam and carrot showed that HPP at 600 MPa, for only 5 min at room temperature, allowed to maintain the color unchanged, mainly due to enzyme inactivation, such as polyphenoloxidase (PPO) and peroxidase (Tribst, Leite, de Oliveira, & Cristianini, 2016). Also in cucumber juice, HPP treatment (at 500 MPa, for 5 min, at room temperature) seems to not have an immediate effect on juice color, since the CIE Lab parameters remained unchanged (Liu, Zhang, Zhao, Wang, & Liao, 2016) (Table 4.13). Nevertheless, after 20 days of storage, some clear changes were perceived, with high values of ΔE, but still, about 3.4-fold lower than the samples treated by high temperature (Liu et al., 2016). Similar results were described by Contador et al. (2014) who found that pumpkin purée treated at 400 MPa showed the same coloration parameters as non-processed purée, presenting an increase of about nine-folds of the ΔE parameter also after storage at refrigeration for 20 days (Contador et al., 2014). Contrasting results were reported by García-Parra et al. (2016), who related the instrumental color and PPO enzyme activity, after HPP treatment of pumpkin purée (Table 4.13). The authors have found that the purée lightness (CIE $L*$) was significantly higher after high pressure/mild temperature (600 MPa/60 °C) treatment. Also, the ΔE parameter was around 3–4, indicating a color difference perceptible by most consumers, even though that those conditions were the most effective to reduce PPO activity (García-Parra et al., 2016).

Table 4.13 Examples of the main effects of HPP on the sensorial properties of vegetables

Vegetable products	HPP conditions	Sensorial effects	Reference
Cocoyam and carrot	600 MPa/5 min/RT	Color parameters unchanged after HPP	Tribst et al. (2016)
Cucumber juice	500 MPa/5 min/RT	Color parameters unchanged after HPP	Liu et al. (2016)
Pumpkin purée	400, 600 MPa/5 min/10 °C	Treated samples (400 MPa) with same coloration parameters as non-processed purée	Contador, González-Cebrino, García-Parra, Lozano, and Ramírez (2014)
Pumpkin purée	300–900 MPa/1 min/60–80 °C	Higher lightness for samples treated by HPP at 600 MPa and 60 °C	García-Parra, González-Cebrino, Delgado, Cava, and Ramírez (2016)
Carrot purée	600 MPa/up to 180 min/118 °C	The formation rate of off-flavors was ten times slower than heated samples at 0.1 MPa	Kebede et al. (2017)
Onion, potato, pumpkin, red beet	600 MPa/15 min/117 °C	HPHT seems to reduce the degradation of Strecker products	Kebede et al. (2014)
Broccoli florets	300, 700 MPa/10 min/20, 82 °C	HPP can maintain a high level of intact glucosinolates in broccoli florets	Blok Frandsen et al. (2014)
Beetroot slices	650 MPa/3–30 min/RT	Great color instability, with high values for total color difference parameters (above 10)	Paciulli et al. (2016)

Flavor is one of the food properties most used by consumers to understand a product as consumable. Nevertheless, this kind of compounds is degraded by thermal processing, producing other compounds, such as volatile aldehydes, responsible for off-flavors development in vegetable products. Kebede et al. (2017) studied the effect of HPP (600 MPa/118 °C) on carrot purée and compared the formation of off-flavors compounds to a thermal-treated sample (Table 4.13). The authors reported a formation rate of that volatiles under high pressure ten times slower than at 0.1 MPa, indicating the importance of the processing conditions (temperature and time) on food quality (Kebede et al., 2017). Many similar results were reported by Kebede et al. (2014) after high-pressure/high-temperature treatment (600 MPa for 15 min at 117 °C) of onion, potato, pumpkin, and red beet.

In cruciferous vegetables, such as broccoli, glucosinolates are products responsible for their odor and taste. Some treatments of HPP can maintain a high level of intact glucosinolates in broccoli florets, mainly due to myrosinase inactivation at 700 MPa, 10 min, 20 °C, allowing preserving the quality of these vegetables (Blok Frandsen et al., 2014).

Table 4.14 Some publications with the main effects of HPP on the sensory properties of fish

Fish products	HPP conditions	Samples	Sensorial effects	Reference
Hake	200 and 400 MPa/ 5 min/7 °C	Samples cooked in boiling water for 5 min	General appearance and odor similar or slightly higher than control samples Higher flavor scores when compared to the control and a decrease with the pressure levels increase	Hurtado, Montero, and Borderias (2000)
Red mullet	220 and 330 MPa/ 5 and 3 min/25 °C	Raw fillets	No influence on appearance and odor	Erkan et al. (2010)
Sea bass	250 and 400 MPa/ 5 min/6 °C	Raw sea bass fillets	Color whitening (cooked fish appearance) Intensified brightness at 400 MPa (firmer fillets) No influence on the fresh odor High sensory acceptance	Teixeira et al. (2014)

4.2.3.2 Meat Products

Fish and Fish-Based Products

For consumer's perception, color is one of the most important sensory characteristics of fish muscles in determining their acceptability. For color measurements in fish processed by HPP is normally to use the CIE LAB system, obtaining values of $L*$ (lightness scale from 0 (black) to 100 (white)), $a*$ (scale ranging from −a (green) and +a (red)), and $b*$ (scale ranging from −b (blue) and +b (yellow)). From these parameters, it is possible to calculate the ΔE value, which is used to predict the differences in perception capacity ($\Delta E > 3.0$ = very distinctive, $1.5 < \Delta E < 3.0$ = distinct, and $\Delta E < 1.5$ = slightly distinct) (Adekunte, Tiwari, Cullen, Scannell, & O'Donnell, 2010). Normally, $L*$ value increases in HPP-treated fish, which shows more clear, gray, typical of cooked meat aspect after application of pressure levels between 150 and 300 MPa (Erkan, Üretener, & Alpas, 2010; Ramirez-Suarez & Morrissey, 2006; Sequeira-Munoz et al., 2006). Regarding $a*$ and $b*$ values, there are some differences in different published studies, but most of them have shown a decrease in $a*$ value (loss of red) (Erkan et al., 2010; Yagiz et al., 2007), and an increase in $b*$ value (up yellow) (Ramirez-Suarez & Morrissey, 2006; Sequeira-Munoz et al., 2006), which depends with the species and the pressure conditions.

The possible effects of HPP detected by instrumental methods are less noticeable during sensory evaluation. Few sensory studies assessed HPP-treated fish, but in general, the changes discretely influence the sensory attributes, most often positively (Table 4.14).

According to Hurtado et al. (2000), HPP-treated hake showed slightly higher scores for overall appearance and odor, as a function of pressure levels, compared to control samples. In addition, lower scores were observed within the pressure levels at 200 and 400 MPa. It is recognized that HPP increases whiteness index (instrumental measurement), giving opaque appearance typical of cooked product. Considering that hake is a white fish, whitening may have contributed to its better appearance. In the same way, Teixeira et al. (2014) verified that HPP caused the loss of red color on sea bass and increased whitening, which was correlated to color instrumental analyses. In addition, the same panel observed an increase in firmness with increasing pressure levels. The pressure levels did not influence fresh odor, although an increase in oxidation products was observed.

HPP has a significant effect on the elimination of microorganisms, inhibiting the production of biogenic amines, volatile nitrogen, and trimethylamine (Murchie et al., 2005), which contribute to improving the sensory quality, and ensure the safety of fish.

Meat and Meat-Based Products

Consumers request for fresh-like/high-quality food products have been increasing, and HPP as a novel non-thermal food processing technology has demonstrated to fulfill these requirements.

One of the most important attributes for consumers regarding meat products is its color. Shortly, it can be said that this parameter is related to the amount and chemical state of the hemoproteins and meat's structure, and its changes are related to ferrous myoglobin oxidation into ferric metmyoglobin. Although changes in several cured/processed meat products are acceptable by the consumers (depending on water content and water activity), HPP applied to fresh meat induces severe changes on this parameter (Sazonova et al., 2017).

Usually, color differences on fresh red meat occur when a pressure level above 200 MPa is applied over a few minutes at low temperatures. Briefly, the lightness ($L*$) parameter can change at a pressure level between 200 and 350 MPa (red into a paler pink), usually redness ($a*$) decreases resulting in a cooked-like appearance of the product at pressures of 400–500 MPa, and yellowness ($b*$) could increase or is not affected (Sazonova et al., 2017).

As myosin is sensitive to pressure it can denature between 180–300 MPa giving an opaque appearance similar to cooked meat. However, in the literature, it is stated that besides myosin unfolding on pressure treatment, some hydrogen bonded structure remains or is formed, being these destroyed by further heat treatment (Ma & Ledward, 2004; Ma & Ledward, 2013).

On the other hand, although myoglobin in pure solution at the same pH values found in meat is relatively stable to heat and pressure, on the product, the pigment is less stable to heat probably due to a pre-denaturation and conformational changes leading to more exposed/available haem to other denatured or denaturing proteins, so that it co-precipitates with them, being the final complex a brown denatured ferric haem pigment at normal pH (Ma & Ledward, 2013). The same is verified for pressure treatments, wherein solution myoglobin denaturation is reversible at all pH values except from those around its isoelectric point, however, in meat, it seems less stable than in solution, probably due to co-precipitation with other proteins and the complexes formed.

Some studies regarding color stability on high-pressure treatments concluded that this kind of technology could increase color stability over storage if a pressure treatment of 80–100 MPa after 2 days post-slaughter is applied. The same did not happen when the same pressure treatment was applied after 7 or 9 days post-slaughter, being this difference probably related to the destruction of the catalytic system responsible for the oxidation of myoglobin to metmyoglobin (Cheah & Ledward, 1997b).

Concerning meat flavor, it is not expected that HPP has a great impact on meat organoleptic characteristics, however as lipids and their oxidation products influence meat flavor and the enzymes responsible for the products formed over chill storage are susceptible to pressure, HPP can be responsible for meat flavor adulterations (Ma & Ledward, 2013).

By the years, it has been concluded that HPP turns polyunsaturated fatty acids in fresh meat more susceptible to oxidation, mainly above 400 MPa, being this impact detected by sensorial analyses (Cheah & Ledward, 1996; Ma, Ledward, Zamri, Frazier, & Zhou, 2007; Wang et al., 2013). This behavior has been explained by the release of metal ions (primarily iron) from the transition metal complexes present in meat, as well as by membrane disruption induced by pressure (Bolumar, Skibsted, & Orlien, 2012; Cheah & Ledward, 1997a; Orlien, Hansen, & Skibsted, 2000). It was also verified that supplementation with EDTA or vitamin E could lead to the lipid oxidation inhibition after pressure treatment, mainly for the former (Ma & Ledward, 2013). In Table 4.15, some works are listed regarding the HPP effect on the sensorial properties of meat-based products.

Table 4.15 Some studies regarding HPP effect on the sensorial properties of different meat-based products

Meat products	HPP conditions	Textural effects	Reference
Meat batters and reduced-fat sausages	200 MPa/ 2 min/10 °C	HPP sausages with 20% fat presented similar sensorial results when compared to AP sausages with 30% of fat	Yang et al. (2016)
Serrano dry-cured ham (30 different samples)	600 MPa/ 6 min/21 °C	Only 8 volatile compounds presented to be HPP affected (higher levels of methanethiol and sulfur dioxide in HPP-treated samples and higher levels of ethyl acetate, ethyl butanoate, ethyl 2-methylbutanoate, ethyl 3-methylbutanoate, dimethyl disulfide and dimethyl trisulfide in untreated samples)	Martínez-Onandi, Rivas-Cañedo, Nuñez, and Picon (2016)
"Lácon" (cured–cooked pork meat product)	500 and 600 MPa/ 5 min/≤16 °C	HPP did not show a considerable effect on the sensory characteristics of sliced "lacón", resulting in its stability over 120 days (at 4 °C), independently of HPP treatment	del Olmo, Calzada, and Nuñez (2014)
Ready-to-eat low-fat pastrami, Strassburg beef, export sausage, and Cajun beef	600 MPa/ 3 min/20 °C	Hedonic ratings revealed no difference in consumer acceptability between HPP and non-treated samples. There was no evidence of sensory quality deterioration over the study (98 days of refrigerated storage)	Hayman, Baxter, O'Riordan, and Stewart (2004)

Table 4.16 Examples of the main effects of HPP on the sensorial properties of milk

Dairy products	HPP conditions	Sensorial properties	Reference
Milk (bovine)	310 MPa/0.3 s	Continuous high-pressure throttling treatment changed milk color, producing lower $L*$, $a*$, and $b*$ values	Adapa et al. (1997)
Milk (bovine)	300, 400, 500, and 676 MPa/5 min/4 °C	After HPP milk color became more yellow	Harte et al. (2003)
Milk (ovine)	100 to 500 MPa/ 10 and 30 min/25 and 50 °C	ΔE rates increased with pressure, with a maximum at 500 MPa, resulted from $L*$ value reduction	Gervilla et al. (2001)

4.2.3.3 Dairy Products

Milk

Lightness value ($L*$) was the main color parameter affected, contributing overall to the color losses in milk after HPP (Table 4.16). Gervilla et al. (2001) observed a decrease in $L*$ and an increase ($p < 0.05$) of greenness ($a*$) and yellowness ($b*$) when the pressure increased. Similar results were obtained by Adapa et al. (1997), producing HPP darker (lower $L*$ value), greener (lower $a*$ value), and bluer (lower $b*$ value) colors in milk. Casein micelles play an important role in light scattering and when HPP is applied, non-covalent forces (hydrogen bonds, ionic interactions, and hydrophobic forces) are disrupted, leading to casein micelles disintegration into small fragments that increase the translucence of the milk (Harte et al., 2003; Trujillo et al., 2007).

Fresh Cheese

After HPP, overall, fresh cheeses presented a more yellow color on the outside but without changes on the off-flavor parameters, when compared to non-processed ones (Table 4.17). Sandra et al. (2004) reported that HPP cheese was not significantly different for most attributes, however, HPP cheeses were slightly less crumbly than the control, but HPP cheeses were different from the control for all attributes, except color. In another study, HPP cheese obtained similar flavor scores to non-pressurized ones, with panelists familiar with fresh cheese more accepting of the texture than those not familiar fresh cheese (Van Hekken et al., 2013).

Panelists in the Evert-Arriagada et al. (2012) study, identified the pressurized fresh cheeses (300–400 MPa, 5 min) as more yellow, firmer, and less watery, but without off-flavors or great differences in flavor and aroma. When a higher pressure was applied (500 MPa for 5 min), an increase in firmness in high pressure-treated cheeses was noticeable, while flavor, aroma, elasticity and off-flavor parameters remained unchanged with HPP treatment of fresh cheese did not affect panelists' preference (Evert-Arriagada et al., 2014).

Table 4.17 Examples of the main effects of HPP on the sensorial properties of fresh cheese

Dairy products	HPP conditions	Sensorial properties	Reference
Fresh Cheese (cow)	600 MPa/3 or 10 min/20 °C	Panelists were able to distinguish the control from HPP cheeses, scoring around 3.4 "moderately liked"	Van Hekken et al. (2013)
Fresh Cheese (cow)	500 MPa/5 min/16 °C	Panelist equally preferred pressurized to non-treated cheeses, although HPP increased firmness in high pressure-treated cheeses	Evert-Arriagada et al. (2014)
Fresh Cheese (cow)	400 MPa/20 min/20 °C	HP cheese was slightly less crumbly than the control Stickiness and sticky residuals of HP cheese increased during storage	Sandra et al. (2004)
Fresh Cheese (cow)	300 or 400 MPa/5 min/6 °C	Panelists classified pressurized cheeses as more yellow, firmer, and less watery, but without off-flavors or great differences in flavor and aroma when compared with the reference cheeses	Evert-Arriagada et al. (2014)

Table 4.18 Effect of HPP on the sensorial properties of different cheeses

Dairy products	HPP conditions	Sensorial effects	Reference
Brie cheese (pasteurized cow milk)	400 or 600 MPa/5 min/9–14 °C	Flavor quality, intensity, and bitterness: did not vary immediately after HPP (at 21 days of ripening)	Calzada, del Olmo, Picon, Gaya, et al. (2014c)
Blue-veined cheese (pasteurized ewe milk)	400 or 600 MPa/5 min/13 °C	Flavor intensity and quality: scores of HPP cheeses did not differ from those of control cheese (exception of Cheeses HPP at 600 MPa at 21 days of ripening, with lower scores)	Calzada, Del Olmo, Picon, Gaya, and Nuñez (2013)
NA (raw cow milk)	400 or 600 MPa/5 min/14 °C	Odor intensity: did not differ significantly among HPP and control cheeses	Calzada et al. (2015)
Ibores Cheese (raw goat milk)	400 or 600 MPa/7 min/10 °C	Odor intensity, flavor intensity, and taste: higher scores for HPP cheeses (better when were HPP at 30 days of ripening)	Delgado et al. (2012)
Casar Cheese (raw ewe milk)	400 or 600 MPa/5 min/14 °C	Flavor intensity and quality: similar scores of HPP cheeses and control cheese (at 60 days of ripening); with time HPP win flavor quality	Calzada, del Olmo, Picon, Gaya, and Nuñez (2014a)

Cheese

In ripened cheese, interesting sensorial results were obtained after cheese HPP. In general, immediately after treatment, the flavor quality and intensity scores were closer to control cheese (Calzada et al., 2015; Calzada, del Olmo, Picon, Gaya, et al., 2014a; Calzada, del Olmo, Picon, & Nuñez, 2014c), but after some days of storage, an increase of these sensorial attributes were verified (Delgado et al., 2012) (Table 4.18).

4.3 Conclusion

The consumers' demand for new and healthier food products with distinctive organoleptic characteristics led to the application of novel food technologies to fulfill their requests. Currently, HPP is one of such novel technologies and has been applied, for instance, on the production of fruit juices and ready-to-eat meals, where higher nutritional foods with exceptional sensory quality are attained. This non-thermal food processing technology not only is capable to guarantee food safety, increasing food products shelf lives and the reduction/avoidance of chemical preservatives, but also can result in fresher-tasting foods. Along with this chapter, the HPP impact on different foods such as fruits, vegetables, meat, and dairy products, was revised and discussed. In the end, it was possible to perceive that HPP, when applied at optimal conditions for a specific product, allows obtaining several benefits depending on the product. It is expected that research regarding HPP effect on foods will continue since its application for new food products' development has been increasing due to novel organoleptic characteristics' achievement, for instance, texture properties' modification. Thus, it is very likely that in a few years the knowledge concerning HPP of different foods not yet studied and, on its constituents, will increase, as well HPP combined to other food technologies could be a reality.

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