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Applications of High Pressure Technology in Food Processing

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Abstract

Consumer trends towards shelf-stable, safe, more natural and free from additives foods drove the need to investigate the commercial application of non-thermal food processing technologies. High pressure processing (HPP) is one such emerging technology where foods are generally subjected to high pressure (100-1000 MPa), with or without heat. Similar to heat pasteurization, HPP deactivates pathogenic microorganisms and enzymes, extends shelf life, denatures proteins, and modifies structure and texture of foods. However, unlike thermal processing, HPP can retain the quality of fresh food products, with little or no impact on nutritional value and organoleptic properties. Moreover, HPP is independent of the geometry (shape and size) of food products. The retention of food quality attributes, whilst prolonging shelf life, are enormous benefits to both food manufacturers and consumers. Researches have indicated that the combination of HPP and other treatments, based on the hurdle technology concept, has potential synergistic effects. With further advancement of the technology and its large-scale commercialization, the cost and limitations of this technology will probably reduce in the near future. The current review focuses on the mechanism and system of HPP and its applications in the processing of fruit, vegetables, meat, milk, fish and seafood, and eggs and their derived products.

Keywords: Emerging technology; High hydrostatic pressure; High pressure processing; Non-thermal technology

1 Introduction

Food processing and preservation activities are as old as the human civilization, where foods were generally subjected to roasting, boiling, sun drying, steaming and smoking. Conventionally, most food products are processed thermally (e.g. blanching, drying, baking, evaporation, pasteurization and sterilization) by heating at 60 to 100 ^{o}C or more for a few seconds to minutes (James, Martin & David, 1992). During the process, the large amount of energy transferred to the food may trigger detrimental reactions thereby leading to objectionable changes in the food products (Barbosa-Cánovas, Pothakamury, Palou & Swanson, 1998). Thermal treatment of food effectively reduces the number of food spoilage microorganisms but it is necessary to also consider the quality attributes of the material as well as the shelf life. An objective of food industrialists is to develop and implement technologies that can maintain or yield desirable organoleptic characteristics of food or decrease the unwanted changes in commodities due to processing (Hogan, Kelly & Sun, 2005). Therefore, non-thermal methods as an alternative concept or complementary techniques of food processing are being developed and employed. In these methods, the food products are subjected to a lower temperature and less energy is transferred to them compared to thermal processing. The degradation of food quality attrib-

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utes expected from high temperatures is nominal in non-thermal treatment (Hogan et al., 2005). Scientists and researchers are driven to apply the potential of non-thermal technologies as an alternative or complementary process to traditional approaches of food processing and preservation. Food materials can be treated non-thermally using methods such as magnetic fields (MF), high pressure processing (HPP), irradiation, pulse electric field (PEF), pulsed light, ultrasound, ozone, cold plasma, gas and hurdle technology (Pou, 2015).

The potential of high pressure (HP) in food processing was first demonstrated by Hite (1899), with the reporting that milk spoilage by microorganisms can be delayed via the application of high pressure. A high pressure unit, with pressure leak proof sealing, was designed to ensure the system maintained a high pressure. Application of high pressure to food processing is an extension of a technology which is generally used in the manufacture of super-alloys, ceramics, sheet metal forming, low-density polyethylene and simulators. The first commercially high pressure processed food product (jams and jellies) appeared on the market in 1991 in Japan (Yaldagard, Mortazavi & Tabatabaie, 2008). Consumer trends towards shelf-stable, safe, more natural and free from additives foods drove the need to investigate the commercial application of non-thermal food processing technologies. High pressure processing is one such technology where foods are subjected to high pressure (100-1000 MPa), with or without heat (Angsupanich & Ledward, 1998; Rao, Chakraborty, Kaushik, Kaur & Hulle, 2014). Research indicates the great potential to apply high pressure technology in the food industry. Food scientists and technologists reported the various positive applications of HP in the processing/preservation of meat and meat products (Angsupanich, Edde & Ledward, 1999; Cheah & Ledward, 1996; Cheftel & Culioli, 1997; Kaur et al., 2016; Martino, Otero, Sanz & Zaritzky, 1998), fruit and vegetables and their products (Andres, Villanueva & Tenorio, 2016; Arroyo, Sanz & Prestamo, 1997; Cao et al., 2012; Chen et al., 2015; Dajanta, Apichartsrangkoon & Somsang, 2012; De Roeck et al., 2009; Kaushik, Kaur & Rao, 2014; Kaushik, Kaur, Rao & Mishra, 2014; Perera, Gamage, Wakeling, Gamlath & Versteeg, 2010; Rodrigo, Van Loey & Hendrickx, 2007; Sanchez-Moreno et al., 2005), milk and milk products (Addo & Ferragut, 2015; Black, Kelly & Fitzgerald, 2005; Chawla, Patil & Singh, 2011; Naik, Sharma, Rajput & Manju, 2013), eggs (Juliano et al., 2012; Ngarize, Adams & Howell, 2005; Singh & Ramaswamy, 2013), and fish and seafood (Angsupanich et al., 1999; Angsupanich & Ledward, 1998; Kaur, Kaushik, Rao & Chauhan, 2013). The current review of HPP discusses its working mechanism and its applications in the processing of foods.

2 Working principles of high pressure processing

2.1 Isostatic rule

The external pressure exerted on a fluid is distributed evenly and instantaneously throughout the food sample under pressure, whether the sample is in direct contact or indirect (flexible package) contact with the pressure medium irrespective of food geometry and equipment size. This isostatic principle enables the scale-up of laboratory findings to full-scale production of HPP (Olsson, 1995; Rao et al., 2014). When an aqueous medium is compressed, the compression energy can be determined as shown in Equation 1 (Cheftel & Culioli, 1997).

$$E = \frac{2}{5} \times P \times C \times V_0 \tag{1}$$

Where E is energy (J), P is the pressure (Pa), C is the compressibility of the medium, and V_o is the initial volume (m^3). Thus, the compression energy required to compress 1 litre of water at 400 MPa is 19.2 kJ as compared to 20.9 kJ for heating 1 litre of water from 20 to 25 ^oC. Consequently, the low energy levels involved in HPP do not affect the covalent bonds of food constituents (Cheftel & Culioli, 1997).

2.2 Le Chatelier's principle

This principle governs the effect of high pressure on food chemistry and microbiology. When a system at equilibrium is disturbed, the system then

responds in a way that tends to minimize the disturbance (Norton & Sun, 2008; Pauling, 1964). In other words, high pressure enhances reactions that result in a decrease in volume (negative activation volume) but opposes reactions that involve an increase in volume (positive activation volume) (Pou, 2015). High pressure reduces the availability of molecular space, favouring the chain interactions and finally inducing negative volume change. An overall volume change enhances the dissociation of ionic interactions and disruption of hydrophobic bonds. High pressure favours the formation of hydrogen bonds, while covalent bonds are not disrupted. Large molecules of microbial cell structures (cell membranes, enzymes, lipids, proteins) are disrupted by HP, while small molecules (flavour components, vitamins) remain unaffected (Rao et al., 2014).

2.3 Heat of compression

Pressure build up (pressurization from P_s to P_1) is accompanied by an increase in temperature (T_s to T_1) through adiabatic heating. During the pressure holding time (P_1 to P_2), the temperature decreases from T_1 to T_2 due to heat loss through the non-insulated pressure chamber as shown in Figure 1 (Balasubramaniam, Ting, Stewart & Robbins, 2004; Rao et al., 2014; Yaldagard et al., 2008). If no heat transfer occurs during the pressure holding time, the product normally cools down to its initial temperature on decompression. The temperature (T_1) at process pressure is independent of the rate of compression provided the heat transfer to the surrounding is negligible. The product temperature increment also depends on material compressibility, specific heat, initial temperature and the pressure requirement. Each product has its own specific heat of compression (fats and oils = 6-8 ^{o}C /100 MPa, water = 3 ^{o}C /100 MPa, 30 % aqueous monopropylene glycol (MPG) = 2 ^{o}C /100 MPa) (Balasubramanian & Balasubramaniam, 2003; Rao et al., 2014) according to its composition.

3 High pressure processing system

The main components of a typical high pressure processing system consist of a high pressure chamber and its closure, a pressure generation system, a temperature control device and a material handling system. The high pressure chamber is the heart of the high pressure processing system, which, in many cases, is a forged monolithic, cylindrical chamber constructed using a low-alloy steel of high tensile strength. The wall thickness of the mono block chamber is determined by the maximum target pressure, chamber diameter and number of cycles (Rao et al., 2014; Yaldagard et al., 2008). The strength of the pressure vessel can be increased by using multilayer, wire-wound or other pre-stressed vessel designs. This type of strengthened pressure vessel is preferred, over a mono block, for safety and reliability in commercial-scale operation at pressures greater than 400 MPa.

The pressurization of food commodities can be achieved by four different approaches, namely, hot isostatic pressing, warm isostatic pressing, cold isostatic pressing and chemical reaction (Mertens, 1995; Rao et al., 2014). In general, high pressure is generated by direct compression, indirect compression and heating of the pressure medium. In direct compression method, the pressure is directly generated by pressurizing a medium with a piston. The large-diameter end of the piston is driven by a low pressure pump. The small-diameter end of the piston pressurizes the pressure medium as shown in Figure 2a. This method allows fast compression, however, the limitations of the high pressure dynamic seal between the piston and internal surface of the pressure vessel confine this approach to small diameter, laboratory or pilot plant systems. Conversely, indirect compression generates pressure indirectly. In this process, a high pressure intensifier is used to force a pressure medium into a closed high pressure chamber from a reservoir through a tubing system until the desired pressure is achieved as shown in Figure 2b. Most industrial operations of the cold and warm isostatic pressing systems employ the indirect compression approach. On the other hand, heating

Table 1: Effect of high pressure processing on fruit and vegetables and their products

Product	Treatment (MPa/°C/min)	Effect	Reference
Guava puree	600/25/15	Extended shelf life up to 40 days stored at 4 °C without any modification in colour, flavour, ascorbic acid concentration, cloudiness and viscosity.	Yen and Lin (1996)
Cauliflower	400/5/30	Induced cell permeability, loss of turgor and structural changes. However, it maintained acceptable flavour and firmness.	Prestamo and Arroyo (1998)
Spinach	400/5/30	Completely destroyed the parenchyma cells and extensively affected the structure.	Prestamo and Arroyo (1998)
Pear	400/20/30	Induced browning, firm texture	Prestamo and Arroyo (2000)
Orange juice	800/25/1	Stabilized fresh orange juice (good cloud stability, lowest level of PME residual activity, less deterioration of ascorbic acid) for a storage period of more than 2 months at 4 °C or 37 °C.	Nienaber and Shellhammer (2001)
Green beans	500/room temperature/1	Extended shelf-life, good firmness, retaining of colour.	Krebbers, Matser, Koets and Van den Berg (2002)
Passion fruit	300/25/5	Not significant change in aroma, flavour, and consistency.	Laboissiere et al. (2007)
Black grape juice	550/44/2	Maximum retention of total antioxidant activity, flavonoids and phenolics.	Chauhan, Raju, Ravi, Roopa and Bawa (2011)
Apricots	300-500/room temperature/5-20	Inactivation of polyphenol oxidase and peroxidase, retention of colour and carotenoids.	Huang et al. (2013)
Apple juice	500/25/3	No significant change in vitamin C content, increase in total polyphenolic content, safe storage for 21 days at 4 °C.	Kim et al. (2012)
Olives	400-600/room temperature/5 and 10	Enhanced shelf-life, no significant change in colour, higher stability and firmness.	Pradas et al. (2012)
Strawberry pulps	400-600/5-25/25	Inactivation of β-glucosidase, polyphenol oxidase and peroxidase enzymes by 41.4, 74.6 and 74.6 % respectively.	Bello, Martinez, Ceberio, Rodrigo and Lopez (2014)
Strawberry	400/room temperature/5	Total anthocyanins content was degraded by 33 % and 57 %, stored at 4 and 25 °C respectively for 45 days.	Gao et al. (2016)
Beet root	650/room temperature/3-30	Up to 25 % inactivation of peroxidase and 10-25 % inactivation of polyphenol oxidase depending on time.	Paciulli, Medina-Meza, Chiavaro and Barbosa-Canovas (2016)
Pear	600/20-100/3-5	Inactivation of peroxidase and polyphenol oxidase by 26 and 68 % respectively, at 20 °C for 5 min. Similarly, 92 and 90 % inactivation at 80–100 °C after 3 min.	Terefe, Tepper, Ullman, Knoerzer and Juliano (2016)
Cloudy apple juice	600/room temperature/3	Up to 50 % inactivation of peroxidase	Yi et al. (2017)

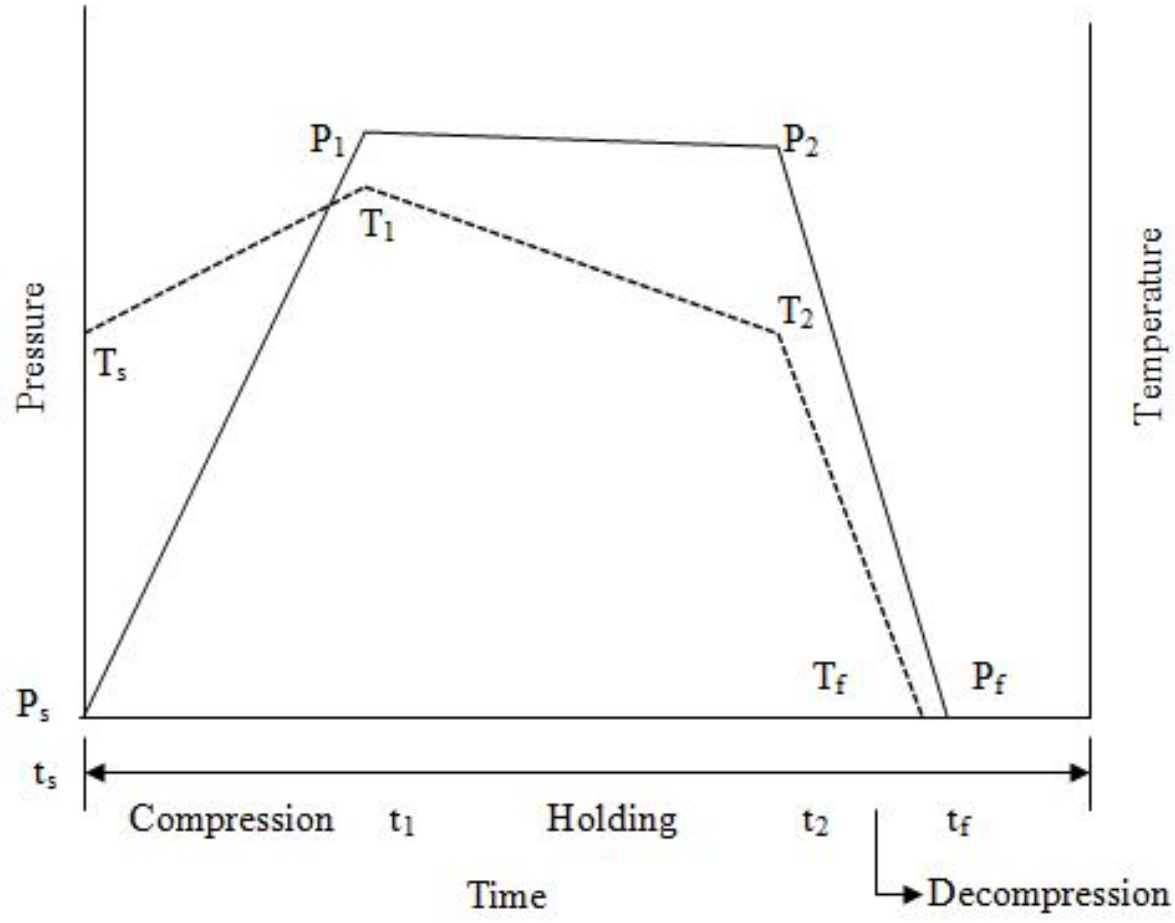

Figure 1: Variation of pressure and temperature in a non-insulated high pressure chamber

of the pressure medium technique utilizes the expansion of the pressure medium with rising temperature to produce high pressure. Therefore, this method is commonly used when high pressure is applied in combination with high temperature (Barbosa-Cánovas et al., 1998; Pou, 2015). Current industrial high pressure modes of operation include batch and semi-continuous systems. The batch mode can process both solid and liquid products. In the batch process, HPP is carried out after food materials are filled and sealed into their final or intermediate package (flexible packaging materials). The advantages of the batch method include freedom from contamination by lubricants and wear particles, and cleaning is not required between food material changes. However, the overall cost of the process is higher as the processing cycle is lengthened due to handling, drying and storage of the packages. In the semi-continuous process, only pumpable products can be used for treatment (Ting & Marshall, 2002). Food products are pumped in and out of the pressure processing chamber by means of special high pressure transfer valves and isolators. The treated foods are packaged using aseptic filling systems (Ting & Marshall, 2002; Ting, Tremoulet, Hopkins & Many, 1999). Pressure transmitting media are used for uniform transfer of pressure to the food products. Some of the most generally used pressure trans-

mitting fluids are water, ethanol, silicone oil, sodium benzoate, glycol and castor oil (Ting et al., 1999). Many of the early pressure processing systems were not fabricated from stainless steel and thus necessitated the use of oils as the pressure transmitting medium. Use of oil as a transmitting medium served the purpose of lubrication and anticorrosion as well as transfer of pressure to the materials. When oils or organic solvents are used as the pressure transmitting medium, the temperature rise is higher than with the use of water, owing to their higher compressibility, lower heat capacity and lower thermal conductivity (Makita, 1992). The main pressure transmitting medium of high pressure in food processing is water because it has the best properties for the process and there is less risk of contamination of the products. Aqueous solutions of mono-propylene glycol (MPG) and isopropyl alcohol (IPA) are also commonly used for high temperature and low temperature high pressure processing, respectively.

4 Biological effects of high pressure processing

4.1 Microorganisms

One of the main objectives of high pressure treatment is the inactivation of food spoilage microorganisms. The inactivation of microorganisms is brought about by the changes in the cell membrane, morphology and biochemical reactions of microorganisms under the influence of HP (Hamada, Nakatomi & Shimada, 1992). The cell membrane of microorganisms is the primary site for pressure induced inactivation of microorganisms, which results in modified permeability and ion exchange. The action of the cell membrane helps the microorganisms to resist some selective chemical inhibitors and maintain homeostasis. However, this tolerance is lost once the cell membrane is damaged and the cells are vulnerable due to high pressure treatment (Manas & Pagan, 2005; McClements, Patterson & Linton, 2001). It is commonly accepted that the reason of cell death is due to the leakage of intracellular constituents through the permeabilized cell membrane. On the other hand, if processing pressure is not high enough to incite total permeabilization of the cell membrane, the permeabilization occurs only in the outer cell membrane and the permeabilized cell is restored upon pressure decompression as in the case of Gram-negative bacteria (Hauben, Wuytack, Soontjens & Michiels, 1996; Yaldagard et al., 2008). The cell membrane fluidity has an effect on the susceptibility of microorganisms to HP. Less fluid cell membrane microorganisms are more sensitive to HP treatments (Macdonald, 1992; ter Steeg, Hellemons & Kok, 1999). High pressure causes the irreversible denaturation of one or more critical proteins in microorganisms, thus leading to the inactivation of microorganisms by altering the proteins responsible for replication, metabolism and integrity. Compression affects the morphology (filament formation, cessation of motility) of the microbes (Kitching, 1957; ZoBell, 1970). High pressure treatment for retardation of reproduction and inactivation of microorganisms is dependent on the types of microorganisms and species, growing stages and level of applied pressure. Cells during the exponential growth phase are more sensitive to pressure than during the stationary phase. In most cases, Gram-negative bacteria are more sensitive to pressure induced inactivation as compared to Gram-positive bacteria. It is well established that spores have higher pressure resistance and for their inactivation high pressures (>1200 MPa) may be required (Knorr, 1995). Generally, pressure treatment at 400-800 MPa for a few minutes at room temperature can satisfactorily achieve microbial reduction. High pressure at around ambient temperature is unfeasible in the inactivation of bacterial endospores. The higher resistivity of spores as compared to vegetative cells is due to the presence of calcium rich dipicolinic acid which defends them from excessive ionization (Sakharam, Prajapati & Jana, 2011; Smelt, 1998). Due to this limitation, high pressure processing is not a suitable method for sterilization; hence, the HP treated products need to be stored under refrigeration. However, HP can stimulate bacterial spore germination, which enables the resultant vegetative form for inactivation by high pressure. Pulsed or oscillatory pressurization, and HP and high temperature combination can enhance the sporicidal effect (Sakharam et al., 2011). Mul-

tiple pulse treatment, repeated cycling between 600 MPa and atmospheric pressure, resulted in a 6.0 log reduction of Bacillus stearothermophilus spores whereas single HPP had little effect (Johnston, 1994). The Bacillus stearothermophilus spores were totally destroyed by six 5 min cycle oscillations of pressurization at 600 MPa at 70 ^{o}C (Hayakawa, Kanno, Yoshiyama & Fujio, 1994).

4.2 Enzymes

The basic structure of an enzyme consists of primary, secondary, tertiary and quaternary structures. The tertiary and quaternary structures of an enzyme are affected by high pressure treatment which results from the modification of hydrophobic and electrostatic interactions as well as hydrogen bonding (Marszalek, Wozniak, Kruszewski & Skapska, 2017). The primary structure of an enzyme is unaffected by HP (Heremans, 1993; Mozhaev, Heremans, Frank, Masson & Balny, 1994) whereas the secondary structure of an enzyme may be affected at a pressure greater than 700 MPa. The shift between the native conformations (mostly tertiary and quaternary structures) of the enzyme is dependent on the interaction between the molecules present near the surface and the surrounding solvent molecules. When this balance is disturbed, its conformational structure may change and lead to the loss of its activity (Rao et al., 2014). Effects of HPP on enzymes can be used to enhance some enzyme activities in food to improve food quality or to inactivate the undesirable enzymes using higher pressure. Also, this enhancement of enzyme activity can be used to improve a food process such as cheese production. The mechanism of high pressure inactivation of enzymes can be explained in terms of protein denaturation, complete or incomplete, reversible or irreversible unfolding of enzymatic structure, and influence on the reaction mechanism by altering the difference in reaction volume. It can also be described in terms of modification of the sensitivity of the substrate after being unfolded by the application of pressure, and the bonding of enzyme and substrate may become stronger by the release of an intracellular enzyme (Cheftel, 1992; Ludikhuyze, Van Loey, Denys & Hendrickx, 2001). High pressure inactivation of enzymes can be influenced by type of enzyme, medium, water activity, pH, composition and temperature.

5 Applications of high pressure technology in food processing/preservation

Consumers have a growing interest in safe, healthy, fresh-like, convenient, quality, additive-free, and better texture, flavour and appearance food products. Thermally processed food often results in the deterioration of quality attributes (vitamins loss, change in colour, off-flavour, modification of texture and change in appearance). It is generally accepted that high pressure treatment can inactivate food spoilage microorganisms without having a negative effect on food quality. Increasing pressure level will generally increase inactivation of microorganisms in shorter times but it may also result in more protein denaturation and other unfavourable changes when compared to the untreated food products. However, as high pressure processing generates no shear forces, the physical structure of most processed foods remains minimally changed (Norton & Sun, 2008). The problem of spatial variation is not encountered as the pressure is transmitted evenly and instantaneously throughout the food sample. Moreover, HP affects only non-covalent bonds (ionic, hydrophobic and hydrogen bonds), and has little effect on the quality attributes of food such as nutritional constituents, flavour and colour. Therefore, in contrast with thermal treatment, HPP has a higher potential regarding retention of the inherent food qualities (Hayashi, 1990). Application of high pressure compresses the water content of the food by about 4 and 15 % at 100 and 600 MPa respectively. Freezing point depression of water was observed at HP to -4, -8 and -22 ^{o}C at 50, 100 and 210 MPa, respectively (Kalichevsky, Knorr & Lillford, 1995; Naik et al., 2013). Hence, this method enables sub-zero processing of food without the formation of ice crystal. This technique also assists quick thawing of conventional frozen food products and pressure shift crystallization. In so doing, very small ice

Table 2: Effect of high pressure processing on milk and dairy products

Product	Treatment (MPa/°C/min)	Effect	Reference
Cheddar cheese	345 and 586/5/1 and 15	Cheese made from HP treated milk resulted in more yield of cheese and no detrimental effects on flavour. Microbiological quality was comparable to cheese prepared from pasteurized milk.	Drake, Harrison, Asplund, Barbosa-Canovas and Swanson (1997)
Cheese	400/20/20	6.0 log reduction of Penicillium roqueforti	O'Reilly, O'Connor, Kelly, Beresford and Murphy (2000)2
Cheese	500/20/15	Goat milk subjected to HP prior to cheese making gives firmer, less cohesive and less fracturable cheese as compared to pasteurized milk (72 °C for 15 sec).	Buffa, Trujillo, Pavia and Guamis (2001)
Milk	200-500/20/60	Periodic oscillation of HP was observed to be very effective for the inactivation of pathogens such as Escherichia coli, Listeria monocytogenes, and Salmonella enteritidis.	Vachon, Kheadr, Giasson, Paquin and Fliss (2002)
Yogurt milk	200/room temperature/20	Acidification of yogurt milk with glucono-δ-lactone at HP (200 MPa) caused fine coagulum and more homogeneous gel than that of heat treated sample.	Harte, Luedecke, Swanson and Barbosa-Canovas (2003), Naik, Sharma, Rajput and Manju (2013)
Mozzarella and Gouda cheese	400-600/room temperature/5-15	Exposure to HP increased the rate of proteolysis in these cheese varieties. A similar trend was observed in cheese made from the milk of ewe.	Juan, Ferragut, Buffa, Guamis and Trujillo (2007), San Martin-Gonzalez, Welti-Chanes and Barbosa-Canovas (2004)
Cheddar cheese	345-483/room temperature/3 and 7	HP treatment accelerates shredability and shreds from unripe milled curd Cheddar cheese can be manufactured with improved visual acceptability and enhanced tactile handling.	Serrano, Velazquez, Lopetcharat, Ramirez and Torres (2005)
Low fat yogurt	676/85/5 and 30	Combined treatment of HPP and heat using different probiotic starter cultures resulted in higher consistency of yogurt gel, and acceptable textural and rheological properties. It also observed dense aggregated protein structure with smooth surface, and improved viscosity and gel texture as compared to untreated yogurt.	Penna, Gurram and Barbosa-Canovas (2006), Penna, Subbarao-Gurram and Barbosa-Canovas (2007)
Chhana (Indian cottage cheese)	200-400/30-70/0-100	The optimum conditions were determined as 280 MPa, 52 °C, and 45 min for minimum lag, inflexion and coagulation time of 0.0028, 5.19 and 3.87 min, respectively.	Sahu (2010)
Acidified milk gel	200-600/15-65/0-60	The treatment pressure and temperature had the maximum effect on decreasing gel pH. Heat assisted high pressure improved the gel strength and reduced the coagulation time.	Sahu and Mallikarjunan (2016)

Table 3: Some of the effects of HPP on fish and seafood

Product	Treatment (MPa/°C/min)	Effect	Reference
Hake	200 and 400/7/5	Instantly after HP treatment, the samples exhibited odour and appearance similar or somewhat greater than controls samples. During refrigerated storage, the HP treated samples retained all sensory parameters compared to the control samples.	Hurtado, Montero and Borderias (2000)
Pollack, mackerel, tuna, cod, salmon trout, carp, plaice, anglerfish, and octopus.	100-1000/0/5	High pressure treatment higher than 150-200 MPa caused a cooked appearance in all the treated samples except octopus which retained a fresh appearance till 400-800 MPa.	Matser, Knott, Teunissen and Bartels (2000)
Octopus	200-400/7 and 40/15	Samples treated at 200 and 300 MPa showed higher hardness values than both the untreated and treated at 400 MPa samples.	Hurtado, Montero, Borderias and Solas (2001)
Sea bass	100-500/10/5	Chewiness and gumminess decreased from 100-300 MPa but increased after 400 and 500 MPa. A similar trend was observed in hardness but remained constant after 400 and 500 MPa. Springiness, resilience, and cohesiveness remained almost constant.	Cheret, Chapleau, Delbarre-Ladrat, Verrez-Bagnis and De Lamballerie (2005)
Bay scallop	200 and 400/22/10	No modifications were indicated in cohesiveness, adhesiveness, and springiness. Resilience observed to be increased with the pressure level. While hardness decreased regardless of the applied pressure intensity and fracturability found to be decreased at 400 MPa.	Perez-Won, Tabilo-Munizaga and Barbosa-Canovas (2005)
Abalones	500-550/20/3, 5 and 8	Samples treated at 500 and 550 MPa no considerable differences were observed as compared to the control samples. However, chewiness and cohesiveness were higher in the HP treated samples.	Briones-Labarca, Perez-Won, Zamarca, Aguilera-Radic and Tabilo-Munizaga (2012)
Smoked cod	400-600//5 and 10	HP treated samples induced no significant changes during refrigerated storage in the quality of odour, appearance, and intensity of smoky odour.	Montiel, De Alba, Bravo, Gaya and Medina (2012)
Sea bass, sea bass fillets	250 and 400/6/5	HP treated influenced on colour, increased whiteness and appeared typical cooked fish. The brightness was intensified at 400 MPa. Pressure levels did not affect the fresh odour, became firmer, and the overall sensory acceptance was high.	Teixeira et al. (2014)
Threadfin bream	200, 400 and 600/10, 30 and 50	HP processing resulted in a decrease in total sulfhydryl content of actomyosin with the rise in pressure intensity level and treatment time.	Zhou et al. (2014)
Barramundi minced muscle	300-500/4/10	Water holding capacity of gels increased with the increase in pressure intensity. HP treatment enhanced the gel-forming ability.	Truong, Buckow, Nguyen and Furst (2017)

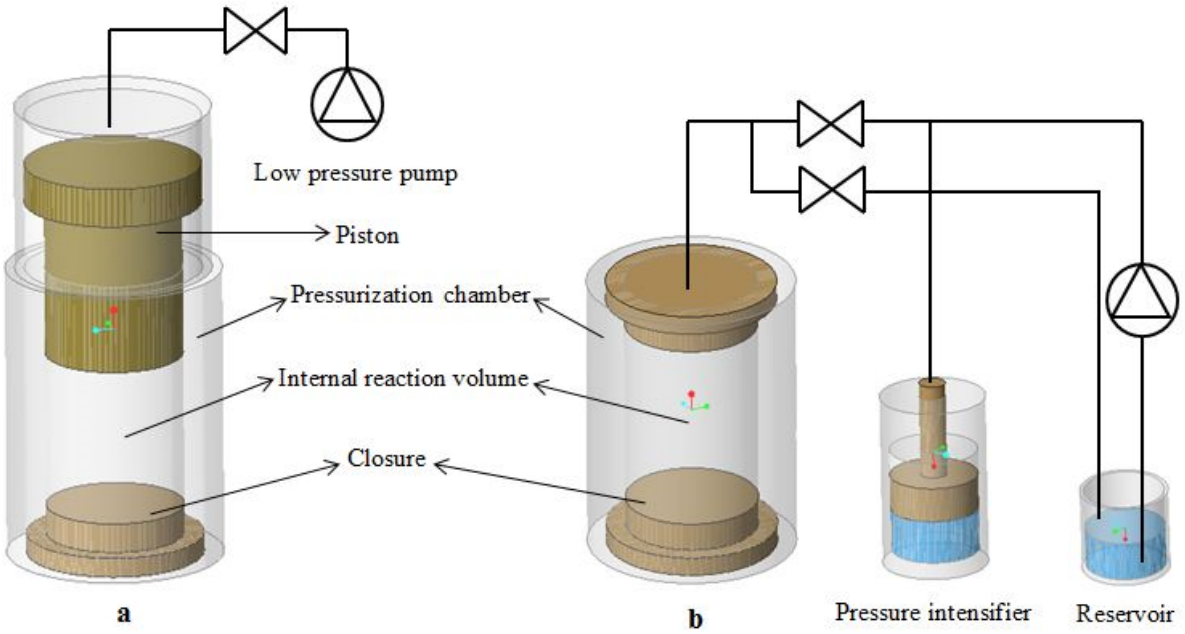

Figure 2: High pressure generation by (a) direct compression, and (b) indirect compression (redrawn from Norton and Sun (2008)

crystals are formed and cooling to sub-zero temperature in the frozen products significantly controls the activities of microorganisms and subsequently improves food quality as well as extending the shelf life of the products (Naik et al., 2013; Sakharam et al., 2011). Bioactive molecules such as simple sugars, vitamins, flavour compounds and amino acids remain unaffected by the application of HPP (Naik et al., 2013).

5.1 Fruit and vegetables and their products

Texture is the most important determinant for the assessment of fruit and vegetables quality. Cell wall polysaccharides are primarily composed of pectin, cellulose and hemicellulose. Pectin is the main component in the middle lamella that strengthens the cell walls and provides elasticity and firmness to the tissues (Kato, Teramoto & Fuchigami, 1997; Rastogi, 2010). Application of pressure can change these compositions, as certain enzymes are deactivated and/or structural modification occurs in the polysaccharide, lipid and protein fraction. The actions of pectinmethylesterase (PME) and polygalacturonase (PG) on pectin caused the texture degradation of fruit and vegetable (Sila, Smout, Vu, Van Loey & Hendrickx, 2005). The action of PME on pectin produced methanol and a pectin molecule with a lower degree of demethylation, which is depolymerized by polygalacturonase, resulting in a drastic softening of tissue (Tangwongchai, Ledward & Ames, 2000; Vu et al., 2004). The rigidity of the cell wall and middle lamella increases due to more crosslinking between pectin chains and divalent cations (like calcium, magnesium) which results from low levels of methoxy pectin (Grant, Morris, Rees, Smith & Thom, 1973; Rastogi, 2010). In some cases, the texture of fruit and vegetable may be enhanced by PME (Villarreal-Alba, Contreras-Esquivel, Aguilar-Gonzalez & Reyes-Vega, 2004). In general, HPP leads to the disruption of membrane and protein denaturation. HP treatment

modifies cell permeability and allows the movement of water through the cell. Consequently, HP treated tissue had a drenched or soaked appearance. Yet, some fruit and vegetables retained acceptable firmness, close to that of the original (Rastogi, 2010). Basak and Ramaswamy (1998) reported that texture recovery of some vegetable products was attained between 25 and 40 min under a pressure level of 100 MPa. Tangwongchai et al. (2000) indicated that textural damage of HP processed tomatoes increased with increase in pressure up to 400 MPa at ambient temperature but HP treatment at 500-600 MPa resulted in less damage of texture. The decrease in cell rupture at 500-600 MPa was due to the action of the PME enzyme, and increase in cell rupture and softening below 500 MPa was attributed to the role of the PG enzyme. The texture degradation of high pressure treated mushrooms was found to be lower when compared to thermal blanching (Matser, Knott, Teunissen & Bartels, 2000). High pressure application to green peas (400-900 MPa, 5-10 min, 20 ^{o}C) showed no significant effect on texture (Pandrangi & Balasubramaniam, 2005). The effect of HPP on texture varies with type of fruit and vegetable and applied pressure.

Generally, the colour of HP processed fruit and vegetable products (such as fruit juices, jams, purees) are preserved once thresholds of temperature and/or pH are observed (Ludikhuyze & Hendrickx, 2001). Van Loey et al. (1998) demonstrated that colour degradation of broccoli juice was observed after exposure to pressures at higher temperature (>50 ^{o}C) due to chlorophyll degradation. But below 50 ^{o}C, high pressure up to 800 MPa showed no negative effect on chlorophyll. In the case of onion, with an increase of the applied pressure intensity, the colour turned browner due to the polyphenol oxidase (PPO) enzyme (Norton & Sun, 2008). Thus, the ability to retain colour at HP treatment is not evident in some fruit and vegetables. When treating mango pulp at 100-400 MPa, with the interval of 100 MPa for 15 and 30 min at 20±1.5 ^{o}C, it was found that, after pressure processing, the changes in colour parameters of mango pulp were not significant, indicating minimal effect on pigments. The total colour change decreased with the increase of pressure intensity. The total soluble solids and pH remained unaffected after the high pressure treatment (Ahmed, Ramaswamy & Hiremath, 2005). High pressure (600 MPa) processed cubes of Granny Smith and Pink Lady apples, with pineapple juice 0-50 % (v/v) at 20 ^{o}Bx for 1-5 min at 20 ^{o}C, showed that the HP treatment with 50 % pineapple juice for 5 min resulted in the best quality retention in both varieties of apple. This combination also inactivated the polyphenol oxidase enzyme by 40 % and 30 % in Granny Smith and Pink Lady apples, respectively. Thus, the combined treatment of high pressure and pineapple juice has better possibilities in retention of qualities in both the apple varieties (Perera et al., 2010). Arroyo et al. (1997) have reported that at the pressure level of 100 and 200 MPa at 20 ^{o}C for 10 min and 10 ^{o}C for 20 min, reduction of microbial populations in vegetables (lettuce and tomatoes) were not significant. For the complete reduction of saccharomyces cerevisiae, the required pressure intensity was 300 MPa at 10 ^{o}C for 20 min, and for Gram-negative bacteria and moulds it was 350 MPa. The Gram-positive bacteria were not completely inactivated at 400 MPa. The viable aerobic mesophiles and molds and yeasts were reduced by 1 log unit at 300 MPa and above. High pressure treatment of litchi fruits at 300 MPa for 10 and 15 min, the aerobic mesophiles, yeasts and molds and psychrotrophs count were reduced by 3.29, 3.24 and 3.77 log10 cycles, respectively. The treatment enhanced shelf life up to 32 days with minimal changes in physicochemical attributes and textural parameters during refrigerated storage (Kaushik, Kaur & Rao, 2014). In most cases, during processing and subsequent storage, high pressure treatment can retain higher levels of antioxidant activity and phenolic compounds in fruits and vegetables, and their derived products, than thermal pasteurisation. At present, a significant number of high pressure treated fruit and vegetable products are commercially available in the United States, Europe, Japan and Australia (Zhao, Zhang & Zhang, 2017). It has been scientifically and commercially demonstrated that high pressure processing can produce microbiologically safe and stable fruit and vegetables products, with better quality characteristics. Some of the effects of high pressure treatment on fruit and vegetables

and their products are shown in Table 1.

5.2 Meat and meat products

The quality of meat is generally defined by compositional quality and palatability factors. The important quality indicators of meat include colour, flavour, tenderness, juiciness, smell, texture, firmness, fat and protein content, fat quality (oxidative stability of fat), and drip and cooking loss. The processing parameters and methods have effects on the quality attributes of meat that may be beneficial or detrimental. HPP influences the organoleptic properties and nutritive value of meat and meat-derived products since high pressure has a considerable impact on the structure and functionality of many proteins (Jung, de Lamballerie-Anton & Ghoul, 2000; Norton & Sun, 2008). Modification of the ultrastructure of meat is highly dependent on the time post-mortem (pre-rigor or post-rigor) when HP is applied. At early pre-rigor high pressure treatment, the muscles experience great contraction, with a length reduction of 35-50 %, causing severe disruption in the structures of meat (Campus, 2010; Cheftel & Culioli, 1997; Kennick, Elgasim, Holmes & Meyer, 1980). The muscle induced no contraction but modified the sarcomere structure when HP was applied post-rigor, and there is no significant effect on tenderization of post-rigor meat at low temperature (Cheftel & Culioli, 1997; Norton & Sun, 2008). Pressurization up to 500 MPa and above is possible due to advancement in pressurization equipment and may achieve tenderization of meat without any additional heating. The combined effects of high pressure and muscle contraction could result in breakage of myofibrillar proteins, and myosin filaments into Z discs, which would explain the effect of tenderization on meat. The tenderization of meat has also been attributed to the enhanced activity of the enzymes, cathepsins and calpains (Simonin, Duranton & de Lamballerie, 2012). HP treatment (200-500 MPa, 10-30 min at 25 ^{o}C) of beef liver increased the swelling of mitochondria and decreased rough endoplasmic reticula in hepatocytes, and the occurrence of such changes might be related to the modification of texture in the treated beef liver (Ogihara, Suzuki, Michishita, Hatakeyama & Okada, 2017). Banerjee et al. (2017) reported that the high pressure treatment of mutton patties at 200 and 400 MPa for 10 min significantly reduced hardness, gumminess and chewiness as compared to control and irradiated (1-3 kGy) products. However, no significant alterations were observed in springiness and cohesiveness between the HP processed and irradiated mutton patties. Comparatively, HP treated meat batters give rise to more elastic gels during cooking than in cooked-only batters, and reduced cooking losses (Iwasaki, Noshiroya, Saitoh, Okano & Yamamoto, 2006; Sikes, Tobin & Tume, 2009; Truong, Buckow, Nguyen & Furst, 2017). No modifications in meat myofibrils were observed in beef treated at 130 MPa at 10 ^{o}C but when beef was treated at 325 and 520 MPa increasing ultrastructure changes to the meat myofibrils were observed (Jung et al., 2000). High pressure (100 MPa at room temperature) treated pork and chicken induced morphological changes and appeared thicker than untreated samples (Iwasaki et al., 2006; Simonin et al., 2012). Kaur et al. (2016) reported the high pressure processing of bovine meat at 600 MPa induced significant changes in texture, visual appearance and myofibrillar structure, which were similar to cooked meat. However, the sample subjected to 175 MPa exhibited no significant modification in texture and appearance as compared to the raw meat product. In contrast to cooked meat, HP processed meat at 600 MPa was found to have better protein digestibility in terms of free amino N release. However, high pressure processing and cooking are not comparable as the HP effect on meat is an entropy-driven process, whilst cooking is essentially an enthalpy-driven process (Kaur et al., 2016). HP induced modifications in texture have effects on myofibrillar proteins and their gel-developing properties, thus, raising the prospect of the development of treated muscle-based food products (Campus, 2010).

Colour is one of the main quality attributes of meat that consumers use as a purchasing criterion. HP processed meat colour greatly depends on the intensity of the applied pressure, as HP treatment at 130 MPa enhanced redness but above 325 MPa induced strong discolouration (intensifying in brown colouration). This

discolouration in meat is due to an increase in the metmyoglobin (Fe^{3+}) content in the sample after the application of pressure (Jung, Ghoul & de Lamballerie-Anton, 2003). Jung et al. (2003) observed that an increase in applied pressure, up to approximately 350 MPa at 10 ^{o}C for 5 min, increased redness (a* values) in raw beef muscle and then decreased redness up to 600 MPa. These authors reported that an increase in redness of samples at pressures below 300 MPa was due to the activation of the enzymatic system accountable for the reduction of metmyoglobin. Marcos, Kerry and Mullen (2010) also observed the decrease in a* values of treated samples at pressures above 350-400 MPa. Dark-firm-dry beef subjected to high pressure at 200 MPa increased the redness value (a*) but treatment at 600 MPa reduced the redness in samples (Utama et al., 2017). High pressure (600 MPa) processed dark-firm-dry beef was found to have higher L* values than those treated at 200 MPa and for the control (Utama et al., 2017). The increase in whitening (L* parameter) has been observed in pork meat processed at 200-400 MPa and 20 ^{o}C (Korzeniowski, Jankowska & Kwiatkowska, 1999), chicken meat treated at 400-500 MPa and 5-10 ^{o}C (Del Olmo, Morales, Avila, Calzada & Nunez, 2010), and beef meat processed at 200-600 MPa and 10 ^{o}C (Carlez, Veciananogues & Cheftel, 1995; Marcos et al., 2010). The meat discolouration in HP processed samples has been related to either (i) a whitening effect due to denaturation of myoglobin and heme group displacement or release, or (ii) oxidation of ferrous myoglobin to ferric myoglobin, or (iii) modification of surface structure and properties due to protein coagulation with a resulting loss of solubility of sarcoplasmic and/or myofibrillar proteins (Campus, 2010; Carlez et al., 1995; Goutefongea, Rampon, Nicolas & Dumont, 1995; Simonin et al., 2012). Comparatively, the colour of raw meat is more affected by pressure than cured meat (Rubio, Martinez, Garcia-Cachan, Rovira & Jaime, 2007). Meat discoloration is not much influenced by the high pressure treatment duration and can be observed after only 1 min of exposure to pressure (Del Olmo et al., 2010). Even though HPP induced visible modifications in colour of raw meat, the colour difference was less perceived after cooking (Mor-Mur & Yuste, 2003; Simonin et al., 2012). High pressure processing has the potential to influence the aroma of treated meat and meat-derived products. The aroma profile of high pressure (400-600 MPa for 15 min at 5 ^{o}C) treated beef and chicken meat had better stability as compared to untreated meat during storage. It was observed that upon opening the bags after 14 days of storage, the untreated samples produced unpleasant off-flavour (Schindler, Krings, Berger & Orlien, 2010). Rivas-Canedo, Juez-Ojeda, Nunez and Fernandez-Garcia (2011) investigated the effect of HP (400-600 MPa for 5-10 min at 12 ^{o}C) on the volatile profile of cooked pork meat and found that the volatile fractions of HP processed meat remained unaltered during the 14 days of refrigerated storage, however, the control samples experienced significant changes. Dry-cured loins subjected to high pressure at 300-400 MPa for 10 min at 20 ^{o}C stabilized the content of free amino acid during storage due to a decrease in the activity of aminopeptidases (Campus, Flores, Martinez & Toldra, 2008). High pressure processing at 200-400 MPa at ambient temperature retained the components (amino acids, nucleotides and peptides) responsible for the flavour of meat during chilled storage for 7 days (Suzuki et al., 1994). Utama et al. (2017) reported that the HP treatment of dark-firm-dry beef at 200-600 MPa induced changes in aroma during 9 days of storage under vacuum at 4 ^{o}C. It was observed that the aroma pattern of untreated meat was always discriminated from HP treated samples during storage. Changes in pH during storage and lipid oxidation products (pentanal and heptanal) might contribute to changes in aroma (Utama et al., 2017). Lipid oxidation is one of the main causes of deterioration of meat and meat-derived products during subsequent storage, particularly cooked poultry and pork meat which contain a significant quantity of unsaturated fatty acids. Lipid oxidation may impair flavour as well as nutritional value (fat soluble vitamins, essential fatty acids). Besides, it may be a health risk as lipid oxidation is linked to the development of cancer and coronary heart diseases (Cheftel & Culioli, 1997). High pressure induces lipid oxidation in meat products, which results in the formation of secondary lipid oxidation products such as thiobar-

bituric acid-reactive substances (TBARS) and hexanal (Kumar, Yadav, Ahmad & Narsaiah, 2015; Simonin et al., 2012). The oxidation rate of the samples subjected to high pressure can be influenced by the physical treatment conditions, mechanical processing, composition and types of products. In several studies, high pressure induced lipid oxidation was not increased immediately after HP treatment but during subsequent storage of the meat and meat products (Beltran, Pla, Capellas, Yuste & Mor-Mur, 2004; Beltran, Pla, Yuste & Mor-Mur, 2003; Orlien, Hansen & Skibsted, 2000). Conversely, Tuboly, Lebovics, Gaal, Meszaros and Farkas (2003) reported an increase in lipid oxidation immediately after the high pressure treatment. It is generally suggested that high pressure induces lipid oxidation by two mechanisms: (i) increase in release of iron from hemoproteins, and (ii) disruption of the membrane (Kumar et al., 2015). Dry-cured ham processed at 400 MPa, and stored for 39 days in a modified atmosphere with 5 % residual oxygen, observed significantly higher values of TBARS, indicating a reduction in oxidative stability during storage (Andres, Adamsen, Moller, Ruiz & Skibsted, 2006). Utama et al. (2017) observed that processed dark-firm-dry beef treated at 200-600 MPa and held under refrigerated storage resulted in the development of lipid oxidation, with significant differences compared to the control. The authors found that the highest values of TBARS were obtained in samples subjected to 600 MPa, at day 3 of storage. Bajovic, Bolumar and Heinz (2012) established the critical pressure levels (between 300 and 600 MPa) that can induce lipid oxidation in meat. Utama et al. (2017) recommended that the temperature in the pressurization vessel should be maintained below 20 ^{o}C in order to minimize the risk of lipid oxidation in pressure treated meat. High pressure induced lipid oxidation may limit the usefulness of high pressure technology for meat and meat-derived products unless antioxidants are added or oxygen-free packaging is used. Adding carbon dioxide prior to pressure application or removing oxygen may be helpful to avoid HP induced lipid oxidation (Campus, 2010; Cheftel & Culioli, 1997). Lipid oxidation may lead to negative effects on flavour and colour, however, the combination of HPP and metal chelators or antioxidant packaging could reduce the lipid oxidation triggered during high pressure processing (Stratakos & Koidis, 2015). The addition of tomato waste (0.30 %) or final tomato paste (0.10 %) to minced meat resulted in a lag phase of 6 days for the development of secondary oxidation products in the meat subjected to a pressure of 600 MPa (Alves, Bragagnolo, da Silva, Skibsted & Orlien, 2012). Chicken patties packed in antioxidant-active packaging made with a film containing 0.45 mg of rosemary extract /cm^2, treated at 800 MPa for 10 min at 5 ^{o}C and then stored at 5 ^{o}C for 25 days, was able to delay the HP induced lipid oxidation (Bolumar, Andersen & Orlien, 2011). Ethylenediaminetetraacetic acid (EDTA) and egg white powder prevented chicken meat slurries from pressure-induced lipid oxidation (300 and 500 MPa) during chilled storage due to their abilities to chelate metal ions (Beltran, Pla, Yuste & Mor-Mur, 2004; Simonin et al., 2012). One of the main purposes of high pressure processing of meat and meat-based products is to improve microbial safety. The effects of HPP on microorganisms are well recognized and accepted. HPP at low temperature or moderate temperature led to inactivation of enzymes and microbial vegetative cells but was not effective for deactivation of spores (Hugas, Garriga & Monfort, 2002; Stratakos & Koidis, 2015). Different combinations of pressure, temperature, time and cycling treatments can be selected to achieve the complete inactivation of spores (Torres & Velazquez, 2005). On the other hand, comparatively moderate pressure levels of 200-300 MPa are enough to inactivate most food parasites (Lindsay et al., 2008; Porto-Fett et al., 2010; Simonin et al., 2012). Garriga, Grebol, Aymerich, Monfort and Hugas (2004) reported, HP treatment of dry-cured ham, cooked ham and marinated beef loin at 600 MPa for 6 min was found to be an effective method for preventing the growth of Enterobacteriaceae and yeasts. Also *Salmonella* spp as well as *Listeria monocytogenes* were absent during 120 days of storage. Cooked chicken breast subjected to HP at 600 MPa for 2 min at 20 ^{o}C resulted in a decrease of *Listeria monocytogenes* by a 3.3 log reduction (Patterson, Mackle & Linton, 2011). High pressure treatment of beef liver at 400 and 500 MPa for 10-30 min at 25 ^{o}C reduced bacteria

by more than 3.0 log, however, the samples subjected to a lower pressure resulted in insufficient microbial reduction for safe consumption (Ogihara et al., 2017). Generally, a higher level of pressure and treatment time led to higher cell reductions (Patterson et al., 2011). However, there are other factors that influence the lethality of high pressure like pH, fat content, water activity (a_w) and the types and growth stages of microorganisms. Cells are most resistant at neutral pH, while the destruction efficiency is decreased at higher or lower values of pH (Huang, Lung, Yang & Wang, 2014). Fat content in meat products can affect the antimicrobial efficiency of high pressure treatment as the fat can have a defensive effect on microorganisms (Huang et al., 2014). Low water activity values of foods can result in a baroprotective effect on microorganisms and thus decrease the inactivation (Hereu, Bover-Cid, Garriga & Aymerich, 2012).

5.3 Milk and dairy products

In general, milk and dairy products are processed at a temperature of 70-145 ^{o}C to inactivate food spoilage microorganisms and to ensure food safety for consumption. However, treatment at high temperature deteriorates the sensory and nutritional qualities of food products as many food nutrients are thermally unstable. To overcome this problem, intensive research has been carried out on the use of high pressure processing as an alternative method to traditional thermal processing of milk and dairy products (Liepa, Zagorska & Galoburda, 2016). Even though milk was the first food product to be processed with high pressure by Hite (1899), thus far, HP treated milk products are not commercially available in the market (Norton & Sun, 2008). HPP influences milk properties, physiochemical properties, constituents and microorganisms present in milk. Rastogi and Knorr (2013) reported that HPP was equally effective for pasteurization in destruction of pathogenic and spoilage microorganisms compared to thermal treatment. Complete destruction of alkaline phosphatase in milk has been observed at 800 MPa for 8 min. Several studies have reported the inactivation of microorganisms either introduced or naturally present in milk. Milk exposed to a microbial 4D HP process at 350 MPa extended shelf life to 12 days at 10 ^{o}C, 18 days at 5 ^{o}C and 25 days at 0 ^{o}C (Mussa & Ramaswamy, 1997). Raw milk subjected to 400 MPa for 30 min at 25 ^{o}C contained less than 7.0 log psychrotrophs/ml after storage at 7 ^{o}C for 45 days, while untreated samples contained more than 7.0 log after storage for only 15 days (Garcia-Risco, Cortes, Carrascosa & Lopez-Fandino, 1998). Raw milk pressurized at 400-600 MPa had a comparable microbiological quality to that of a pasteurized sample at 72 ^{o}C for 15 s, depending on the initial microbiological load of milk samples (Trujillo, 2002). High pressure treated milk at 400 MPa for 15 min or 600 MPa for 3 min at 20 ^{o}C achieved the shelf life of 10 days stored at 10 ^{o}C (Trujillo, 2002). Generally, moulds and yeasts can be destroyed at 200-400 MPa but in the state of a spore or ascospore or in a high sugar concentration food, a pressure of about 600 MPa may be required for inactivation (Bello, Martinez, Ceberio, Rodrigo & Lopez, 2014). Many researchers have reported the inactivation of bacteria in milk at pressures around 400-600 MPa (Amador Espejo, Hernandez-Herrero, Juan & Trujillo, 2014; de Oliveira, Augusto, da Cruz & Cristianini, 2014; Liepa et al., 2016; Patterson, 2005; Udabage et al., 2010).

High pressure has potential to modify the size and distribution of fat globules in milk. On exposure to a high pressure up to 500 MPa, at 25 and 50 ^{o}C, there was an observed tendency to increase the number of small fat globules in the range of 1-2 μm (Gervilla, Ferragut & Guamis, 2001), whilst this tendency was reversed at 4^{o}C. The modification in distribution of fat globules in milk is related to aggregation and disintegration of the fat globule membrane under high pressure. However, there is no damage to the milk fat globule membrane (Dhineshkumar, Ramasamy & Siddharth, 2016). When raw milk was processed at 200 MPa at 4 ^{o}C for 10 or 20 min, the free fatty acids (FFA) content did not alter but slightly increased when treated for 30 min (Kim, Kim, Choi, Min & Kwak, 2008). When ewe's milk was subjected to HP at 100-500 MPa at 4, 25 and 50 ^{o}C, there was no change in the FFA content. In fact, some samples resulted in a lower content of FFA than fresh raw milk when treated

at 50 ^{o}C (Gervilla et al., 2001) thus, ameliorating the effects of rancidity in milk during storage. High pressure influenced the colour of milk due to modification in size of fat globules and casein micelles. The optical parameter L* (lightness) of milk exposed to 100-200 MPa slightly differed from the untreated sample whereas those treated at 200-400 MPa saw a progressive reduction (Huppertz, Fox & Kelly, 2004; Huppertz, Kelly & de Kruif, 2006; Needs, Stenning, Gill, Ferragut & Rich, 2000). HP treated skim milk at 200 MPa at 4 ^{o}C was found to decrease L* values (Lee, Choi, Cho & Davaatseren, 2016). Harte, Luedecke, Swanson and Barbosa-Canovas (2003) reported that milk reduced its white colour and changed to yellow when the sample was subjected to thermal treatment followed by high pressure processing (300-676 MPa) but regained its white colour when the sample was exposed to HPP followed by thermal processing. This recovery of the whitish colour may be attributed to the reaggregation of disrupted micelles or the reversible nature of casein micelles. During heat treatment, milk lactose may isomerise in lactulose and consequently degrade to form acids and other sugars. But no modifications in these compounds are detected after the pressure treatment at 100-400 MPa for 10-60 min at 25 ^{o}C, signifying that the Maillard reaction or lactose isomerization did not take place in milk during pressurization (Chawla et al., 2011; Liepa et al., 2016; Lopez-Fandino, 2006). Sierra, Vidal and López (2000) reported that there was no degradation of B group vitamins in HP treated milk. The authors observed no significant loss of vitamin B1 and B6 in milk subjected to high pressure at 400 MPa (2.5 MPa/sec for 30 min at 25 ^{o}C). High pressure processing does not affect the minerals' content of milk but may influence the food matrix leading to an improvement in bioavailability and health benefits (Barba, Terefe, Buckow, Knorr & Orlien, 2015). Milk exposed to HP increases the ionised calcium level, as well as the level of total calcium in the serum phase. The concentration of Ca, Mg and P in serum was found to increase with an increase of pressure to 400 MPa (Barba et al., 2015; Lopez-Fandino, 2006). High pressure induced shifts in the mineral balance leads to an increase in pH of the milk by about 0.1 units. The increase in milk pH and shifts in salts can be reversed rapidly after the treatment of HP, predominantly when the milk is stored at above 10 ^{o}C (Huppertz, Kelly & Fox, 2002; Liepa et al., 2016).

Since high pressure treatment influences the components of milk, it will certainly affect the technological properties of milk during production of various milk products. Milk exposed to 300-400 MPa considerably increased wet curd yield (up to 20 %) and decreased the loss of protein in whey and the volume of whey. The effect is explained by the denaturation of β-lactoglobulin and hence its incorporation in the curd. This results in a high yield of cheese to the extent of 7 %. HP treatment at 400-600 MPa/5-15 min cycle resulted in quick maturation and development of a stronger flavour in cheese (Huppertz et al., 2002). The cheese curd obtained from HP treated milk provides dense network of fine strands, thus showing a great potential for the manufacture of new products owing to the formation of modified textures, tastes and functional properties (Naik et al., 2013). High pressure processing improves the quality and shelf life of yogurt. Exposure of packaged yogurt to high pressure (200-300 MPa at 10-20 ^{o}C) neither changed the texture nor inactivated the viable lactic acid bacteria, however, it prevented acidity development. Above 300 MPa, it resulted in over acidification and reduced viable lactic acid bacteria (Tanaka & Hatanaka, 1992). HP treated (550 MPa) yogurt retained desirable sensory characteristics longer than controls during 4 weeks' storage at 4 ^{o}C or 20 ^{o}C temperature (Jankowska, Reps, Proszek & Krasowska, 2005). Ewe's yogurt made with high pressure processed pasteurized milk (70 ^{o}C for 10 min), using different combinations of pressure and temperature (HP: 200, 350 and 500 MPa and 10, 25 and 55 ^{o}C for 15 min), gave a firmer product on increasing applied pressure. There was a significant increase in gel water retention with the combination of 350 and 500 MPa at 25 and 55 ^{o}C, respectively. Yogurts stored for 20 days at 4 ^{o}C were observed to have good stability (firmness) in all the treatments, however, water retention was only found in yogurt made from high pressure treated milk (Ferragut, Martinez, Trujillo, Güamis et al., 2000; Trujillo, 2002). Yogurt made from HP treated (200-300 MPa at 30 and

40 ^{o}C) milk was found to delay lipid oxidation and reduce the degree of lipolysis (Dhineshkumar et al., 2016; Serra, Trujillo, Pereda, Guamis & Ferragut, 2008). High pressure also has impacts on dairy products such as ice cream, butter and cream. HPP has the potential for fast ageing of ice cream mixes and the physical ripening of dairy cream for the manufacture of butter. High pressure treatment (300 MPa for 15 min) improved the foaming properties of whey protein concentrate, which improved the body and texture of low fat ice cream when added. The ice cream mix containing HP treated whey protein showed better overrun and foam stability and hardness as compared to ice cream prepared with untreated whey protein. This is due to the influence of high pressure on the functional properties of whey protein (Lim, Swanson & Clark, 2008; Lim, Swanson, Ross & Clark, 2008; Rastogi & Knorr, 2013). Dumay, Lambert, Funtenberger and Cheftel (1996) reported that the pressurization (450 MPa at 10 or 25 ^{o}C) of pasteurized cream (35 % fat) did not alter the size distribution of fat globules, pH and flow behaviour. It was also observed that there was no further acidification during storage of cream at 4 ^{o}C for 8 days. On the other hand, HP treatment at 40 ^{o}C resulted in a modification of fat globules, which is partly reversible with storage. The whipping properties enhanced when cream was subjected to high pressure (600 MPa up to 2 min), possibly due to improved crystallization of milk fat (Eberhard, Strahm & Eyer, 1999; Sakharam et al., 2011). Some of the effects of high pressure treatment on milk and dairy products are shown in Table 2.

5.4 Eggs

Egg products (whole liquid egg or blended liquid egg) are used in a number of food products owing to their high nutritional value and physicochemical properties (such as coagulating, emulsifying and foaming). In general, the quality parameters considered during processing of eggs include texture, microbial inactivation, physicochemical parameters, sensorial quality and shelf life (Wang, Huang, Hsu & Yang, 2016). More than 90 % of food borne *Salmonellosis* is caused by *Salmonella enteritidis* which occurred through egg shell (White et al., 2007). In general, eggs are pasteurized thermally under mild conditions in order to avoid extensive denaturation of proteins. Even the thermal treatment at 60 ^{o}C for 20-25 min led to partial denaturation of proteins and coagulation, and thus a deterioration in the functional properties of the eggs. Therefore, HPP can be an alternative method to heat treatment as the former has the potential to inactivate microorganisms without adversely influencing the functional characteristics of the egg (Ahmed, Ramaswamy, Alli & Ngadi, 2003; Ponce, Pla, Sendra, Guamis & Mor-Mur, 1999). The impact of HPP on proteins/enzymes and microorganisms has been found to be comparable with that of heating, however, its influence on quality attributes is commonly considered to be minimal. Texture is generally accepted as one of the main sensory characteristics in determining overall quality. Egg white behaves differently to egg yolk and whole liquid egg due to its high protein content (Singh & Ramaswamy, 2013). HP treatment triggered the coagulation of egg white, and an increasing level of applied pressure and treatment time induced the gelation of egg white similar to that of an egg patty. High pressure processing of egg (600-900 MPa for 0-15 min) resulted in full set egg gels with enhanced physicochemical characteristics and without any cooked flavours. Egg white became opaque at 600 MPa and was able to form egg gels at a treatment of 600 MPa for 15 min. Egg yolk and whole liquid egg were able to form gels at HP treatment of 700 MPa for 15 and 10 min, respectively (Singh & Ramaswamy, 2013). Liquid whole egg exposed to a pressure of 150 MPa for 60 min at 25 ^{o}C was unable to coagulate but at a pressure higher than 250 MPa and a treatment temperature up to 45 ^{o}C instantaneous coagulation was observed (Lee, Heinz & Knorr, 1999). Egg yolk formed a soft and adhesive gel at HP processing of 400 MPa for 30 min at 25 ^{o}C. The hardness of the gel increased and adhesiveness reduced with an increase in pressure (Farr, 1990). Similar observations were also found by Singh and Ramaswamy (2013), where HP induced gels were highly elastic and soft. Cohesiveness and hardness of all the egg components were observed to increase with increasing applied pressure, and

the increase in egg yolk was greater than in other egg components. The springiness of whole liquid egg was higher compared to egg white and egg yolk, with increased springiness at higher pressure intensity and treatment time. Aguilar, Cordobes, Jerez and Guerrero (2007) reported that rising pressure caused a dramatic alteration in the linear viscoelastic behaviour, undergoing a sol-gel transition. High pressure treatment was also investigated as a function of pH and solids contents. The impact of HPP on aggregation and network development can be modulated by pH to a great level by changing the balance between hydrophobic and electrostatic interactions. HPP (400-600 MPa) caused sufficient modifications in the viscosity of egg components so as to form a gel with enhanced quality attributes as compared to thermally induced gels. Gels formed by HP have been observed to be more elastic and softer without any cooked flavour and taste, and no formation of lysinoalanine and destruction of vitamins have been detected (Hayashi, Kawamura, Nakasa & Okinaka, 1989; Singh & Ramaswamy, 2013).

HPP is being investigated to improve shelf life and reduce the detrimental impact of the pasteurization process. Anton, Chapleau, Beaumal, Delepine and de Lamballerie-Anton (2001) found that high pressure can be used to extend the shelf life of egg yolk based emulsions while reducing the number of microbial counts without modifying their physicochemical properties. Multi-pass HP processing (100 MPa) of whole liquid egg, inoculated with 4.0 and 7.0 log CFU/ml *Salmonella enterica* serovar Enteritidis, was found to exhibit first order inactivation kinetics (Patrignani et al., 2013). *Salmonella enteritidis* inoculated in whole liquid egg was efficiently inactivated after a high pressure treatment at 300-450 MPa for 5-15 min at various temperatures of 15, 20 or 50 ^{o}C (Lai et al., 2010; Ponce et al., 1999). Application of high pressure (300 MPa for 3 min) followed by heating (52 ^{o}C for 3.5 min or 55 ^{o}C for 2 min) of whole liquid egg in the presence of 2 % triethyl citrate resulted in a similar microbial quality level to that of whole liquid egg processed at 71 ^{o}C for 1.5 min but the functional properties remained as those of untreated whole liquid eggs (Monfort et al., 2012). The whole liquid egg subjected to high pressure at 300 MPa for 3.3 min had a reduction of the total microbial count of 1.6 to 3.8 log CFU/g. Also, the authors found that the addition of antimicrobial agents (nisin, monolaurin, lysozyme and EDTA) and subsequent pressure treatment resulted in the reduction of microbial count on average by 3.0 log. The synergistic effect was observed if the antimicrobial agent nisin (or monolaurin) was combined with high pressure (Schenkova et al., 2009). Egg patties exposed to high pressure and temperature (700 MPa and 105 ^{o}C) resulted in the inactivation of *Bacillus stearothermophilus* spores (Rajan, Pandrangi, Balasubramaniam & Yousef, 2006). Koutchma, Guo, Patazca and Parisi (2005) also reported that egg patties treated at 700 MPa for 4 min at 105 ^{o}C led to inactivation of *Bacillus stearothermophilus* spores by 6.0 log whilst *Clostridium sporogenes* PA 3679 was reduced by 6.0 log at 700 MPa for 5 min at 110 ^{o}C. The effects of HPP on the physicochemical properties and structure of ovotransferrin concentrate induced an increase in the surface hydrophobicity of protein without any modifications in the total sulfhydryl groups, hence, aggregation was inhibited. This would be of great help in the development of a microbiologically safe high quality product (Acero-Lopez, Ullah, Offengenden, Jung & Wu, 2012; Wang et al., 2016).

High pressure processing triggered a number of changes in the colour parameters (L*, a*, and b* values) of all the egg components (whole liquid egg, egg yolk and egg white). Singh and Ramaswamy (2013) investigated the effect of HPP (600-900 MPa for 0-15 min) on the colour parameters of egg components. For egg white, the L* (brightness), a* (redness) and b* (yellowness) values were found to increase with a rise in pressure intensity level and treatment time. On the other hand, egg yolk changed its colour from pale yellow to orange yellow whilst L* values remained unchanged and a* values were observed to decrease. However, b* values increased considerably indicating an increase in the yellow colour of the egg yolk. In the case of whole liquid egg, all the colour parameters (L*, a*, and b* values) increased significantly with an increase in applied pressure and time. The increased lightness and reddish yellow colour implied the whole liquid egg was more attractive. When whole li-

quid egg was exposed to 300 MPa for 3.3 min, the L* value remained unchanged whereas a* and b* values were found to decrease (Schenkova et al., 2009). However, the total colour difference (ΔE*) of HP treated samples immediately after HP treatment and after 7 days of refrigerated storage was found to be lower when compared to pasteurized samples (65 ^{o}C for 3 min), indicating that the HP treated whole liquid egg colour retention was relatively similar to that of the fresh untreated samples. Egg yolk subjected to high pressure (400 MPa for 30 min) retained its original colour (Farr, 1990).

5.5 Fish and seafood

Seafood is exceedingly perishable and post-mortem modifications follow rapidly compared with other muscle foods. It is because of its high water activity, pH close to neutral, unsaturated fatty acids content as well as free amino acids and active autolytic enzymes, thus prone to oxidative and microbial degradation (de Oliveira, Cabral Neto, Rodrigues dos Santos, Rocha Ferreira & Rosenthal, 2017). Chemical tests and total viable counts such as analysis of total volatile basic nitrogen (TVB-N) and trimethylamine (TMA-N) have been used to assess the spoilage of seafood in the seafood industry. The value of TMA-N below 15 mg/100 g and TVB-N less than 300 mg/100g indicates good quality seafood (Ali, Sharif, Adhikari & Faruque, 2009; Kaur et al., 2013). A pressure intensity level of 100-600 MPa for a few seconds to 10-15 min are the most commonly used treatment conditions. With high pressure treatment (200-400 MPa) it was possible to effectively avoid microbial growth, trimethylamine development and autolytic activity in sliced raw squids (Gou, Xu, Choi, Lee & Ahn, 2010). HP processed (250 MPa for 5 five min at 3 ^{o}C and 250 MPa for 10 min at 25 ^{o}C) cold smoked salmon was acceptable for up to eight weeks of storage, hence the shelf life was improved by 2 weeks compared to untreated products (Erkan et al., 2011). Hurdle technology of high pressure processing (250 MPa for 2 two min and 200 MPa for 2 two min) followed by mild heat treatment (45 ^{o}C for 15 min and 50 ^{o}C for 5 five min) of oysters reduced *Vibrio vulnificus* and *Vibrio parahaemolyticus* to non-detectable levels, and retained the sensory characteristics for an extended shelf life (Ye, Huang & Chen, 2012). Black Tiger Shrimp extended its shelf life to 15 days compared with 5 days in untreated samples during chilled storage when treated at 435 MPa for 5 min at 25 ^{o}C (Kaur et al., 2013). Fish are highly susceptible to oxidation due to their high content of polyunsaturated fatty acids, pro-oxidants such as enzymes and transition metals and heme-containing protein such as hemoglobin. The influence of high pressure processing on lipid oxidation depends on various factors such as high pressure intensity, treatment time, ante-and post-mortem, fat profile, age, pre-processes, chemical composition, fibre type and age among others (Truong, Buckow, Stathopoulos & Nguyen, 2015).

A stronger catalytic oxidation power at a pressure level of 300 MPa was reported, even though higher levels of thiobarbituric acid (TBA) were detected from 150-300 MPa in salmon, carp, bonito fish, cod, sea bass, and mahi-mahi (Angsupanich & Ledward, 1998; Lakshmanan, Patterson & Piggott, 2005; Medina-Meza, Barnaba & Barbosa-Canovas, 2014; Sequeira-Munoz, Chevalier, LeBail, Ramaswamy & Simpson, 2006; Teixeira et al., 2014; Wada & Ogawa, 1996; Yagiz, Kristinsson, Balaban & Marshall, 2007). Conversely, smoked fish showed more stability to lipid oxidation after pressure treatment, most likely due to antioxidants derived from the smoke (Jo et al., 2014; Montiel, De Alba, Bravo, Gaya & Medina, 2012). Kaur et al. (2013) reported that the HP treatment of black tiger shrimp at 100, 270 and 435 MPa for 5 min at 25 ^{o}C did not significantly change the free fatty acids (FFA) content, indicating that HP did not affect the hydrolysis mechanism of fatty acids. Similar results were observed in mackerel, turbot and salmon (Chevalier, Le Bail & Ghoul, 2001; Figueiredo, Bragagnolo, Skibsted & Orlien, 2015; Ortea, Rodriguez, Tabilo-Munizaga, Perez-Won & Aubourg, 2010). On the other hand, horse mackerel exposed to HP at 150, 300 and 450 MPa for 0, 2.5 and 5.0 min exhibited an increase in the concentration of free fatty acids, with a significant correlation to HP intensity level and treatment time (Torres, Vazquez, Saraiva, Gallardo & Aubourg, 2013). Sequeira-Munoz et al.

(2006) also revealed a similar phenomenon in carp pressurized at 100-200 MPa for 15 and 30 min. The increase in concentration of FFA may be explained by the unfolding of myofibrillar proteins and interference of interactions between free fatty acids and these proteins triggered by high pressure. The myofibrillar proteins and FFA interact with each other through van der Waals, electrostatic, hydrogen bonding and hydrophobic forces, which result in a decrease of protein extractability (de Oliveira et al., 2017).

Several studies have shown that high pressure processing impacts on the structure and texture of fish and seafood. HP treatment of sea bass fillets (100-500 MPa for 5 min at 10 ^{o}C) showed that above 300 MPa fish were harder after chilled storage as compared to untreated samples, indicating the ability of HP to enhance the textural quality of fish fillets (Cheret, Chapleau, Delbarre-Ladrat, Verrez-Bagnis & De Lamballerie, 2005). Liang, Guo, Zhou, Xiao and Liu (2017) indicated the processing of bighead carp surimi gels at 100-500 MPa for 30 min at 25 ^{o}C exhibited less hardness and chewiness but greater gels' strength than traditional two-step heat treated gels when treated above 300 MPa. The highest gel springiness and strength were found at 500 MPa. They also observed that the adductor muscle of bay scallop decreased hardness as compared to the control samples after HP treatment. Barramundi minced muscle subjected to HP (300-500 MPa for 10 min at 4 ^{o}C) and subsequent cooking (90 ^{o}C for 30 min) increased hardness, springiness, gel-forming ability and water holding capacity, with an increase of pressure level and salt concentration (Truong et al., 2017). HP treatment at 2 % salt concentration developed barramundi gel with greater gel strength, mechanical properties and smoother texture than heat induced gels (90 ^{o}C for 30 min) (Truong et al., 2017). The HP treatment of black tiger shrimp (100, 270 and 435 MPa for 5 min at 25 ^{o}C) resulted in a hardening effect with an increase of the applied pressure (Kaur et al., 2013). Similar trends were observed in tuna, salmon, cod, mahi-mahi and trout (de Oliveira et al., 2017; Ramirez-Suarez & Morrissey, 2006; Yagiz et al., 2007; Yagiz et al., 2009). Modifications in texture can be directly linked to the influence of high pressure on proteins such as protein denaturation and aggregation, denaturation of myofibrillar proteins, α-actinin release and alterations in the actin-myosin interaction (Guyon, Meynier & de lamballerie, 2016; Yagiz et al., 2007).

It is important to understand the effects of HP on fish colour, as colour is one of the main attributes for considering freshness, perception of product quality and influence on the purchase decision of consumers. Several studies have reported that the L* values increase in HP treated fish, which appeared more clear, typical of cooked meat characteristics and grey when exposed to 150-300 MPa (Cheret et al., 2005; de Oliveira et al., 2017; Jo et al., 2014; Truong et al., 2015; Yagiz et al., 2007). HP processed black tiger shrimp gave a significant increase in L* parameters with increased pressure intensity. It was also observed that a* value decreased while the b* value increased after HP treatment (Kaur et al., 2013). Barramundi minced muscle subjected to high pressure resulted in a substantial increase in whiteness, with rise in pressure level (Truong et al., 2017). Similar observations were found in HP treated bighead carp surimi gels (100-500 MPa for 30 min at 25 ^{o}C), where the L* values were observed to increase and a* parameters decrease, with the increase of applied pressure. The b* values were observed to decrease at lower pressures; however, it varies at 300 MPa or greater (Liang et al., 2017). The total colour change (ΔE) tends to increase with high pressure processing as revealed in most of the studies (salmon, carp, cod, oyster, bluefish, mahi-mahi, sea bass, tuna, turbot, shrimp) (de Oliveira et al., 2017). Even though there are some variances between results, most investigations indicate a decrease in redness (a* value) and increase in yellowness (b* value), which differs with high pressure treatment conditions and species of fish and seafood. The colour changes induced by HP might be due to denaturation of globin and/or release or displacement of heme (Cheftel & Culioli, 1997; Kaur et al., 2013). Sequeira-Munoz et al. (2006) proposed that the coagulation of sarcoplasmic and myofibrillar proteins induced by high pressure were responsible for the modifications of colour parameters in the samples. An additional possible cause suggested for the change in colour is lipid oxidation due to degradation of the major carotenoid pigment which results in the release of Fe and Cu ions

from the muscles (Cruz-Romero, Kerry & Kelly, 2008; de Oliveira et al., 2017; Kaur et al., 2013). Some of the effects of high pressure processing on fish and seafood are shown in Table 3.

6 Some drawbacks of high pressure technology in food processing

Whilst there are a number of countries worldwide such as USA, Japan, France, Romania, Greece, Belgium, Spain, Portugal and Netherlands manufacturing HPP food products (Bajovic et al., 2012; Rastogi, Raghavarao, Balasubramaniam, Niranjan & Knorr, 2007), HPP use is still limited to a comparatively small number of countries. One of the main limitations of HP applications at the present time is the cost of this technology (including the cost of investment and maintenance of equipment, and limited production throughput due to a discontinuous process) (Stratakos & Koidis, 2015; Zhao et al., 2017). The HPP phenomenon is based on compression, so the food must contain water. High pressure treatment may not inactivate spores and some enzymes are very resistant to pressure. Foods that are structurally fragile require special attention (Naik et al., 2013). Another downside is the restriction on selection of packaging materials, as HPP requires flexible/soft packaging materials and is thus only limited to plastic. The limited large-scale commercialization of HP technology is also caused by the difficulty in fabrication of pressure vessels that will endure the very high pressures required. In addition, repeatedly compressing and decompressing may damage the air-tight HP body and pressure adding container. Also, lack of regulatory approval has hindered a larger implementation of this technology on an industrial scale (Wang et al., 2016). Consequently, considering some of the above difficulties, food manufacturers may prefer conventional methods of food processing/preservation over high pressure technique.

7 Conclusions

High pressure is an emerging non-thermal technology which can accomplish food safety standards comparable to those of heat pasteurization. High pressure processing can destroy pathogenic microorganisms and enzymes, extend the shelf life and change structures, with little or no influence on the nutritional and sensory quality attributes of food products. Several studies have shown the great potential of high pressure processing/preservation of meats, fruits, vegetables, seafood, eggs, milk and their derived products. The combination of HPP and other processing methods (thermal, antimicrobial, antioxidant, metal chelators, vacuum packaging, chilled storage, non-thermal methods, among others) can be suitably selected for the effective treatment of foods. High pressure processing may not replace traditional methods of food processing but it may complement such methods. The future application of high pressure technology in food processing/preservation is promising with the advancements in development of high pressure machinery.

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