



Review

New opportunities and perspectives of high pressure treatment to improve health and safety attributes of foods. A review



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ABSTRACT

High pressure (HP) treatment has emerged as a novel, additive-free food preservation technology. It has been scientifically and commercially proven that HP can produce microbially safe and stable products with improved quality characteristics such as enhanced flavor and color. Recent studies have focused on the effects of HP on health attributes and allergenic potential of foodstuff to develop the next generation of convenience foods. This review provides an overview on the current knowledge of HP treatment to improve the extraction and bioavailability of bioactive compounds, to reduce allergenicity, to retain essential fatty acids, to reduce the salt content, and to reduce formation of processing contaminants. HP has shown encouraging potential to manipulate the functionality, extractability, allergenicity and bioavailability of micronutrients and components in a diverse variety of foods. However, the underlying principles and mechanisms are not yet fully understood and warrant further investigation. More studies are needed to optimize HP treatment conditions and develop a mechanistic understanding of the impacts of HP on different bioactive compounds in food products with health benefits. This can open the doors to new HP applications in the food industry.

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1. General introduction

The efficacy of high pressure (HP) treatment is governed by Le Chatelier's principle, which implies that reactions or phase transitions associated with a decrease in volume are favored, while those accompanied with a volume increase are inhibited. Low molecular weight molecules like aroma compounds, vitamins, and minerals are rarely affected as such by HP because of the very low compressibility of covalent bonds. On the other hand, macromolecules, such as proteins and starch, can change their native structure during HP in a manner similar to thermal treatments (Gross & Jaenicke, 1994; Heinz & Buckow, 2010).

HP treatment is characterized by three processing parameters: temperature T , pressure P , and exposure time t . The three processing parameters allow great flexibility in the design of the process (Heinz & Buckow, 2010). Generally, the pressure is transmitted instantaneously and uniformly throughout the food system independent of the size and geometry of the food product, unlike heat processing, where heat is gradually transferred through the food system. The momentary pressure transmission can reduce processing time, processing energy and the risk of over-processing of some parts of voluminous products.

It is frequently claimed that HP can be used to produce healthy and fresh-like foods due its minimal effects on nutritional and aroma compounds (Rastogi, Raghavarao, Balasubramaniam, Niranjan, & Knorr, 2007). For the last two decades, HP treatment has been mainly applied to increase food safety and/or extend the shelf-life of refrigerated foods of high value (Barba, Criado, Belda-Galbis, Esteve, & Rodrigo, 2014; Barba, Esteve, & Frígola, 2012a). Some of the current and potential applications of HP treatment are shown in Fig. 1.

This review is intended to highlight several opportunities of HP treatment of foodstuffs beyond the current commercial applications for food safety and shelf-life extension. The great potential of HP treatment to a) recover health-related compounds, b) improve health attributes of foods through increased bioavailability of micronutrients and

phytochemicals, c) reduce allergenic potential, d) preserve healthy lipids, e) reduce salt intake by increased saltiness perception, and f) reduce formation of processing contaminants is presented.

2. Effect of HP on bioactive compounds recovery

Bioactive compounds from plant food materials are interesting due to their health and nutraceutical benefits (Barba, Esteve, & Frígola, 2014). Polyphenols have been related to reduction in risk of coronary heart diseases and degenerative human diseases because of their antioxidant and free radical scavenging properties (Barba, Esteve, & Frígola, 2013; Wang, Melnyk, Tsao & Marcone, 2011; Wootton-Beard & Ryan, 2011). Carotenoids are known to be functional components of a healthy diet, some of them with vitamin A function (β -carotene, α -carotene, and β -cryptoxanthin) (Melendez-Martinez, Vicario, & Heredia, 2003). In addition, glucosinolates and the derived isothiocyanates have attracted much interest from both food and pharmaceutical industries due to their potential health benefits (Deng et al., 2014; Dinkova-Kostova & Kostov, 2012).

In general, cellular tissue must be denatured to become permeable for the intracellular compounds targeted by extraction. In industry, such tissue permeabilization is most often achieved through a thermal process (e.g., using steam or hot water) and consumes a high amount of energy. The heating process may degrade the thermo-sensitive compounds of plant tissue affecting the quality of the products (loss of vitamins, colors, flavors, etc.) and complicating the purification of the extracts. Alternative physical, chemical, or enzymatic treatments can also be used to denature the cellular structure of plants and biological suspensions (yeast, seaweeds), and make the extraction of cellular compounds easier. Some physical treatments (microwaves, ohmic heating, sub- and supercritical water) allow shortening of product exposure to heat. Some other alternative treatments (e.g., supercritical carbon dioxide, pulsed electric fields, shockwaves, ultrasound, high-pressure homogenization) are considered as “non-thermal” even if the temperature elevation of products by these treatments is far from negligible (sometimes tens of degrees) (Deng et al., 2014; Parniakov, Barba, Grimi, Lebovka, & Vorobiev, 2014; Rosello-Soto et al., 2015). The classical treatments (grinding, heating), and the different alternative treatments currently used in industry to make extractions easier, degrade and disrupt the tissue structure (membranes and cellular walls) in an uncontrollable way. Unfortunately, the entirely disrupted tissue loses its selectivity (capacity to sieve) and becomes permeable not just for the target cell compounds, but also for undesirable compounds (impurities) passing into the extract. As a result, the extract is contaminated by auxiliary compounds (cell debris, pectins, etc.), which are difficult to separate (Barba, Grimi, & Vorobiev, 2015). Organic solvents such as dichloromethane, dichloroethane, acetone, hexane, and alcohol are widely used for the extraction of different molecules of agricultural origin (carbohydrates or polysaccharides, proteins, bioactive compounds, aromas, flavors, etc.). Extraction is often linked with the use of environmentally polluting chemical or biological agents. Among solvents considered to be “green”, water should be primarily noted, with supercritical fluids (such as carbon dioxide), renewable solvents (bio-solvents such as ethanol or isopropanol) and ionic liquids also considered ‘green’. Unfortunately, the “green” solvents, and particularly water at room temperature, are often inadequate for an efficient extraction from food plants (Kerton, 2009).

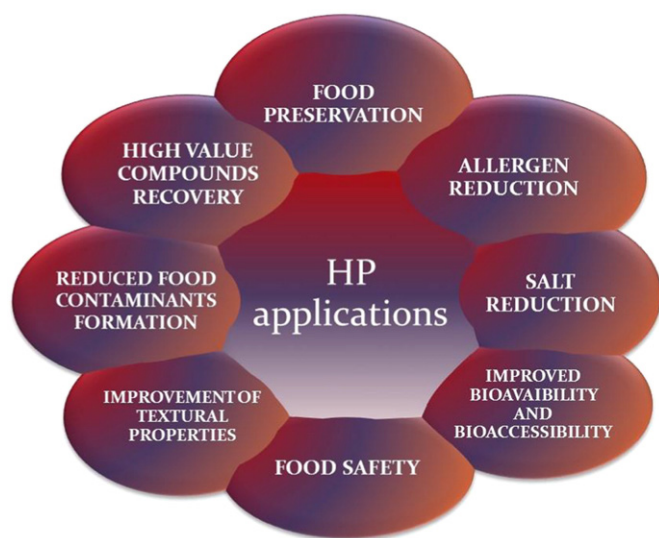


Fig. 1. Current and potential applications of high pressure (HP) treatment in food, wastes and by-products.

HP treatment has been suggested as an environmentally friendly technology, being able to enhance mass transfer processes within plant or animal cellular tissues, as the permeability of cytoplasmic membranes can be affected (Doernenburg & Knorr, 1993; Toepfl, Mathys, Heinz, & Knorr, 2006). The use of HP can enhance mass transfer rates by increasing cell permeability as well as secondary metabolite diffusion (Richard, 1992). The application of HP treatment produces the physical disruption of plant tissue, thus inducing changes in the permeability of cell membranes (Gonzalez & Barrett, 2010). Knorr (1992) attributed these changes to modifications in the molecular organization of the lipid–peptide complex and disruptions in the phosphatidic acid bilayer membrane structure. These changes may play an important role in the raw material fragmentation promoting the extraction of intracellular compounds, including bioactives.

The factors that may influence the efficiency of HP extraction are the pressure level, pressure holding time, liquid/solid ratio, type of solvent, and solvent concentration (Knorr, 1999; Sanchez-Moreno, Plaza, De Ancos, & Cano, 2004a). For an enzymatic or thermal disintegration, heating of the raw material and considerable holding time at high temperature is required, heat transfer is slow, and heat recovery is poor as plate heat exchangers can hardly be applied for fruit mashes. An HP treatment can be performed at ambient temperature and the overall timescale required for an HP treatment is in the range of minutes. Galanakis (2012) established five different recovery stages for the recovery of antioxidant compounds: 1) Macroscopic pre-treatment; 2) macro and micro-molecule separation; 3) extraction; 4) isolation

and purification and 5) product formation. Processing often progresses from the macroscopic to the macromolecular level and afterwards to the extraction (or removal) of specific micro-molecules, prior to the purification and encapsulation of the target ones. The versatility of HP allows this technology to be used as a macroscopic pre-treatment to permeabilize cell membrane, thus facilitating the extraction of bioactive components before conventional solvent extraction. An exemplary flow chart of such a process is shown in Fig. 2.

2.1. Polyphenols

Polyphenols are commonly found in plant food materials like fruits, vegetables, cereals, legumes, and nuts. The beneficial health-related effects of certain polyphenols or their potential antioxidant properties, especially when these compounds are present in large quantities in foods, are of importance to consumers (Barba, Esteve, & Frigola, 2012b; Barba et al., 2012a; Craft, Kerrihard, Amarowicz, & Pegg, 2012). Natural antioxidants are widely used because they are perceived safer than their synthetic counterparts by the consumer. Therefore, there is an interest in safe, cost-effective and natural antioxidants with high activity to replace the synthetic antioxidants. The antioxidant compounds present in plant food materials have recently been promoted as natural food additives because they display little or no toxic side effects (Han, Lo, Choi, Kim, & Baek, 2004). There are various studies focusing on HP-assisted extraction of phenolic compounds in different plant food materials and by-products (Table 1).

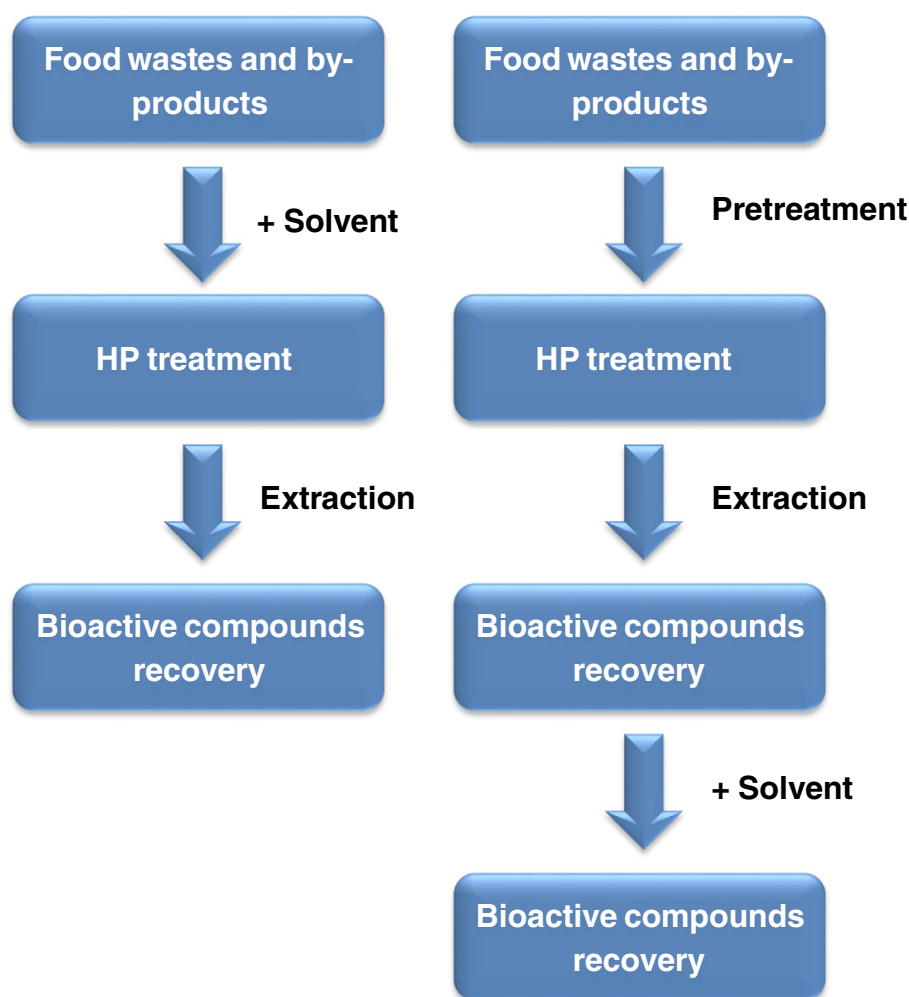


Fig. 2. Flow chart for plant food HP extraction coupled to conventional solvent extraction or HP pretreatment prior to liquid–solid separation.

Grape by-products have attracted significant interest as they are good sources of polyphenols and are obtainable in large quantities. Hence, the effects of HP on extraction of polyphenol from grape by-products were evaluated (Corrales, Butz, & Tauscher, 2008a; Corrales, Garcia, Butz, & Tauscher, 2009; Corrales, Toepfl, Butz, Knorr, & Tauscher, 2008b). Overall, these studies found a significant increase in the total and individual anthocyanin content after HP in comparison to conventional extraction methods. Specifically, they observed that the yield of each individual anthocyanin was highly influenced by the HP treatment applied. It was concluded that anthocyanin extraction from plant materials is influenced by their chemical nature, the extraction method employed, sample particle size, storage time and conditions, as well as presence of interfering substances.

Seo et al. (2011) reported that HP assisted extraction (500 MPa/60 °C/5–15 min) significantly increased the extraction yield of phenolic compounds from Korean black raspberry (*Rubus coreanus*) fruits compared to conventional extraction (24 h/100 °C) using a reflux condenser. Furthermore, higher concentrations of caffeic acid, catechin and ferulic acid were observed in the HP extract (12.3 mg/L, 10.1 mg/L and 6.9 mg/L, respectively) than the water extract at 100 °C (24 h) (10.1 mg/L, 3.1 mg/L and 2.6 mg/L, respectively).

Other authors compared the effects of HP-assisted and conventional extraction on phenolic compounds (gallic acid, corilagin, ellagic acid and total phenolic compounds) from longan fruit pericarp (Prasad et al., 2009a; Prasad et al., 2010). They found a significant increase in corilagin, and total phenolic yield when they applied HP (200–500 MPa/30–70 °C/2.5–30 min) in comparison to conventional ethanolic extraction during 12 h. Moreover, a shorter extraction time resulted in increased yield compared to conventional extraction. Similarly, Prasad et al. (2009b) reported a significant increase in the yield of polyphenols from litchi fruit pericarp after HP treatment (200–500 MPa/30–90 °C/2.5–30 min) compared to other conventional

extraction methods. A significant increase in extractable phenolic compounds was also reported after HP treatment (400 MPa/40 °C/1 min) of orange juice with pulp (Sanchez-Moreno et al., 2005).

HP treatment was also used to extract flavonoids from propolis (Shouqin, Jun, & Changzheng, 2005; Shouqin, Junjie, & Changzhen, 2004) and *Rhodiola sachalinensis* (Zhang, Bi, & Liu, 2007). Compared with traditional extraction methods (ultrasonic extraction, leaching extraction, soxhlet extraction and reflux extraction), HP extraction (400–600 MPa/20 °C/15 min) provided more flavonoids. Not only higher yield was achieved using HP extraction, but Shouqin et al. (2005) suggested that HP extraction can greatly reduce the extraction time compared to all the other extraction methods investigated. These authors determined that HP extraction (500 MPa/room temperature (RT)/1 min) gave higher extraction yield of flavonoids than the extraction at room temperature for 7 days and heat reflux extraction for 4 h.

Tea leaves are also an important source of antioxidant compounds, especially polyphenols. For instance, Xi et al. (2009) compared the effects of HP treatments (100–600 MPa/20 °C/1–10 min) with heat reflux (85 °C, 45 min), extraction at room temperature, and ultrasonic extraction (250 W, 20–40 °C, 90 min) on total phenolic compounds (TPC) extraction from tea leaves using different solvents (acetone, methanol, ethanol and water). These authors obtained an increase (up to 30%) in TPC after applying HP treatment (500 MPa/20 °C/1 min), using a concentration of 50% (v/v) of ethanol, 20:1 (v/w) of liquid/solid ratio. These values were similar to those found when they used extraction at room temperature for 20 h, ultrasonic extraction for 90 min and heat reflux extraction for 45 min, respectively. In another study, the extraction of four major catechins (epicatechin gallate, epigallocatechin, epigallocatechin gallate, epicatechin) and gallic acid from green tea was done in a comparative study using organic solvent extraction and HP aqueous extraction at different pressures (from

Table 1
Effects of high pressure (HP)-assisted recovery of polyphenol from plant food materials.

Plant food material	Treatment conditions			Solvent ratio water: ethanol (v/v)	Phenolic compounds increase	References
	MPa	°C	min			
Blackberry puree	400–600	20	15		Non-significant changes	Patras, Brunton, Da Pieve, and Butler (2009)
Grape by-products	600	70	60	50:50	Total anthocyanin content (41%) Anthocyanin monoglucosides (cyanidin (10%), delphinidin (18%), malvidin, petunidin (38%)) Acyated anthocyanin glucosides (cyanidin (7%), delphinidin (164%), malvidin (35%), peonidin (11%), petunidin (10%))	Corrales, Toepfl, Butz, Knorr, and Tauscher (2008)
	200–600	20–70	30–90	80:20–0:100	Total anthocyanin content (22–83%) Anthocyanin monoglucosides (58–130%) ((cyanidin (8–15%), delphinidin (up to 29%), malvidin (58–107), peonidin (46–150%), petunidin (477%)) Acyated anthocyanin glucosides (4–54%) (cyanidin (up to 15%), delphinidin (up to 7%), malvidin (5–26%), peonidin (8–82%), petunidin (12%)) Catechin (76%), caffeic acid (22%), ferulic acid (68%)	Corrales et al. (2009)
Korean black raspberry (<i>Rubus coreanus</i>)	500	60	5–15	100:0		Seo et al. (2011)
Longan fruit	200–500	30–70	2.5–30	50:50	Corilagin (up to 4-fold), ellagic acid (up to 20%), TPC (up to 2-fold higher) compared to CE.	Patras, Brunton, Da Pieve, and Butler (2009)
	200–500	30	30	50:50	Corilagin (up to 4-fold higher), TPC (up to 2-fold higher) compared to CE.	Prasad et al. (2010)
Litchi fruit pericarp	200–500	30–90	2.5–30	65:35 to 5:95	TPC (1.6%)	Prasad et al. (2009)
Orange juice with pulp	400	40	1	–	Naringenin (20%) and hesperetin (40%).	Sanchez-Moreno et al. (2005)
Propolis	500	RT	1	10:90	Flavonoids (4.5%)	Shouqin et al. (2004, 2005)
<i>Rhodiola sachalinensis</i>	400–600	20	15	–	Flavonoids (10%)	Zhang et al. (2007)
Tea leaves	100–600	RT	1–10	50:50	TPC (up to 30%)	Xi et al. (2009)
	100–600	RT	15	50:50	TPC (similar extraction yields of catechins and gallic acid after 400 MPa/15 min than organic solvent extraction for 2 h)	Jun et al. (2010)
	380	RT	10	20:80	Polyphenols (28%)	Shouqin et al. (2004)

RT: room temperature. CE: conventional extraction. TPC: total phenolic compounds.

100 MPa up to 600 MPa). The results showed that the extraction yields of these active ingredients with HP extraction (400 MPa) for only 15 min were the same as those of organic solvent extraction for 2 h (Jun et al., 2010).

The extraction of polyphenols from green tea was also carried out in a comparative study employing ultrasonic extraction, leaching extraction, reflux extraction, and HP extraction (380 MPa/RT/10 min). Solvents used in this study were water, methanol and ethanol (Shouqin et al., 2004). Results in this research showed that the achievable ratio (mass of essential components/mass of raw herb) of HP is the largest. Moreover, these authors also observed that HP extraction can greatly reduce the extraction time compared to all the other extraction methods studied.

2.2. Carotenoids

Some authors have reported that HP treatment can increase extractable carotenoid amount in plant-based products (Table 2). The increase in carotenoid extraction from HP-processed orange juice, persimmon purée, and tomato products could be attributable to various factors such as permeabilization of the plasma membrane cell and denaturation of the carotenoid-binding protein induced by HP (400–600 MPa/20–25 °C/2–15 min) (Sanchez-Moreno et al., 2004a, 2005).

In this line, Patras, Brunton, Da Pieve, Butler, and Downey (2009) investigated the effects of HP on carotenoid recovery from carrot purée. These authors observed a significant increase (3%) in total carotenoids after HP treatment at 600 MPa/RT/15 min. Other authors evaluated the feasibility of HP treatment to increase the amount of extractable carotenoids in fruit- and vegetable-based beverages obtaining good results.

Plaza, Sanchez-Moreno, De Ancos, and Cano (2006) found a significant increase of β -carotene, γ -carotene, lutein, lycopene, and lycopene-epoxide in HP-treated (400 MPa/40 °C/1 min) vegetable beverage. In another study, a significant recovery of β -criptoxanthin, zeaxanthin, lutein, β -carotene and α -carotene was observed in HP-treated orange juice with pulp (Sanchez-Moreno et al., 2005). It should be noted that the extractability of carotenoids in these samples was clearly influenced by HP treatment conditions, and it is necessary to conduct further investigation to establish the feasibility of selective extraction of these carotenoids.

De Ancos, Crespo, Sanchez-Moreno, Elez-Martinez, and Cano (2007) also found an increase in some individual carotenoids from papaya

slices when they used HP. Moreover, these authors also obtained an increase in total carotenoids content of persimmon purée after HP treatment (400 MPa/25 °C/1 min) (De Ancos, Gonzalez, & Cano, 2000).

HP impact on tomato and by-product's carotenoid recovery has been investigated by several authors. Krebbers et al. (2003) and Qiu, Jiang, Wang, and Gao (2006) found an improvement in lycopene yield of tomato purées (60% and 21%, respectively) when they used HP treatment (500 MPa/20–25 °C/2–12 min). In another study, Jun (2006) obtained a lycopene recovery of 92% from tomato waste when they applied HP at 500 MPa/room temperature/1 min, and 75% ethanol concentration.

2.3. Glucosinolates

Glucosinolates are alkyl aldoxime-O-sulfate esters with a β -D-thioglucopyranosyl at the aldoximecarbon in Z-configuration to the ester group synthesized by plants from any of the eight amino acids alanine, valine, leucine, isoleucine, phenylalanine, methionine, tyrosine, and tryptophan (Hayes, Kelleher, & Eggleston, 2008). They are found in most of the cruciferous vegetables, such as broccoli, Brussels sprouts, cabbage, cauliflower, and kale.

Various isothiocyanates such as sulforaphane, phenethyl isothiocyanate, and benzyl isothiocyanate with beneficial properties (Dinkova-Kostova & Kostov, 2012) are formed from glucosinolates by the action of myrosinase enzyme. However, during conventional thermal processing myrosinase is inactivated and it is not able to transform the glucosinolates into the beneficial products. Van Eylen, Oey, Hendrickx, and Van Loey (2007) and Van Eylen et al. (2009) compared the effects of conventional thermal treatments and HP treatment on isothiocyanates (ITC) degradation from broccoli juice and heads, respectively. These authors observed that HP treatment (100–500 MPa/20–40 °C/15–35 min) may lead to myrosinase catalyzed conversion of glucosinolates into isothiocyanates by enhancing cell disruption or membrane permeabilisation.

Van Eylen et al. (2009) also evaluated the impact of HP on glucosinolates and their degradation products (sulphoraphane, glucoraphanin, iberin). These authors observed a significant negative effect of treatment time on glucosinolates degradation mainly due to leaching. In addition, they found an increase in glucosinolate hydrolysis when pressure was higher. They explained this phenomenon due to cell permeabilisation during a pressure treatment, with the permeabilisation rate increasing with pressure. Overall, the authors observed an increase

Table 2
Effects of high pressure (HP)-assisted recovery of carotenoid from some plant food materials.

Plant food material	Treatment conditions			Solvent ratio water: ethanol (v/v)	Phenolic compounds increase	References
	MPa	°C	min			
Carrot purée	400–600	20	15	–	Increase in total carotenoids	Patras, Brunton, Da Pieve, and Butler (2009)
“Gazpacho soup”	400	60	15	–	Increase in extractable carotenoids (β -carotene, γ -carotene, lutein, lycopene, lycopene-epoxide)	Plaza et al. (2006)
Orange juice with pulp	400	40	1	–	β -Cryptoxanthin (43%), zeaxanthin (45%), lutein (75%), β -carotene (30%) and α -carotene (34%) contents.	Sanchez-Moreno et al. (2005)
Papaya slices (cv Sunrise)	400	25	1	Water:ethanol (100:0)	Increase in some extractable carotenoids (β -criptoxanthin, -criptoxanthin-5,8-epoxide, β -carotene, lutein, zeaxanthin, lycopene, neolycopene)	De Ancos et al. (2007)
Persimmon purée	400	25	15	–	TC (16%)	De Ancos et al. (2000)
Tomato purée	400	25	15	–	β -Carotene (36%) and lycopene (49%).	Sanchez-Moreno, Plaza, De Ancos, and Cano (2006)
	500	20	2	–	Lycopene (60%)	Krebbers et al. (2003)
	500	25	12	–	Lycopene (21%)	Qiu et al. (2006)
	400–600	20	15	–	Total carotenoids	Patras, Brunton, Da Pieve, Butler, and Downey (2009b)
Tomato paste waste	100–600	RT	1–10	Chloroform:ethanol (95:5, v/v) Ethanol:water (45:55–95:5, v/v)	Lycopene (up to 92% recovery)	Jun (2006)

–: without solvent.

in isothiocyanate formation after HP treatment although they did not find a clear trend in their formation. This is mainly due to the complex myrosinase–glucosinolate interactions that occur when HP treatment (100–500 MPa/20–40 °C/15–35 min) is applied. They also found that the degradation rates of the isothiocyanate sulforaphane and phenylethyl isothiocyanate were lower when they applied HP in comparison to thermal treatment (30–100 °C), concluding that myrosinase activity might be controlled by the use of HP treatments.

In line with this, Alvarez-Jubete, Valverde, Patras, Mullen, and Marcos (2014) also obtained a significant increase in total isothiocyanates after HP (200–600 MPa/20–40 °C/5 min) compared to blanching (90–95 °C/3 min), although with the spectrophotometric measurement they were not able to determine the isothiocyanate profile. Similarly, Penas, Limon, Vidal-Valverde, and Frias (2013) studied the effect of HP (300 MPa/40 °C/10 min) and subsequent refrigerated storage (3 months) on indole glucosinolate (GLS) breakdown products (ascorbigen, indole-3-carbinol and indole-3-acetonitrile) from naturally fermented cabbage and sauerkraut produced by fermentation with *Lactobacillus plantarum* and *Lactobacillus mesenteroides*. They did not observe significant modifications in indole-3-carbinol and indole-3-acetonitrile after HP and subsequent storage. However, they found significant losses (33–67%) in ascorbigen content after HP and 3 months storage.

3. Effect of HP on bioactive compounds and micronutrients bioaccessibility and bioavailability

The bioavailability and bioaccessibility of nutrients is highly dependent on the structure of the food matrix (Carbonell-Capella, Buniowska, Barba, Esteve, & Frígola, 2014). As HP can induce significant changes in the food structure, it can influence the bioavailability and bioaccessibility of components that are intracellularly located. From the discussion in Section 2, it is clear that HP may enhance the extractability of polyphenols, carotenoids, and glucosinolates, which may favor their bioaccessibility and bioavailability (Cilla et al., 2012). However, there is no simple and direct correlation between process-induced matrix disruption and the extractability and bioavailability of nutrients.

Van Buggenhout et al. (2010) noted in relation to carotenoids, that the influence of processing on bioaccessibility and potential bioavailability of nutrients is more complex than the positive effect that would be anticipated based on its effect on food matrix structure. Indeed, studies so far indicate that the impact of processing, in general and HP treatment in particular, on the bioaccessibility and bioavailability of nutrients is dependent on the type of nutrient, the structure and composition of the food matrix and the processing technique employed.

3.1. Micronutrients and phytonutrients

There are a number of studies in literature on the effects of HP on the bioaccessibility and bioavailability of nutrients. Most of these studies are in vitro bioaccessibility studies using simulated gastrointestinal digestion. Although, data from human intervention studies are required in order to conclusively establish the bioavailability of nutrients, such in vitro studies could be used as surrogates for estimation of pre-absorption events such as stability and bioaccessibility (Cilla et al., 2012; McInerney, Seccafien, Stewart, & Bird, 2007; Van Buggenhout et al., 2010).

McInerney et al. (2007) studied the effect of HP (400–600 MPa/RT/2 min) on carotenoid bioaccessibility in carrot, broccoli and green beans. HP did not have significant effect on the bioaccessibility of carotenoids in carrot. On the other hand, HP at 600 MPa slightly improved lutein bioaccessibility in green beans and reduced β -carotene bioaccessibility in broccoli.

Knockaert et al. (2011) conducted a study to determine the effects of thermal and HP-assisted pasteurization and sterilization processes on the bioaccessibility of β -carotene in carrots. In contrast to the study of

McInerney et al. (2007), mild ($10^4 F_{70\text{ °C}} = 2$ min: A process equivalent to 2 min treatment at 70 °C assuming $Z = 10$ °C) and intense thermal ($10^4 F_{90\text{ °C}} = 10$ min: equivalent to 10 min at 90 °C with $Z = 10$ °C) and HP (mild: 500 MPa/25 °C/16 min, intense: 600 MPa/45 °C/20 min) pasteurization processes resulted in a significant increase (37–75%) in the bioaccessibility of β -carotene in carrot compared to the raw sample. Interestingly, mild HP pasteurization resulted in 1.2 times higher bioaccessibility of β -carotene in carrots compared to mild thermal pasteurization. On the other hand, intense HP pasteurization and pressure assisted thermal sterilization (600 MPa/117 °C/ F_0 equivalent of 3 min) resulted in over 1.2 and 2.5 times lower bioaccessibility of β -carotene compared to intense thermal pasteurization and thermal sterilization ($F_0 = 3$ min) respectively. Thermal sterilization improved the bioaccessibility of β -carotene by about 80% while pressure assisted sterilization resulted in about 30% reduction compared to the raw sample (Knockaert et al., 2011).

An earlier study by the same group showed that the bioaccessibility of β -carotene in carrot tissue is inversely related to hardness (Lemmens, Van Buggenhout, Oey, Van Loey, & Hendrickx, 2009). Moreover β -eliminative degradation of pectin during thermal processing increases the tendency for intact cell separation rather than cell rupture as in raw tissue during mastication potentially leading to the encapsulation of carotenoids and reduced bioaccessibility (Van Buggenhout et al., 2010). Although, mild thermal pasteurization and mild HP pasteurization caused similar reduction in firmness, the softening in HP-pasteurized carrot tissue is mainly due to turgor pressure loss. This may explain the higher bioaccessibility of β -carotene in the sample that was subjected to mild HP pasteurization compared to mild thermal pasteurization. At the more intense pasteurization and sterilization conditions, thermal processing resulted in a softer tissue compared to HP treatment resulting in higher bioaccessibility in the thermally-treated samples (Knockaert et al., 2011).

The same group compared the influence of HP treatment (600 MPa/45 °C/20 min) on the bioaccessibility of β -carotene in HP-homogenized carrot puree with and without added olive oil. HP treatment did not improve the bioaccessibility of β -carotene in the HP-homogenized puree whereas an equivalent thermal pasteurization ($10^4 F_{90\text{ °C}} = 10$ min: equivalent to 90 °C/10 min at $Z = 10$ °C) more than doubled the bioaccessibility of β -carotene with 20–30% higher bioaccessibility observed in samples with added olive oil (Knockaert et al., 2012a).

Gupta, Kopec, Schwartz, and Balasubramaniam (2011) compared the effect of thermal processing (TP) (93 °C/60 s), HP (500–700 MPa/30 °C/0–10 min) and pressure assisted thermal processing (PATP) (500–700 MPa/100 °C/10 min) on the bioaccessibility of lycopene in tomato juice. Although HP and PATP resulted in up to 12% increase in the extractability of lycopene, this was not translated into improvement in bioaccessibility. Regardless of the processing method, less than 0.5% of lycopene appeared in micellar form and was therefore bioaccessible. More prominent lycopene crystals appeared in pressure treated samples. However, the crystals appeared to be enveloped in all the processed samples. Moreover, higher extent of all-trans- β -carotene micellarization was observed in processed juice compared to raw juice. 15–30% improvement in all-trans- β -carotene micellarization was observed in hot break juice subjected to pressure assisted thermal processing compared to raw juice that has undergone the same process.

Knockaert et al. (2012b) investigated the effects of equivalent thermal and HP pasteurization and sterilization processes on the bioaccessibility of lycopene in HP-homogenized (10 MPa) hot break (95 °C/8 min) tomato puree containing oil. Mild and intense thermal pasteurization ($4.3^3 F_{60\text{ °C}} = 1$ min: equivalent to 60 °C/1 min at $Z = 4.3$ °C and $10^4 F_{90\text{ °C}} = 10$ min: equivalent to 90 °C/10 min at $Z = 10$ °C, respectively) or mild and intense HP pasteurization (450 MPa/20 °C/15 min and 600 MPa/45 °C/20 min, respectively) did not have significant effects on the bioaccessibility of lycopene. A significant decrease (~30%) in the relative bioaccessibility of lycopene was observed after thermal

sterilization ($F_0 = 1.5$ and 3 min) and HP-assisted sterilization (600 MPa/117 °C/holding times of 1.7–3 min or 4.5–10 min), although these were mainly attributed to the oxidative degradation of lycopene during the processes (Knockaert et al., 2012b).

Cilla et al. (2012) compared the effect of HP (400 MPa/40 °C/5 min) and TP (90 °C/30 s) on the bioaccessibility of carotenoids in 12 milk based fruit beverages where the milk component is skimmed milk, soymilk or whole milk. Both HP and TP decreased the bioaccessibility of carotenoids in all the beverages, although bioaccessibility in HP samples was significantly better than TP. The authors also investigated the effect of these processes in the bioaccessibility of tocopherol and vitamin C. HP maintained the bioaccessibility of tocopherol in the skimmed milk and whole milk based beverages, while a significant decrease was observed in the soy milk beverage. On the other hand TP/30 s caused a significant decrease in bioaccessibility of tocopherol in all the beverages. The opposite was observed in the case of vitamin C where TP improved the bioaccessibility of vitamin C in all the beverages while HP decreased it (Cilla et al., 2012). Clearly, the conflicting results observed for the various nutrients in different matrices reflects the importance of factors such as the type of nutrient (hydrophilic, lipophilic) (Van Buggenhout et al., 2010), matrix structure, and matrix composition (e.g., the amount of absorption factors such as fibers, fats, phytosterols) (Cilla et al., 2012) and the interaction of the applied processes with these factors on determining the bioaccessibility and eventual absorption of nutrients and phytonutrients.

Only a handful of human intervention studies have been reported on the effect of HP on the bioavailability of nutrients. Sanchez-Moreno et al. (2003a) conducted a study to determine the bioavailability of vitamin C from HP-treated orange juice. They did not find significant differences with the result obtained after the consumption of fresh and HP-treated orange juice. However, in another study by the same group, it was found that consumption of 500 mL per day of HP-treated (400 MPa/40 °C/1 min) orange juice significantly elevated plasma vitamin C concentration in healthy subjects, indicating that vitamin C in HP-treated orange juice is bioavailable (Sanchez-Moreno et al., 2003b). The level of biomarkers of oxidative stress and inflammation, F2-isoprostanes, uric acid, C-reactive protein and prostaglandin E2 also lowered significantly at the end of the 14 day study, indicating that consumption of orange juice may help to decrease the risk of chronic diseases (Sanchez-Moreno et al., 2003b). However, the study did not compare the effect of HP with other processing techniques on the bioavailability of vitamin C in orange juice. Similar results were reported for the consumption of HP treated 'gazpacho' vegetable soup (Sanchez-Moreno et al., 2004b).

Apart from its effect on food structure, HP may influence the bioavailability of nutrients through its effect on the activity of endogenous enzymes. For instance, folates in vegetable sources usually exist in the less bioavailable polyglutamate forms. Upon cell decompartmentalization, the endogenous enzyme γ -glutamyl hydrolase hydrolyses the polyglutamyl folates into the more bioavailable short-chain or monoglutamyl folates. However, processes such as freezing are usually preceded by blanching, which inactivate this enzyme, preserving the long chain polyglutamyl folates and thereby reducing the bioavailability of folates from such sources (Wang, Riedl, Somerville, Balasubramaniam & Schwartz, 2011).

HP treatment enables cell decompartmentalization without inactivation of the enzyme and facilitates the hydrolysis of long chain polyglutamyl folates potentially improving their bioavailability. A study by Melse-Boonstra et al. (2002) compared the effects of various treatments at pilot and large scales on the formation of monoglutamate folates in leeks, cauliflower and green beans. The pilot scale study compared blanching (boiling water, 10 min); freezing (−18 and −80 °C) followed by refrigerated (4 °C) thawing and blanching; freeze-drying, followed by rehydration, 6 h refrigeration and blanching; and HP (50–200 MPa/RT/5 min), followed by 6 h storage and blanching on the formation of monoglutamate folates in leeks. HP (200 MPa/RT/5 min)

and freezing (−18 °C/16 h) and thawing (4 °C, 24 h) resulted in the highest yield of monoglutamate folates.

Further investigation at a larger scale compared the effects of blanching; steaming; HP (200 MPa/RT/5 min); freezing (−18 °C) followed by refrigerated thawing and blanching; HP (200 MPa/RT/5 min) followed by blanching; blanching followed by freezing and refrigerated thawing; and blanching followed by HP (200 MPa/RT/5 min) on the formation of monoglutamate folates in leeks, cauliflower and green beans. Freezing–thawing–blanching and HP (200 MPa/RT/5 min)–blanching caused the highest loss of total folates of 85% in leeks, 65 and 55% respectively in cauliflower and 79 and 81% respectively in green beans. The lowest total losses of 16–38% were observed in samples that were blanched or steamed regardless of the subsequent process.

On the other hand, both blanching and steaming reduced the proportion of monoglutamate folates in all the vegetables compared to the raw sample from 33% to 6 and 11% respectively in leeks, from 9% to 3 and 2% respectively in cauliflower and from 33% to 7 and 2% respectively in green beans. Similar reductions were observed in samples subjected to blanching prior to freezing or HP. In contrast, HP or HP followed by blanching resulted in an increase in proportion of monoglutamate folates to 74 and 65% respectively in leeks and 82 and 72% respectively in green beans, whereas the effect was less significant in cauliflower with 9 and 12% respectively after HP and HP–blanching. Freezing–thawing–blanching had a similar effect of significantly boosting the proportion of monoglutamate folates in all the vegetable (Melse-Boonstra et al., 2002).

Wang, Melnyk, Tsao, and Marcone (2011) studied the influence of HP on the polyglutamyl chain of 5-methyltetrahydrofolate (5MTHF) in carrot greens, baby carrots and cauliflower. HP was conducted at 300, 450 and 600 MPa and 30 °C for 0 and 5 min. HP at the various conditions investigated significantly increased the conversion of 5MTHF to short chain and monoglutamyl forms and the highest extent of conversion to the monoglutamyl forms occurred at 600 MPa and 5 min with 4, 23, and 2.5 fold increases of the monoglutamyl content in cauliflower, baby carrot, and carrot greens, respectively.

3.2. Minerals

It is known that minerals are part of a healthy diet required to maintain essential metabolic processes in the body. Nevertheless, the intake of these essential minerals through the daily diet is not always guaranteed. Important minerals such as calcium, iron, phosphorous, potassium, magnesium, and zinc are often lacking in the human body due to inadequate intake or insufficient bioavailability or bioaccessibility (Cilla et al., 2011). HP does not affect minerals as such, but may affect the food matrix resulting in improved bioavailability and health benefits. The studies on the HP effects on minerals are scarce and Table 3 summarizes results of the recent studies.

HP treatment of apple at 500 MPa for short times (2–10 min) increased the content of minerals markedly by 2–303% for Ca, 4–11% for Fe, and 8–28% for Zn (Briones-Labarca, Venegas-Cubillos, Ortiz-Portilla, Chacana-Ojeda & Maureira, 2011). It was suggested that the pressurization disrupted the plant cell walls and thereby released the minerals into the extracellular phase. The bioaccessibility of the minerals was assessed by in vitro solubility and digestibility assays, and surprisingly, it was evident that the bioaccessibility was not dependent on the concentration of the minerals in the extracellular content. The HP treatment lowered the dialysability of calcium considerably, while it slightly increased the dialysability of iron and zinc.

The pressurization of algarrobo (*Prosopis chilensis*) seeds decreased the total contents of calcium, iron, and zinc but improved the bioaccessibility of iron and zinc in the seed treated at 500 MPa for 10 min (Briones-Labarca, Munoz, & Maureira, 2011).

It is well known that meat contribute to the intake of iron, though the effect may be positive or negative on health depending on the

Table 3
Effect of high pressure (HP) treatment on minerals.

Product	Treatment conditions	Major findings	References
Apple	500 MPa/20 °C/2, 4, 8, and 10 min	Ca, Fe, and Zn content increased. Minerals dialysability and solubility were reduced by HP.	Briones-Labarca et al. (2011)
Beef, cooked ham, and dry ham	600 MPa/31 °C/10 min	No significant differences were found in Ca, K, Mg, Na, Cu, Fe, and Zn content.	Garcia-Regueiro et al. (2002)
Bovine milk	100–300 MPa/9 or 20 °C/15 min	Ca and P released from the micelles.	Regnault et al. (2006)
Bovine skim milk	200–600 MPa/60 min	No significant effect on Ca activity.	Johnston et al. (1992)
Bovine whole milk	100, 250, 400, and 600 MPa/20 °C/30 min	Increased concentration of ionic Ca irrespective of pressure.	Zobrist et al. (2005)
Bovine, caprine, and ovine milks	100–400 MPa/20 °C/5–30 min	Increased levels of Ca, P, and Mg in the serum, but small increase in the Ca ²⁺ .	Lopez-Fandino et al. (1998)
Milk-based fruit juices	400 MPa/36 °C/5 min	HP improved Ca and P bioaccessibility, but only improved P bioavailability.	Cilla et al. (2011)
Goat milk	100–500 MPa/20 and 40 °C/10 min	No significant effect on levels of colloidal Ca and inorganic P.	Law et al. (1998)
Reconstituted skim milk	Up to 700 MPa/20 °C/22 min	A slight increase in Ca up to 200 MPa, then return to the initial value.	Desobry-Banon et al. (1994)
Reconstituted skim milk	250, 450, and 600 MPa/4, 20, and 40 °C/30 min	A slight solubilization of Ca and P.	Gaucheron et al. (1997)
Seed of <i>Prosopis chilensis</i>	500 MPa/20 °C/2, 4, 8, and 10 min	Ca, Fe, and Zn content decreased, but mineral dialysability and solubility were increased at 500 MPa, 10 min.	Briones-Labarca, Munoz, and Maureira (2011)

amount of meat consumed. However, meat also contains other essential minerals. To our knowledge, only one study investigated the mineral composition in different meat products subjected to HP treatment, and no significant change in the mineral content was found after pressurization at 600 MPa (Garcia-Regueiro et al., 2002).

On the other hand, as evident from Table 3, the impact of HP on milk minerals has been investigated to a much larger extent. HP treatment of milk changes the mineral balance in general and of calcium in particular between the micellar and serum phases. Regnault, Dumay, and Cheftel (2006) observed an increased concentration of both Ca and P in the serum phase 1–2 h after pressurizing raw skim milk up to 300 MPa. An increasing concentration of Ca, P and Mg in serum upon increasing pressure to 400 MPa was also reported for bovine, caprine, and ovine milk immediately after HP treatment (Lopez-Fandino, la Fuente, Ramos, & Olano, 1998).

Zobrist, Huppertz, Uniacke, Fox, and Kelly (2005) found a 12% increase in ionic calcium after pressurization and incubation at 30 °C for 15 min, but reported that the concentration of ionic calcium was reversed within 4 h upon storage at 20 °C. However, non-significant changes or only small effect of HP on milk minerals was found by different authors (Desobry-Banon, Richard, & Hardy, 1994; Gaucheron et al., 1997; Johnston, Austin, & Murphy, 1992; Law et al., 1998). The milk system is a complex system and especially the micelles are dynamic in nature and the effect of pressure is very dependent on pressure level, time, and temperature (Orlien, Boserup, & Olsen, 2010; Orlien, Knudsen, Colon, & Skibsted, 2006).

Moreover, the observed HP effect is extremely dependent on the time between pressurization and measurement, and of measurement conditions. Two opposing phenomena affect the results. On the one hand, the conversion process between soluble (serum) calcium and insoluble (micelle) calcium is reversible, and will change back and forth depending on the milk conditions. On the other hand, released minerals from the micelles may bind to proteins or inorganic compounds.

One study investigated the effect of HP on the transport and bioavailability of milk minerals using a cell based assay utilizing Caco-2 cells. The study showed that HP treatment (400 MPa/36 °C/5 min) of milk based (whole, skimmed, and soya) fruit (orange, pineapple, kiwi, and mango) beverages positively modulated Ca and P bioaccessibility and P bioavailability (Cilla et al., 2011). They found that Ca solubility, transport, and Caco-2 uptake did now show parallel trends. Thus, although the calcium may be in a solubilized form, and available for absorption in the body, other factors influenced the Ca uptake.

4. Effect of HP on allergenicity of food

Food allergies are increasing in developed countries and some evidence indicates an increase also in less studied, developing countries (Perry, Conover-Walker, Pomes, Chapman, & Wood, 2004; Wang & Sampson, 2011). Most allergenic proteins, particularly plant allergens, appear to belong to a limited number of proteins with common characteristics that may render them allergenic (Breiteneder & Mills, 2005; Jenkins, Griffiths-Jones, Shewry, Breiteneder, & Mills, 2005; Radauer & Breiteneder, 2006).

The most frequently reported food allergies are allergies to bovine milk, eggs, apples, peanuts, shellfish, soy, and wheat (Cianferoni & Spergel, 2009). True allergens (epitope sources) are protein molecules found in bovine milk (whey proteins such as β -lactoglobulin, α -lactalbumin), egg white (ovalbumin), birch pollen (Bet v 1) and apples (Mal d 1), carrot (Dau c 1), celery (Api g 1), peanut (Ara h 1) and many others (Besler, Steinhart, & Paschke, 2001; Breiteneder & Mills, 2005). The most dangerous allergens, due to severe patient reactions, are members of the prolamin family, so called lipid transfer proteins (LTPs). They are often referred to as heat stable. Apple allergen Mal d 3 and peanut allergen Ara h 2 reportedly have the highest prevalence of sensitized patients in south European states such as Spain, Italy and the USA (Cianferoni & Spergel, 2009; Mills & Mackie, 2008).

The different methods of storing and processing foods complicate analysis of the structural and functional properties of allergens that contribute to enhanced or reduced allergenicity (Maleki et al., 2003). During the manufacture of food, their allergenicity may be altered by various processing parameters. The allergenic activity may be unchanged, decreased or even increased by food processing. The molecular basis of changes in the allergenic activity is the inactivation or destruction of epitopes structures or the formation of new epitopes or better access of cryptic epitopes by denaturation of the native allergen.

Moreover, allergen contamination can occur in processed foods (Besler et al., 2001).

HP treatment can give rise to structural changes in proteins and, therefore, has been used to alter conformation and allergenic potential of food proteins. Furthermore, HP has shown potential to reduce the allergy risks of some foods without eliminating the allergenic proteins themselves, but through extraction or release of membrane-bound allergens into the environment where they can be removed or attacked by hydrolytic enzymes (Kato, Katayama, Matsubara, Omi, & Matsuda, 2000). It is also known that HP can accelerate the activity of some enzymes (Knorr, Heinz, & Buckow, 2006). For example, this effect has

been successfully used for accelerated enzymatic hydrolysis of β -lactoglobulin in dairy products (Zeece, Huppertz, & Kelly, 2008) and bovine serum albumin in beef extracts (Han, 2006) reducing their allergenic potential.

HP has been reported to reduce the allergenic potential and risk of a number of products (Table 4), primarily of nuts, fruits and vegetables, dairy products and seafood (Huang, Hsu, Yang, & Wang, 2014). However, there is a high degree of variability between studies possibly due to the different methods deployed to establish the changes in allergenic potential. Most commonly, methods like ELISA and immuno-assay blots, SDS-page or simply by structural analysis through Fourier transform infrared (FTIR) or circular dichroism (CD) spectroscopy have been applied.

4.1. Dairy products

A few studies have been conducted regarding the modification that HP may induce in true allergy targets found in milk-based products.

β -Lactoglobulin (β -lg) is the major allergen in bovine milk. It is the main whey protein fraction in the milk of many mammals; however, it is absent in human breast milk.

HP treatment of whey and skim milk at 200 to 600 MPa and 20 to 68 °C significantly increased the antigenicity response of β -lg by up to 14 fold (Table 4) possibly due to weakening of non-covalent bonds under pressure resulting in a better accessibility for the antibodies (Kleber, Maier, & Hinrichs, 2007). This effect increased with increasing pressure but also holding time and treatment temperature were important parameters to modulate the antigenicity of β -lg in milk products. Another study indicated that HP treatment of β -lg solutions at 200 and 400 MPa (for 20 min at RT) increased the binding to β -lg specific rabbit IgG but did not affect the binding to IgE from allergic patients (Chicon, Lopez-Fandino, Alonso, & Belloque, 2008). The increase in antigenicity may be associated with exposure of epitopes of the native protein molecule which becomes accessible for antibodies after pressure-induced unfolding and aggregation (Bu, Luo, Chen, Liu, & Zhu, 2013).

Table 4
Effect of HP treatment on allergens in different foods.

Food allergen source	Treatment conditions	Observations	Reference
Apple	600 MPa/RT/5 min	Structural alteration of Mal d 1 detected by circular dichroism and FTIR	Scheibenzuber (2003) Meyer-Pittroff, Behrendt, and Ring (2007) Fernandez et al. (2009) Johnson et al. (2010) Johnson et al. (2010)
	600 MPa/RT/5 min	Hyposensitization of patients against apple allergy after 3 weeks immunotherapy with HP treated apple samples.	
	400–800 MPa/60 °C/10 min	IgE binding capacity of Mal d 1 was not affected.	
	150–700 MPa/20 °C/10 min	Minor changes in structure and allergenicity of Mal d 1b; Mal d 3 unaffected.	
	400–700 MPa/80 °C/10 min	Immunoreactivity of Mal d 3 was reduced by 50–60%. Mal d 1b only showed minor structural and immunoreactivity changes. Changes were attributed to aggregation and heat during treatment.	
	700 MPa/20 °C/60 min	30% decrease of immunoreactivity of Mal d 3. No significant reduction of Mal d 3	Husband et al. (2011) Husband et al. (2011) Somkuti, Houska, and Smeller (2011)
	700 MPa/115 °C/10 min	75% loss of Mal d 1 and Api g 1 reactivity	
	100–1200 MPa/30 °C/5 min	Mal d 1 irreversibly unfolds at pressures of 150–250 MPa as detected in-vitro by FTIR.	
Celery	500 MPa/50 °C/10 min	No significant change of Api g 1 allergenicity; however, structural changes observed CD	Houska et al. (2009) Husband et al. (2011)
	700 MPa/118 °C/10 min	Some changes and reduction of Api g 1 allergenicity	
Milk	200–600 MPa/25–68 °C/10–30 min	The antigenicity of β -lactoglobulin increased with an increase in pressure and holding time, but decreased with increasing treatment temperature. Antigenicity of β -lg in milk increased up to 14 fold after treatment at 600 MPa/25 °C/10 min compared to untreated milk.	Kleber et al. (2007) Chicon et al. (2006)
	100 MPa/RT/20 min	HP treatment of milk in the presence of chymotrypsin and trypsin accelerated the proteolysis of β -lg, resulting in a rapid decrease of allergenic potential. However, some hydrolysates retained some residual IgE-binding properties that could be traced to the preferential release	
	500 MPa/40 °C/30 min	Tryptic and chymotryptic hydrolysis of β -lg and α -lactalbumin (α -la) under HP significantly decreased residual immunochemical reactivities compared to atmospheric pressure hydrolysed controls	
Prawns	600 MPa/25 °C/10 min	King prawn tropomyosin reactivity was reduced by 63% as detected by ELISA and IgE assays	Senay et al. (2008) Liu and Xue (2010) Johnson et al. (2010)
Silver carp	100–300 MPa/20 °C/10–60 min	No change of the allergenicity of silver carp allergens was detected by IgE immunoblotting.	
Peanuts	150–700 MPa/20–80 °C/10 min	Treatment did not affect structure and allergenicity of Ara h 2, 6	
Almonds	500 MPa/37 °C/10 min	HP treatment alone had no effect on major peanut allergens. However, HP at 500 MPa combined with polyphenol oxidase induced a major reduction of peanut allergens and IgE binding.	Li et al. (2013) Dhakal et al. (2014)
	600 MPa/4–70 °C/5–30 min	HP treatment did not change allergenicity and IgE binding capacity of almond proteins.	
	450 and 600 MPa/30 °C/0.5–10 min	Amandin immunoreactivity was undetectable by ELISA in almond milk after all HP treatments. However, this was likely due to the loss of protein solubility (up to 75%), rather than the epitope destruction by HP	
Sesame	100–500 MPa/RT/10 min	HP markedly decreased the antigenicity of sesame proteins especially at 400 and 500 MPa and pH 7 and 10 possibly due to unfolding proteins into a more tightly packed structure obscuring the allergen epitopes,	Achouri and Boye (2013)
Soybean	300 MPa/40 °C/15 min	Treatment resulted in a significant decrease in allergenicity of soybean sprout proteins while the nutritional value was largely retained.	Penas, Gomez, Frias, Baeza, and Vidal-Valverde (2011) Li, Zhu, Zhou, and Peng (2012) Yamazaki and Sasagawa (1998)
Soy protein isolate	300 MPa/RT/15 min	Treatment resulted in structural changes of soy protein and reduced allergenicity by 48.6%.	
Rice	400–600 MPa/20 °C/30 min	Glutelin and prolamin are solubilized and released from the rice grain	
	300–400 MPa/20 °C/30 min	HP treatment resulted in the release of major rice allergens into the surrounding solution. Allergen content disappeared when HP treated in the presence of protease-N enzyme.	Kato et al. (2000)

On the other hand, HP-induced conformational changes of proteins facilitates enzymatic digestion. Chicon, Lopez-Fandino, Quiros, and Belloque (2006) successfully applied proteolytic enzymes (chymotrypsin and trypsin) during HP treatment of β -Ig solutions. The IgE-binding capacity of the resultant hydrolysates was lower after only 20 min HP treatment (100 MPa/RT) than after 8 or 48 h enzyme hydrolysis at ambient pressure. Similarly, other studies used proteolytic enzymes to hydrolyze whey protein isolates during HP treatments at 100 to 300 MPa (Beran et al., 2009; Penas, Prestamo, Luisa Baeza, Martinez-Molero, & Gomez, 2006). The resulting peptides exhibited reduced antigenicity and IgE binding depending on the used enzyme and treatment conditions. However, immunoreactivity was generally lower in HP treated systems than those treated at ambient pressure. Again, this reduction was explained by an increase of accessibility of potentially immunogenic hydrophobic regions to the enzyme, thereby resulting in an improved hydrolysis (Bonomi et al., 2003). Hence, HP application during enzymatic hydrolysis of whey proteins can be used to rapidly prepare hypoallergenic foods possibly with better sensory and nutritional attributes.

4.2. Nuts, peanuts, walnuts and almonds

Hazel nuts, peanuts, walnuts and almonds (though the last three are botanically not nuts) are common sources of severe food allergies. A few studies have been conducted using HP to modify and/or reduce the allergenic risk of peanuts and almonds (Table 4). HP treatment alone for 10 min at up to 700 MPa and 80 °C did not significantly change the structure and IgE binding of peanut allergen Ara h 2 (Chung, Houska, & Reed, 2013; Johnson et al., 2010). Similarly, Li et al. (2013) did not find a change of allergenicity and IgE binding capacity of almond proteins after HP treatments at 600 MPa and up to 70 °C for 30 min. In this line, it was found that HP treatment (500 MPa/37 °C/10 min) alone had no effect on major peanut allergens, whereas, application of 500 MPa/37 °C/3 min in combination with polyphenol oxidase induced a two-fold reduction of major peanut allergens and IgE binding compared to enzyme only treatments (for up to 10 min) (Chung et al., 2013).

4.3. Fruits and vegetables

Many fresh fruits and vegetables can cause an oral allergy syndrome in affected persons which is caused by a cluster of allergic reactions in the mouth in response to food intake. Cooking or peeling can often reduce the allergenic potential of these foods which is why some fruit allergens are considered sensitive to treatment.

Scheibenzuber (2003) evaluated the effects of HP treatment on allergenicity and structural changes of Mal d 1, which is the major allergen in apple, and also in Bet v 1-like proteins (Bet v 1-related food allergens), which are the main allergens found in apples, hazelnuts, carrots, peaches and celery. He found important modifications in allergens, observing that 19 allergic patients tolerated HP-treated apple Mal d 1 (600 MPa/RT/5 min) without symptoms of oral allergy syndrome. Prick to prick tests show a correlation between allergen inactivation and applied pressure level. HP treatment caused evident structural changes in allergens as indicated by CD and FTIR spectra. Similarly, the immunoreactivity of the apple allergen Mal d 3 was decreased 30% after treatment at 700 MPa and 20 °C for 60 min (Husband et al., 2011). On the other hand, many other studies did not find significant reductions of (extracted) apple Mal d 1 and Mal d 3 (Fernandez, Butz, & Tauscher, 2009; Johnson et al., 2010) even after intense HP treatments at up to 800 MPa and 60 °C for 10 min (Table 4). However, reactivity of apple Mal d 1 and Api g 1 could be reduced up to 75% if HP was combined with temperature treatment at 80 °C or 115 °C (Husband et al., 2011; Johnson et al., 2010).

Combined HP and thermal treatment also reduced the allergenicity of celery Api g 1 (Husband et al., 2011), whereas HP alone at up to

500 MPa and 50 °C for 10 min did not change Api g 1 allergenicity despite the observed structural changes (Houska et al., 2009). HP treatment at 400 to 550 MPa and 50 °C for 10 min changed the secondary structure of carrot allergen rDau c 1 (Heroldova et al., 2009). However, this change was not accompanied by a reduction of allergenicity as detected by skin prick test and basophil activation test.

4.4. Other products

The effect of HP treatments on a few other food allergens, including those of fish and shellfish, rice and legumes, has been investigated (Table 4). Liu and Xue (2010) treated the silver carp allergen with HP (100–300 MPa/20 °C/10–60 min). The secondary structure of the allergen had changed after the pressure treatment, while the protein composition, molecular weight, and allergenicity were not affected.

HP treatment at 600 MPa and 30 °C for 10 min resulted in significant loss of tropomyosin ELISA reactivity (37%) in raw king prawns but not in black tiger prawns (12% loss) (Senay, Buckow, O'Hehir, & Lopata, 2008). However, this HP treatment was not effective in reducing residual levels of tropomyosin in already cooked raw king prawns.

Kato et al. (2000) studied the effect of HP on natural allergens from rice grains (*Oryza sativa* L. *japonica* var. Akitakomachi). These authors observed that when HP treatments (100–400 MPa/20 °C/30–120 min) were applied to rice grains immersed in distilled water, low molecular weight proteins, including the major rice allergens, were preferentially released, with maximum amounts obtained in the pressure range 300–400 MPa. However, no apparent structural changes in protein bodies were detected. They also obtained that pressure-released proteins were predominantly Glb33, α -Glb, and the albumin Alb16, suggesting that the removal of allergens by pressurization alone was insufficient to reduce allergenic activity due to the fact that 80% of Al 16 albumin and α -Glb remained in the pressurized grains. However, they found that allergenic proteins from rice grains were completely eliminated by pressurization in the presence of protease.

Zhang, Li, Tatsumi, and Kotwal (2003) showed that soybean glycinin was denatured completely after processing at 400 MPa/10 min. Moreover, some of the glycinin's α -helix and β -sheet structures were destroyed and converted into random coils after processing at 500 MPa/10 min.

5. Effect of HP on preserving lipids and reducing salt

The promising application of HP treatment to produce healthy food products is not exclusively limited to improving the recovery and bioavailability of bioactive compounds and reducing allergenicity. Nowadays, the growing interest in HP technology is to increase the range of food products that are safe, stable and healthy. The later not limited to increasing the bioaccessibility of naturally occurring bioactive compounds, but from a technological point of view, to obtain minimally modified compounds or changed/improved functionality. A change in functionality can have a positive health impact by avoiding negative health additives like salt and phosphates. Table 5 summarizes the various studies on how to utilize HP to produce healthy food products.

5.1. Lipids

Seafood contains healthy polyunsaturated lipids (PUFA), especially the fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), and is, therefore recommended in a healthy diet. However, seafood is also very sensitive towards various degradation reactions and processes resulting in a very short shelf-life of often less than 7 days for fresh fish and shellfish. The hydrolysis of lipids by lipase enzymes results in free fatty acids (FFA), and of special concern are the polyunsaturated fatty acids (PUFAs), which are highly reactive and easily oxidized, resulting in lower nutritional value of the fish.

Table 5

Effect of HP on lipid composition and salt content or perception.

Lipid	Treatment conditions	Major findings	References
<i>Fish and shellfish</i>			
Carp	100, 140, 180, and 200 MPa/4 °C/15 and 20 min	Free fatty acid levels increased.	Sequeira-Munoz et al. (2006)
Oyster	260 (3 min), 500 (5 min), or 800 (5 min) MPa/20 °C	No significant change in fatty acid profile.	Cruz-Romero et al. (2008)
Salmon	135, 170, and 200 MPa/15 °C/30 s	HP led to an increased free fatty acid formation.	Ortea et al. (2010)
Salmon	150 and 300 MPa/20 °C/15 min	No significant change of total saturated, monoenes, n – 3, and n – 6 fatty acid profile.	Yagiz et al. (2009)
Sardine	300 MPa/20 °C/15 min	Significant increase in FFA of HP sardine with and without coatings.	Gomez-Estaca et al. (2007)
Turbot	100, 140, 180, and 200 MPa/4 °C/15 and 30 min	No significant change in free fatty acid values.	Chevalier et al. (2001)
<i>Milk</i>			
Ewe milk	100–500 MPa/4, 25, and 50 °C/10 and 30 min	Pressurized milk had lower free fatty acid levels than control.	Gervilla et al. (2001)
Orange juice–milk and vegetable beverage	100, 200, 300, and 400 MPa/15 °C/9 min	No change in fat content. No change in SFA, MUFA, and PUFA for vegetable beverage. No change in PUFA for orange juice–milk. A significant decrease in SFA and a significant increase in MUFA for orange juice–milk.	Barba et al. (2012b)
Milk	200 MPa/–4 °C/10, 20, and 30 min	The concentration of short-chain fatty acids increased.	Kim et al. (2008)
<i>Meat</i>			
Beef <i>pectoralis profundus</i>	200, 300, and 400 MPa/20 and 40 °C/20 min	No change in fatty acid profile was found.	McArdle et al. (2010)
Beef <i>pectoralis profundus</i>	400 and 600 MPa/35, 45, and 55 °C/20 min	A significant increase in n – 6/n – 3 fatty acid ration was found.	McArdle et al. (2011)
Beef <i>M. sternomandibularis</i>	200 or 800 MPa/60 °C/20 min	HP significantly affected the concentration of several fatty acids.	Tume et al. (2010)
Pork <i>longissimus</i>	200, 350, and 500 MPa/20 °C/20 min	No significant effect on the content and fatty acid composition of total lipids and triglycerides. A significant increase in free fatty acids.	He et al. (2012)
Pork <i>longissimus</i> ± EDTA	500 MPa/20 °C/20 min	No change in total lipids and composition. Significant increase in free fatty acids.	Huang et al. (2012)
<i>Saltiness</i>			
<i>Dry-cured meat</i>			
Dry-cured loin and Iberian chorizo	600 MPa/15 °C/5 min	Higher salty taste.	Bover-Cid et al. (2011)
Dry-cured ham	600 MPa/15 °C/6 min	HP increased saltiness perception.	Clariana et al. (2011)
Dry cured-restructured minced pork	500 and 600 MPa/13 °C/7 min	HP allows production of drycured meat with reduced salt without affecting appearance.	Ferrini et al. (2012)
Dry-cured restructured ham	600 MPa/10 °C/6 min	K-lactate (reduced salt content) and HP had no effect on color and increased saltiness.	Fulladosa et al. (2012)
Dry-cured restructured ham	600 MPa/10 °C/6 min	K-lactate (reduced salt content), transglutaminase, and HP increased saltiness, umami, and sweetness.	Fulladosa et al. (2009)
Parma ham	600 MPa/3, 6, and 9 min	HP-treated hams have a saltier taste.	Tanzi et al. (2004)
<i>Meat products</i>			
Beef sausage	0–400 MPa/10 °C/2 min	Sensory panels reported a greater acceptability of HP treated sausages of lower salt.	Sikes et al. (2009)
Chicken batters	500, 700, and 900 MPa/40 °C/30 min	Microbial transglutaminase and HP (reduced salt content without phosphates) produced gels with enhanced textural properties.	Trespalacios and Pla (2007)
Frankfurter	150 or 300 MPa/20 °C/5 min	Panelists preferred products formulated at 1.5% salt after HP at 150 MPa.	Crehan et al. (2000)
Pork and chicken batters	200 and 400 MPa/60, 70, and 80 °C/30 min	Pressure-induced gels had lower binding and textural properties.	Jimenez-Colmenero et al. (1998)
Pork sausage	400, 600, and 800 MPa/5 and 40 °C/5 min	Carrot fiber or potato starch (reduced salt content without phosphates) and HP improved texture and water binding.	Grossi et al. (2012)
Pork sausage	200, 300, and 400 MPa/10 min	200 MPa produced a low salt sausage with good sensory and technological quality.	Hayes and Allen (2011)
Restructured pork	200 MPa/4 °C/30 min	Glucono-δ-lactone, κ-carrageenan, and HP resulted in high binding characteristics and minimal discoloration.	Hong et al. (2008)
Various meat products	150 or 300 MPa (unknown T and t)	HP reduced the need for fat, salt, and phosphate in meat products without significantly altering their quality.	Troy et al. (2001)
<i>Other</i>			
Cheddar cheese	405 MPa/9 °C/3 min	Non-treated and HP-treated cheeses had similar sensory flavor profile during ripening.	Ozturk et al. (2013)

Consequently, new production and/or preservation techniques have attracted interest by both industry and the consumer.

A number of studies have been conducted on the effects of HP on fatty acid composition of sea foods. Immediately after pressure treatment there was no significant change of the fatty acid composition in Atlantic salmon dark muscle (150 and 300 MPa/20 °C/15 min) (Yagiz et al., 2009) and turbot muscle (100, 140, 180, and 200 MPa/4 °C/15 and 30 min) (Chevalier, Le Bail, & Ghoul, 2001). Storage of the pressurized Atlantic salmon at 4 °C up to 6 days did not change the levels of

n – 3, n – 6 PUFA and saturated fatty acid contents compared to raw stored fish (Yagiz et al., 2009). However, in both studies an increase in lipid oxidation was reported despite the unchanged fatty acid profile. In general HP induces lipid oxidation, and two explanations have been suggested; heme proteins as catalysts and destruction of lipid membranes (Bolumar, Andersen, & Orlén, 2014).

To overcome the lipid oxidation process, Gomez-Estaca, Montero, Gimenez, and Gomez-Guillen (2007) investigated the HP effect (300 MPa/20 °C/15 min) on cold-smoked sardine in combination with

an edible gelatin film-coating enriched with antioxidants (oregano extracts). They found significant increases in free fatty acids of the pressurized fish and the control (non-treated) fish during 20 days of storage at 5 °C. The same levels of FFA indicated that pressure did not inactivate the lipase enzymes (Gomez-Estaca et al., 2007). However, they reported that the pressurization did not result in an increased lipid oxidation.

Cruz-Romero, Kerry, and Kelly (2008) found that HP (260, 500, or 800 MPa/20 °C/3 or 5 min) of oysters did not change the fatty acid profile compared to untreated oysters. They also reported that the $n-3/n-6$ ratios were numerically higher, though not statistically significant, in HP-treated oysters, which indicates increased availability of $n-3$ PUFAs, which are beneficial for human health. On the contrary, Ortea, Rodriguez, Tabilo-Munizaga, Perez-Won, and Aubourg (2010) and Sequeira-Munoz, Chevalier, LeBail, Ramaswamy, and Simpson (2006) found that HP of salmon (135, 170, and 200 MPa/15 °C/30 s) and carp (100, 140, 180, and 200 MPa/4 °C/15 and 20 min), respectively, increased the FFA formation as a function of pressure level, pressure time, and storage. The difference in the reported effects and the hydrolysis mechanism cannot be explained based on data from such limited number of studies. However, it is suggested that differences in fish species, and pre-handling history (caught, slaughter, transport) besides pressure level, time, and temperature would significantly influence the endogenous enzyme systems and the observed effects after high pressure processing.

Milk is another food product containing important nutraceuticals like essential FFAs. Unfortunately milk is also subject to lipolysis resulting in nutritional degradation. To our knowledge, only two studies have investigated the effect of HP on the FFA content in milk (excluding human milk), and with opposing results. Kim, Kim, Choi, Min, and Kwak (2008) reported that when raw milk was pressurized at 200 MPa at -4 °C for 10 or 20 min the short-chain FFA did not change, while treatment for 30 min increased the FFA content slightly. In contrast, Gervilla, Ferragut, and Guamis (2001) found that pressurization (100–500 MPa/4, 25, and 50 °C/10 and 30 min) of ewe's milk showed lower FFA levels than control, and suggested that a partial or total inactivation of the native lipoprotein lipase was the reason. The difference between the results of the two studies could be explained by the difference in the applied pressure level.

A study combining milk and orange juice as a superior nutritional beverages and the HP technology as a superior preservation method was conducted by Barba et al. (2012b). It was found that PUFA content did not change due to pressure, while monounsaturated fatty acids (MUFAs) and saturated fatty acids (SFAs) increased after processing at 100 and 200 MPa and decreased after processing at 300 and 400 MPa. For a vegetable beverage (tomato, green pepper, green celery, cucumber, onion, carrot, lemon, and 0.8% virgin olive oil), the HP treatment had no effect on the three FFA groups (Barba et al., 2012b).

Meat also delivers essential and health promoting FFA. HP treatment (200 or 800 MPa/60 °C/20 min) of beef meat significantly affected the amount of specific fatty acids; myristic, palmitic, and *trans*-vaccenic increased, while *cis*-vaccenic and linoleic decreased with increasing pressure level (Tume, Sikes, & Smith, 2010). McArdle, Marcos, Kerry, and Mullen (2010) found that HP treatment above 200 MPa (20 and 40 °C/20 min) had no significant effect on either fatty acid composition and PUFA/SFA ratio or $n-6/n-3$ ratio, and concluded that the nutritional value of beef fatty acids was not altered due to HP.

In a subsequent study, McArdle, Marcos, Kerry, and Mullen (2011) observed that storage up to 30 days increased the $n-6/n-3$ ratio of the HP treated beef to the same extent as, untreated beef. In a comprehensive work, the effect of HP on the fatty acid profiles of the FFA, triglycerides, and phospholipids was studied by He and co-workers (He et al., 2012; Huang, He, Li, Li, & Wu, 2012). Overall, the proportion of FFA and phospholipids in the intramuscular lipids increased significantly after HP treatment of pork meat above 200 MPa (20 °C/20 min) and during storage, while the amount of triglycerides did not change. This indicated that FFA came mainly from phospholipids. HP and

subsequent storage at 4 °C significantly affected the fatty acid composition of FFA, and most interestingly linoleic acid (18:2), linolenic acid (18:3), eicosatrienic acid (20:3), arachidonic acid (20:4), and total PUFA increased, whereas SFA and MUFA decreased.

In a follow up study, the same group investigated the effect of antioxidants on the fatty acid composition in pressurized pork meat (Huang et al., 2012). The results showed that addition of ethylenediaminetetraacetic acid (EDTA) to minced pork before pressurization did not inhibit lipolysis of phospholipids, i.e., the fatty acid composition of FFA and phospholipids changed similarly to the change in HP treated meat without EDTA. It can in this context be argued that EDTA, as a metal chelator, will have no effect on enzymatic hydrolysis, as indicated by the findings of Huang et al. (2012).

5.2. Salt

HP technology has the potential to indirectly produce healthy foods by changing the needs for unhealthy additives. Salts are the most criticized compounds in food and the concern of many European food agencies (FSA, 2004; WHO, 2006). Thus different strategies are under development in order to reduce the salt content especially in processed meat products, cheeses, and bread. In most food products the sensory characteristics such as texture, juiciness, flavor and taste as well as the appearance, mainly the color, are the most important quality characteristics in relation to the overall acceptability by consumers. The manufacturing of meat products, cheeses, and bread involves the use of salts and additives due to the beneficial textural and sensory properties they impart into the products. Thus, the critical concern in reducing the amount of salt or additive in these products is the negative consequence on functional properties.

Dry-cured meat products have a high salt content and contribute markedly to the too high intake of salt by the consumer. Therefore, it is of interest to assess the effect of HP on dry-cured meat products in line of finding salt substitutes. The effect of HP on the taste of manufactured dry-cured meat products was investigated (Bover-Cid, Guardia, Claret, & Arnau, 2011; Clariana et al., 2011; Tanzi et al., 2004), and in all cases (Iberian chorizo and dry-cured loin, dry-cured ham, and Parma ham) the saltiness of the products increased after applying HP treatments (>500 MPa). Since no increase in the salt content was found after pressurization, the increased saltiness perception could not be related to an increase in salt concentration (Clariana et al., 2011). It was suggested that HP changed the interactions between the sodium ions and proteins resulting in the release of Na^+ ions making them more accessible for the taste buds (Clariana et al., 2011). Thus, it seems that HP may provide a natural increase in saltiness, and means for reducing salt.

The research group of Arnau and Gou (Ferrini, Comaposada, Arnau, & Gou, 2012; Fulladosa, Sala, Gou, Garriga, & Arnau, 2012; Fulladosa, Serra, Gou, & Arnau, 2009) investigated strategies to substitute sodium in dry-cured restructured ham. With different combinations of potassium lactate, transglutaminase, drying levels, and HP treatment (600 MPa/10 °C/6 min), these authors were able to produce hams with a 50% reduction in salt content compared to normal Serrano ham. The HP significantly increased saltiness, but also affected the sensory texture parameters e.g., hardness (increasing) and adhesiveness (decreasing). Similarly, another group succeeded in producing a HP treated (405 MPa/9 °C/3 min) cheddar cheese at different salt levels (from normal 5.3% to no salt $\sim 0.2\%$) with no change in textural and rheological parameters after 1 month of ripening (Ozturk, Govindasamy-Lucey, Jaeggi, Johnson, & Lucey, 2013). HP-treated and untreated cheeses had the same sensory intensities of acid, salt, and bitterness within same concentration of salt. However, reducing salt concentration increased the intensities of acid and bitterness, while saltiness was markedly reduced.

Generally, consumers do not consider ready-to-eat meat products, like sausages, as healthy meat products due to the high level of salt

and fat. Crehan, Troy, and Buckley (2000) studied the effects of salt level and HP on cook loss, emulsion stability, color, texture and sensory characteristics of frankfurters. Prior to the manufacturing of the frankfurters, the raw minced beef meat was subjected to HP treatment (150 or 300 MPa for 5 min at 20 °C), following mixing of the other ingredients to produce frankfurters. It was shown that the salt level could be reduced to 1.5%, thus decreasing the maximum average level of salt added to meat products ($\approx 3\%$ salt) for food preservation purposes. Among the treatment conditions investigated, the HP treatment at 150 MPa gave the best results. Similarly, Hayes and Allen (2011) investigated the effect of HP pre-treatment (100–300 MPa, 10 min) of raw minced pork and fat following preparation with salt reduction (1.4%) of pork breakfast sausages. They found that pressure below 200 MPa was enough to produce sausages with similar cook loss, color, water holding capacity, texture, and sensory attributes as normal salt level (2.5%) non-treated sausages.

Another strategy is to produce the meat batters based on different formulations and afterwards HP treat and assess the various functional and sensory properties over a range of different salt levels and pressure conditions. Sikes, Tobin, and Tume (2009) investigated the effect of HP and simple salt reduction (NaCl concentrations of 0–2%) on beef sausages. They found that HP (0–400 MPa/10 °C/2 min) of the low-salt sausages reduced cooking losses and improved texture. Moreover, sensory panels reported a greater acceptability in both appearance and texture of the sausages.

Sikes et al. (2009) suggested that HP caused an increase in solubilization of the fibrous proteins myosin and actin which would aid in the binding of the meat particles. Grossi, Soltoft-Jensen, Knudsen, Christensen, and Orlén (2012) found that with addition of carrot fiber or potato starch, it was possible to lower the salt content to 1.2% (and no phosphates) in pressurized (400–800 MPa/5 and 40 °C/5 min) pork sausages compared to the normal percentage of salt added to meat products for preservation purposes (1.5–3%).

An important finding regarding salt reduction was that the use of starch or fiber had more impact on textural properties than the level of salt. The water binding capacity of the product was also improved by the treatment. Salt and phosphates affect the solubility of myofibrillar meat proteins (like myosin and actin), thereby affecting their ability to form a protein matrix. Thus, to aid or improve acceptable meat binding, other functional ingredients are needed when reducing the salt content. On the one hand, HP increases the solubility of muscle proteins and thus improves the functional properties of certain myofibrillar proteins. On the other hand, HP may also induce protein denaturation and aggregation resulting in loss of solubility of the main myofibrillar proteins. The use of HP (400, 600, and 800 MPa) and natural starch or fiber clearly enhanced protein binding and resulted in increased hardness. Moreover, mild heating during pressurization acts synergistically with pressure further improving meat emulsion characteristics (Sikes et al., 2009).

Sensory assessment showed that this approach is promising for producing low salt sausages (Grossi et al., 2012). Hong, Ko, Choi, and Min (2008) evaluated the combined effects of salt levels and the functional ingredients glucono- δ -lactone and κ -carrageenan on the binding properties of restructured pork using HP treatment (200 MPa/4 °C/30 min). Their aim was to study the cold-set meat binding at pressures below the pressure needed for protein solubility and denaturation limiting the formation of gel structures. In conclusion, a reduction in NaCl could be obtained with glucono- δ -lactone and κ -carrageenan at low pressure (200 MPa) resulting in palatable binding properties and meat restructuring (Hong et al., 2008).

Trespacios and Pla (2007) showed that combined use of microbial transglutaminase, egg proteins, and HP (500–900 MPa/40 °C/30 min) with reduced salt and without phosphates produced chicken meat batter gels with substantially more enhanced textural properties than the batter treated without enzyme or just heat. The pressure level and the processing temperature seem to be important for the formation of

pressure-induced meat gel network. Jimenez-Colmenero, Fernandez, Carballo, and Fernandez-Martin (1998) found that HP produced meat gels were of lower quality regarding binding properties and texture profile parameters than standard heat-induced gels irrespective of meat type (pork or chicken) and salt level upon pressurization at moderate pressure levels (200 and 400 MPa) and high temperatures (60, 70, and 80 °C).

Finally, Troy, Crehan, Mullen, and Desmond (2001) aimed at using HP (150 or 300 MPa) to develop a range of meat products formulated with none or reduced levels of preservatives, non-meat ingredients and/or additives like salt and phosphates while maintaining high product quality and safety. Overall, they found that HP reduced the need for fat, salt, and phosphate in meat products without significantly altering their quality. Moreover, they recommended that manufacturers of processed meats and ready meals closely monitor developments in HP treatment.

6. Effect of HP on formation of food processing contaminants

By definition food processing contaminants (FPCs) are substances present in foods as a result of food processing/preparation that are considered to exert adverse physiological (toxicological) effects in humans, i.e., substances which create a potential or real risk to human health. Although humankind has always been exposed to these kinds of compounds since the day humans started preparing and preserving food with fire/heat, in the recent years, attention has been given to known and suspected carcinogenic FPCs. Furthermore, the consumer today demands high quality, minimally processed food and the analytic tools at hand make it possible to analyze these compounds on a $\mu\text{g}/\text{kg}$ basis.

Little data has been published supporting the possible formation or reduction of unwanted FPCs, such as furan, acrylamide or monochloropropandiols and their esters (MCPD/MCPD-esters), by HP treatment or conventional heat processing in general.

6.1. Maillard and acrylamide

The sources of FPCs in foods are manifold; one point of origin is the Maillard reaction (thermal degradation) between free amino groups and reducing sugars. Other reaction pathways start with polyunsaturated fatty acids, ascorbic acid or carotenoids (Crews & Castle, 2007; Vranova & Ciesarova, 2009). The mitigation strategy for FPCs cannot be to remove the reactants from the product since most of them have structural or nutritional benefits.

Acrylamide was one of the first FPCs to cause common concern in foods (e.g., potato chips, French fries). The Maillard reaction between the amino acid asparagine and a reducing sugar was shown to be the predominant formation pathway for acrylamide (Stadler et al., 2002). De Vleeschouwer, der Plancken, Van Loey, and Hendrickx (2010) conducted trials by using equimolar asparagine–glucose model systems, to study the formation of acrylamide under high pressure (600 MPa) and high temperature (100–115 °C) conditions. Based on the analyses of the model systems, it could be demonstrated that maximal acrylamide concentration generated during 60 min at high pressure high temperature (HPHT) treatment at 115 °C and 600 MPa was considerably lower than during a conventional heat treatment. Similarly, Buckow, Wendorff, and Hemar (2011) showed that heat-induced Maillard reactions between bovine serum albumin and glucose at pH 9 are reduced under pressures up to 600 MPa.

6.2. Furan

Sevenich et al. (2013, 2014) looked into the formation/mitigation of furan and MCPD-esters in different food systems by high pressure thermal sterilization (HPTS).

Furan is an aromatic heterocyclic compound, generally more abundant in closed heated food systems like cans and glasses and is associated with the flavor of the food. The furan-induced toxicity is due to cytochrome P450 (liver enzyme CYP2E1) activity which converts furan into cis-2-butene-1,4-dial. The compound formed can bind with proteins and nucleosides, which causes severe DNA damage and a deficit of function in the affected compounds (Bolger, Shirley, & Dinovi, 2009).

There are studies available on the efficiency (molar yield) of furan formed from different precursors. Mark, Pollien, Lindinger, Blank, and Mark (2006) reported that the potential to form furan goes after the following order: ascorbic acid > PUFAs > sugars (glucose, fructose). However, Crews and Castle (2007) reported that when ascorbic acid is present in real foods and model systems, less furan is produced, than if ascorbic acid is heated alone. Based on this it can be concluded that the formation of furan is not only dependent on the treatment conditions but also on the formation potential of the precursors in foods. High amounts of precursor do not automatically lead to high amounts of furan.

High amounts of furan have been found in canned soups, canned meat, canned vegetables and coffee (239–5050 µg/kg). Furan contents between 20 and 70 µg/kg can be described as moderately high (Crews & Castle, 2007). Sevenich et al. (2013) showed that high pressure treated (600 MPa/90–121 °C) sardines in olive oil showed, depending on treatment conditions, a reduction of furan from 71 to 97% (in comparison to retorting). Even at sterilization conditions of 121 °C and 600 MPa, a reduction of 78% was possible.

In baby food puree, Sevenich et al. (2014) demonstrated a furan reduction by HPTS in comparison to retorting by 81–96%, even at conditions equal to the thermal sterilization. The consumer groups of this food are infants and babies. Reducing harmful substances, such as furan, in their daily diet is clearly an advantage given by HPTS over conventional thermal processing.

6.3. Monochloropropandiols and esters

The formation of MCPD/MCPD–esters is mostly associated with fat-containing food systems where refined fats or oils are used. These ingredients can already contain high amounts of MCPD/MCPD–esters due to prior steps during the refining of these fats/oils (EFSA, 2013). Precursors are glycerol, glycerides and chlorides (Hamlet, Sadd, Crews, Velisek, & Baxter, 2002). 3-MCPD is known to be an animal carcinogen (Tomar, Feng, & Martha, 2010). However, studies concerning the toxicity of MCPD–esters are limited, although there are evidence of kidney and testicular damage similar to the effects of free 3-MCPD (Crews et al., 2013).

Many internationally recognized authorities (Bundesinstitut für Risikoforschung (BfR), European Food Safety Authority (EFSA), U.S. Food and Drug Administration (FDA)) see a demand for action to reduce amounts of these compounds in foods (BfR, 2012; EFSA, 2013). The amounts of MCPD–esters found in refined edible vegetables oils can range from 0.3 to 10 mg/kg, in other foods e.g., French fries (0.04–0.40 mg/kg) and jarred foods (0.011 mg/kg) are lower but still reasonably high (Crews, 2012). For the MCPD–esters, Sevenich et al. (2013) found that neither process (HPTS or retorting) makes a difference in terms of formation/mitigation of MCPD–esters. Here the main goal should be to reduce the amounts of MCPD–esters in the food by changing the recipe towards non-refined oil.

All these factors mentioned show that a reduced thermal load is applied in comparison to the retorted samples which leads to less FPCs formed in the food and therefore to a better quality even for equal Fo-values. The benefits offered by HPTS – compression heating and decompression cooling could lead to a valuable and safe product because unwanted reactions, such as the temperature and time dependent Maillard reaction, might not occur or might be reduced by high pressure (De Vleeschouwer et al., 2010; Ramirez, Saraiva, Lamela, & Torres, 2009;

Sevenich et al., 2013). The formation of unwanted and harmful substances could be limited, if their specific reaction volume is positive (Le Chatelier's principle) (Escobedo-Avellaneda et al., 2011; Ramirez et al., 2009; Segovia-Bravo et al., 2012).

7. Conclusions

Our review of the current literature has shown new perspectives and commercial opportunities on potential applications of HP to improve health and safety attributes of foods. For example, applying a pressure above 200 MPa can be used to effectively disrupt plant cell and thereby increase extraction efficiency and yields of polyphenolic compounds and carotenoids from different plant sources (e.g., citrus fruits, berries, tomatoes, and tea leaves). However, the recovery effectiveness and commercial viability often depends on the applied HP conditions, the type of solvent, the target compound, and the structure and composition of the biomaterial matrix. The studies so far indicate that HP-assisted extraction can potentially enable the cost effective production of a new generation of functional extracts, which can be used as ingredients in novel healthy food products, nutraceuticals and pharmaceuticals.

Pressure-induced matrix disruption at room temperature can also be used to increase bioaccessibility and bioavailability of nutrients, phytonutrients and minerals in food. Conflicting results on the effectiveness of HP to improve bioavailability stress the importance of the interaction of the applied process and food matrix and structure. For example, in vitro studies showed that the bioaccessibility of β-carotene from HP-treated (500 MPa) carrots was increased, while the bioaccessibility of lycopene from HP-treated (500–700 MPa) tomato juice was not improved, stressing the need for more mechanistic studies on understanding the effects of HP on the structure of food matrices and the consequence on the bioaccessibility and bioavailability of micronutrients and bioactive compounds. This would allow the rational application of HP for intelligently manipulating food matrix structure to improve the bioaccessibility and bioavailability of specific bioactives and micronutrients.

HP treatment can change the structure of many animal and plant proteins and, thereby, reduce their allergenic activity or potential. Of the many food types investigated, the use of HP to reduce allergenic potential was most successful in milk. Treating milk (or β-Ig solutions) with pressure above 100 MPa increases the antigenicity of β-Ig due to pressure-induced denaturation and/or to pressure-induced enzymatic hydrolysis. Other food proteins may be less affected by HP and the effectiveness to significantly reduce the dangerous allergens in other foods including apples and seafood is not conclusively verified. For example, the very common allergenic food group are nuts, which seems to be unaffected even by severe HP treatments (>600 MPa/>50 °C). Clearly, the potential application of HP for reducing allergenic activity is food matrix dependent.

The pressure-induced change of protein structure can also be a useful tool to produce healthy food products by targeted inactivation of endogenous enzymes or improved protein functionality. For example, HP-treatment at 300 MPa for 5 min can preserve the fatty acid profile of salmon indicating inactivation of endogenous lipase systems. However, using HP processing for preserving nutritional fatty acids is a delicate balance between pressure high enough to control degradation enzymes and low enough to minimize quality changes in muscle food systems.

Among the various potential applications of HP explored in the context of improving the health attributes of processed food products, the most compelling evidence exists for the use of HP for reducing salt content in meat products. Several studies showed that HP treatment can reduce salt up to 50% in dry-cured ham without compromising its sensory perception. This promising application of HP is based on pressure-induced modification of meat proteins, which gives the meat industry a new tool to produce healthier meat products. In addition, the potential of HP treatment to reduce contaminants such as

acrylamides in processed food products is also demonstrated by different studies.

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