SpringerBriefs in Food, Health, and Nutrition

Hafiz Muhammad Shahbaz · Farah Javed ·
Jiyong Park

Advances in Food Applications for High Pressure Processing Technology

Springer

SpringerBriefs in Food, Health, and Nutrition

Springer Briefs in Food, Health, and Nutrition present concise summaries of cutting edge research and practical applications across a wide range of topics related to the field of food science, including its impact and relationship to health and nutrition. Subjects include: Food Chemistry, including analytical methods; ingredient functionality; physic-chemical aspects; thermodynamics Food Microbiology, including food safety; fermentation; foodborne pathogens; detection methods Food Process Engineering, including unit operations; mass transfer; heating, chilling and freezing; thermal and non-thermal processing, new technologies Food Physics, including material science; rheology, chewing/mastication Food Policy And applications to: Sensory Science Packaging Food Qualtiy Product Development We are especially interested in how these areas impact or are related to health and nutrition. Featuring compact volumes of 50 to 125 pages, the series covers a range of content from professional to academic. Typical topics might include:

- A timely report of state-of-the art analytical techniques
- A bridge between new research results, as published in journal articles, and a contextual literature review
- A snapshot of a hot or emerging topic
- An in-depth case study
- A presentation of core concepts that students must understand in order to make independent contributions

Hafiz Muhammad Shahbaz • Farah Javed
Jiyong Park

Advances in Food Applications for High Pressure Processing Technology

Springer

Hafiz Muhammad Shahbaz
Food Science and Human Nutrition
University of Veterinary & Animal Sciences
Lahore, Pakistan

Farah Javed
Food Science and Human Nutrition
University of Veterinary & Animal Sciences
Lahore, Pakistan

Jiyong Park
Biotechnology
Yonsei University
Seoul, Korea (Republic of)

ISSN 2197-571X ISSN 2197-5728 (electronic)
SpringerBriefs in Food, Health, and Nutrition
ISBN 978-3-031-33642-3 ISBN 978-3-031-33643-0 (eBook)
https://doi.org/10.1007/978-3-031-33643-0

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

List of Figures

List of Tables

About the Authors

Hafiz Muhammad Shahbaz is an Associate Professor at the Department of Food Science and Human Nutrition, University of Veterinary and Animal Sciences, Pakistan. Previously, he worked as a Postdoctoral Researcher at the Department of Biotechnology, Yonsei University, Korea. His research focuses on food processing technology, food product development, food and health, and process optimization. He has published numerous journal articles in top-ranked peer-reviewed international journals.

Farah Javed is a PhD researcher at the Department of Food Science and Human Nutrition, University of Veterinary and Animal Sciences, Pakistan. Her research interests are solving nutritional-related issues, food toxicity, and product development.

Jiyong Park is a Professor Emeritus of the Department of Biotechnology at Yonsei University, Korea. He also works as CTO at Nutrex Technology Co., Ltd., Korea. He previously worked as a Senior Scientist at CJ Food R&D Center, Korea. His research interests are food processing technology, high pressure processing, and titanium dioxide-UV photocatalysis. He has published numerous research articles in international peer-reviewed journals.

Chapter 1
Introduction and Advances in HPP Equipment and Packaging Material

Abstract Food processing technologies that use non-thermal methods have become increasingly popular due to consumer demand for fresh-like food products, nutritious foods, and healthy foods. High pressure processing (HPP), also called as high hydrostatic pressure (HHP), is one technology that has achieved great commercial success in recent years among non-thermal technologies. HPP can extend shelf life and enhance food safety while retaining the natural state of sensory and nutritional attributes of foods. At present, more than 400 industrial HPP units are being used around the world for processing different food commodities, including meat products, ready-to-eat meals, vegetable and fruit products, avocado products, dairy products, dips and condiments, wet salads and sandwich fillings, fermented products, and baby and infant foods. HPP is an in-package food processing technology. During HPP processing, packaging materials (polymers and copolymers) can adapt to a 15% volume drop and then reshape without affecting sealing properties. In this chapter, the working mechanism of HPP and advancements in HPP industrial equipment and packaging materials are discussed.

Keywords HPP · Shelf life · Sensory property · HPP industrial unit · Packaging material for HPP

1.1 Introduction to HPP Technology

Increasing demands from health-conscious consumers for natural and clean-label foods with a fresh taste and chemical preservative–free foods have led to the development of non-thermal pasteurization processes, such as high pressure processing (HPP) technology. HPP allows processors to reduce or eliminate the use of preservatives with the benefit of a clean label, which, in many cases, is the primary consumer appeal of HPP. Modern consumers understand ingredient statements. HPP goes a step beyond preservatives, which can only prevent microorganisms from growing. HPP actually kills microorganisms.

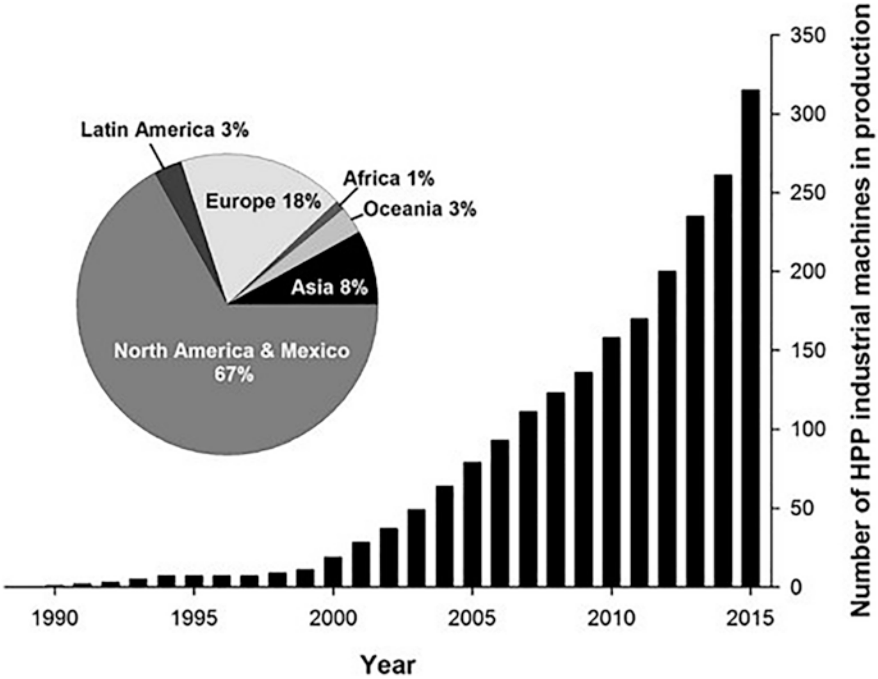
H. Muhammad Shahbaz et al., *Advances in Food Applications for High Pressure Processing Technology*, SpringerBriefs in Food, Health, and Nutrition,
https://doi.org/10.1007/978-3-031-33643-0_1

HPP can increase inactivation of pathogenic and spoilage microorganisms and destroy some food enzymes without affecting product quality, fresh flavor, and nutrient content compared with conventional heat processing methods (Rastogi, 2013). HPP has a role in enhancement of the health benefits of food products, retains the freshness of products, and allows processors to minimize use of chemical preservatives. HPP also reduces destruction of natural components in fruits and vegetables, thus making it a suitable technology for pasteurization of heat-sensitive food products (Abera, 2019). Food products processed using HPP have a lower glycemic index and increased resistant starch content, allowing better control of blood glucose levels and reduction of caloric intake (Xia et al., 2017). This enhances the clean label concept that is the primary consumer appeal of HPP technology.

The effects of high pressures on organisms were first described by Certes in 1883 (Knorr, 1995). The effects of HPP at 600 MPa to preserve milk were first discussed by Bert Hite, working at an agricultural experiment station at West Virginia University in 1899 (Hite, 1899). Later, in 1914, high pressure was applied to vegetables and fruits (Hite et al., 1914). Subsequently, there was no published research regarding HPP until the 1980s, when interest in HPP developed as an alternative non-thermal pasteurization method. A major revolution was brought about by the release of the first high-pressure processed product onto the Japanese market in 1992. An acidic jam was the first commercial HPP-treated food product, leading to a major revolution in HPP technology (Knorr, 1993). HPP has been effectively used in the food industry over the past several years, and much research has focused on understanding HPP technologies for production of safe, nutritious, and innovative high-quality premium food products (Bansal et al., 2015). Use of HPP is now widespread in the food industry in the Asia/Pacific region (Hiperbaric, 2020) and has been used commercially in the United States and elsewhere for over 15 years. Applications of HPP technology are forecast to grow in the coming years. Visiongain (2015) and Huang et al. (2017) have anticipated that global HPP food markets are expected to reach 55 billion US dollars by the end of 2025 (Fig. 1.1).

Consumer acceptance of HPP-treated foods has seen an increase over the years (Veflen & Grunert, 2010; Mújica-Paz et al., 2011; Jermann et al., 2015; Jaeger et al., 2015). Non-thermal HPP processing is more popular with consumers in the United States, the United Kingdom, and Australia due to improved safety and quality (Lavilla & Gayan, 2018). Consumers in Norway, Denmark, Hungary, Serbia, Slovenia, and Slovakia also responded positively to HPP technology (Mireaux et al., 2007; Boel et al., 2009; Lee et al., 2015).

HPP processes can be applied to a wide range of food products, including both liquid and semi-solid foods. However, the largest application of HPP technology is in the beverage sector (Allied Market Research, 2021) (Fig. 1.1). Highly acidic beverages with a pH of less than 4.6 are the best candidates for HPP processing. Highly acidic products require lower pressures and a shorter holding time than less acidic products to achieve the same shelf life. Beverage formulations, for the most part, require little or no adjustment when switching from thermal processing to non-thermal HPP processing. The technology does not impact the performance of acidulants, proteins, or sweeteners. HPP-treated juices, also called cold-pressed juices,



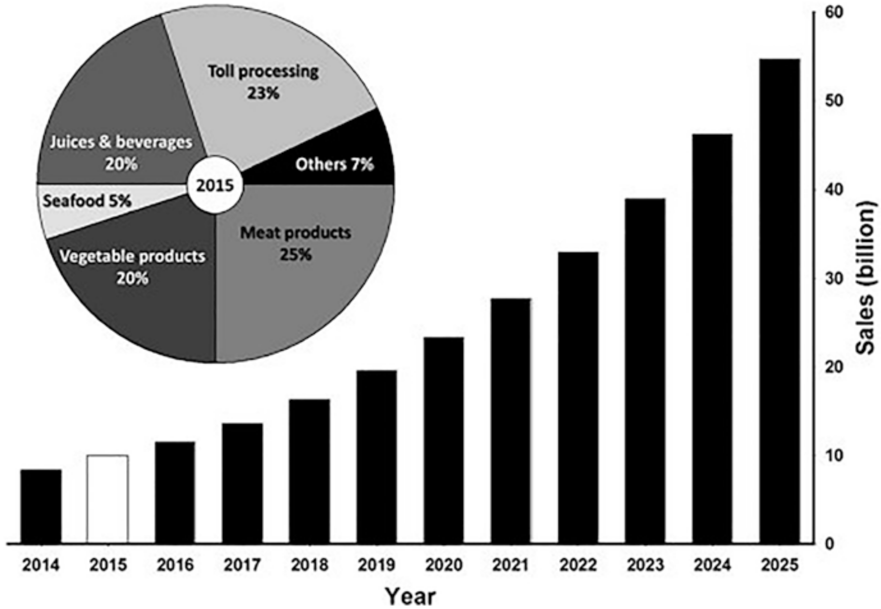


Fig. 1.1 HPP foods share of global market in 2015 and forecasted share in 2025. Continued growth is expected to accelerate. (Visiongain, 2015; Huang et al., 2017)

have a shelf life of 1 week to approximately 30 days if kept refrigerated (Danyluk et al., 2012). Major beverage companies, including Coca-Cola, Campbell's, and Starbucks, have invested in the cold-pressed juice market. Coca-Cola became a shareholder of Suja Juice, while Starbucks acquired Evolution Fresh (Hiperbaric, 2017).

Applications of HPP have expanded beyond inactivation of microorganisms. For example, HPP technology has been linked with alterations in metabolic pathways in cellular biological material, and HPP provides a method for biosynthesis of useful metabolites, particularly γ-aminobutyric acid (GABA) in brown rice (Poojary et al., 2017). HPP can also maintain the immunoglobulin content in dairy products (Sanchez et al., 2020). Use of HPP has enabled reduction in the sodium content, in combination with other chloride salts, in processed foods, thus reducing the risk of cardiovascular disease (Rodrigues et al., 2016). HPP is also used for extraction and enhancement of functional components from food processing wastes. Huang et al. (2020) reported that HPP increased the nutritional value of several food products and increased biosynthesis of GABA in food products, immunoglobulin component retention in dairy products, enhanced the resistant starch content in cereals, and decreased the glycemic index of fruit and vegetable products, which accelerates better control of blood glucose levels and reduces calorie intake.

Application of HPP technology has also expanded for other products. For example, coconut water, a natural isotonic beverage, is gaining popularity as natural sports drink. Application of HPP in the manufacturing of packaged coconut water has increased because thermal treatment destroys nutrients and flavor components in coconut water (Huang et al., 2017). HPP applications have been expanded for meat and seafood products. Vegetable products, baby and infant foods, and dairy products constitute a smaller segment of the HPP market (Fig. 1.2). HPP soups, condiments, sauces, and dressings are also available in the market (Bolumar et al., 2015).

1.2 Working Mechanism of HPP Technology

Le-Chatelier's principle, isostatic pressure, and microscopic ordering are the basis of how HPP works. Le-Chatelier's principle predicts the behavior of a system due to changes in pressure, temperature, or concentration and states that changes in the temperature, pressure, volume, or concentration of a system will result in predictable and opposing changes in the system in order to achieve a new equilibrium state. According to Le-Chatelier's principle, at equilibrium, states a chemical system experiences a reaction change followed by decrease in volume when pressure is increased, and vice versa (Yordanov & Angelova, 2010; Jaeger et al., 2012). Isostatic pressing (Pascal's Principle) indicates that pressure is transmitted equally in all directions, or very nearly equally. After decompression, a material returns to an initial shape (Yordanov & Angelova, 2010). The microscopic ordering principle states that an increase in pressure increases the degree of molecular ordering of a

Fig. 1.2 HPP products in commercial markets around the world. (**a**) fruit juice, smoothie, dairy, and beverage products; (**b**) meat products; and (**c**) baby and infant food products

substance at a constant temperature. Thus, pressure and temperature show antagonistic effects on molecular structure (Benet, 2005).

HPP is a non-thermal technology means that HPP does not use heat energy. HPP uses isostatic pressure, generally in the range of 300–600 MPa, equivalent to 43,500–87,000 psi, for a specific length of time, generally 3–5 min. Isostatic pressure inactivates bacteria, yeasts and molds, viruses, and endogenous enzymes in food and extends product shelf life under refrigerated conditions, therefore, it is also called as high hydrostatic pressure (HHP) technology (Sevenich et al., 2016). No covalent bonds are broken or created during high-pressure treatment. Because covalent bonds are intrinsically stable, flavors, colors, and the nutritional quality of foods are not affected at pressures below 2000 MPa. The cleavage of intra-molecular and inter-molecular bonds in biological systems occurs when the pressure exceeds 400 MPa (Knorr et al., 2006; Li & Wang, 2019).

Food samples are packed in hermetically sealed, flexible packages and then loaded into carrier baskets. These baskets are inserted into a vessel that is sealed using plugs. A pressure transmission fluid, such as distilled water or glycol, is usually pumped into the vessel to create isostatic pressure. Different types of food products require different levels of pressure and pressure-holding times. The product is subjected to pressure uniformly, regardless of its size, volume, or shape. As the product is pressure-treated in a sealed retail container, it is ready for distribution immediately and remains secure until opened by the consumer (Hogan et al., 2005). The values of the temperature rise during pressurization (adiabatic heating) are, for water and compression fluid, approximately 2–3 °C per 100 MPa (Balasubramanian & Balasubramaniam, 2003; Matser et al., 2004). Figure 1.3a, b shows the HPP working mechanism.

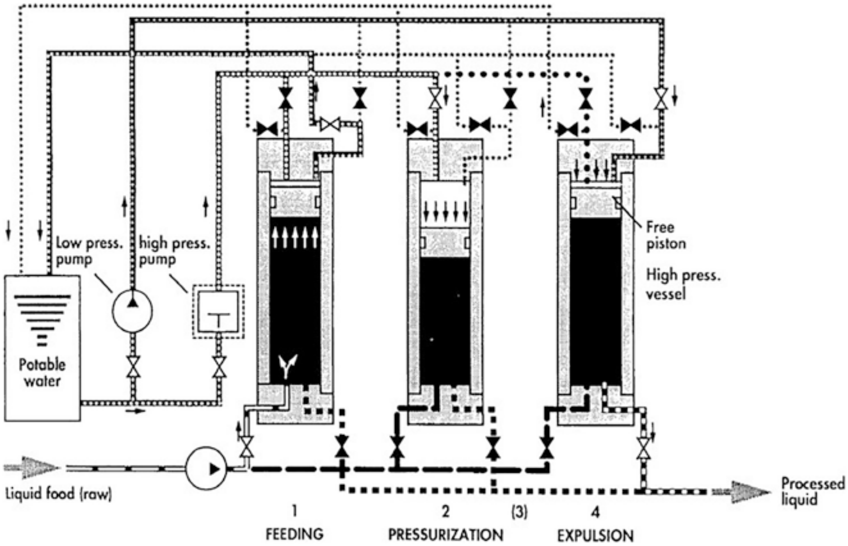
1.3 HPP Industrial Equipment Manufacturers

In 1899, milk was pressure-treated using HPP equipment (Hite, 1899). Various components of the equipment included a collapsible tin tube containing milk enclosed with a cap, which was then positioned in a lead tube inside a steel cylinder filled with water. The bottom of the cylinder was locked with a steel plug. A steel piston was used to apply pressure to the lead tube and the internal components of the cylinder, which were located between two steel blocks. This machine was prepared at the National Transit Company in Pennsylvania. Eventually, HPP technology was used in other countries, starting with Japan. The late commercial spread of this technology was due to the high cost of equipment.

The first high-pressure food processing vessels were manufactured by Mitsubishi Heavy Industries (Palou et al., 1997). Later, several other equipment manufacturers entered the market (Palou et al., 1999). Universities, governmental departments, and research institutions have been actively involved in HPP research to establish a common technical standard for food preservation. A list of major industrial and laboratory HPP equipment manufacturers is shown in Table 1.1. At present, more than 400 industrial-scales HPP machines have been installed around the world (Pottier et al., 2017), and this number is increasing every year, particularly in the beverage sector. Some food companies and their commercial HPP products are listed in Table 1.2.

HPP industrial machines are available for both small- and large-scale production. Small and medium-scale production units are generally applicable in developing economies, whereas large-scale production units are prominent in developed economies. HPP commercial units usually work on a batch or semi-continuous process using multiple sequential chambers connected in series. The batch mode can process both liquid and solid products at an industrial scale, whereas a semi-continuous process can be applied to liquid or pumpable products (Tao et al., 2014).

In recent years, there have been developments that have freed HPP users from the constraints of packaging before processing. For instance, Hiperbaric launched the



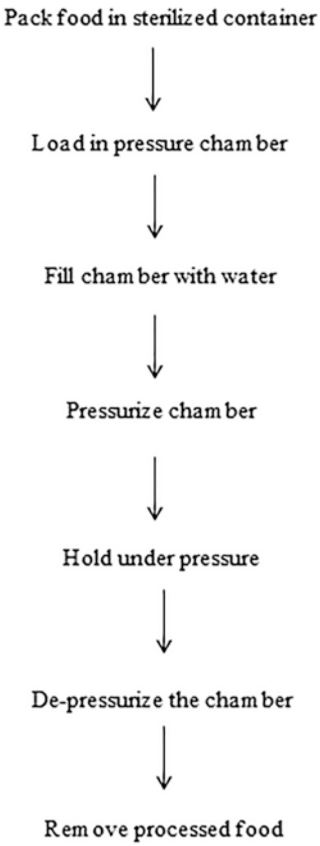


Fig. 1.3 (**a**) Working mechanism of HPP. (**b**) Working mechanism flow diagram of HPP

Table 1.1 Some of the leading HPP equipment manufacturing companies

Manufacturer	Country	Website
Hiperbaric	The United States	www.hiperbaric.com
Avure Technologies Inc	The United States	www.avure-hpp-foods.com
Bao Tou KeFa High Pressure Technology Co., Ltd.	China	www.btkf.com
Kobe Steel Ltd.	Japan	www.kobelco.co.jp
MULTIVAC	Germany	www.multivac.com
Thyssenkrupp AG	Germany	www.thyssenkrupp.com
Mitsubishi Heavy Industries, Ltd.	Japan	www.mhi.com
Stansted Fluid Power Ltd.	England	www.stanstedfluidpower.com

Table 1.2 Food companies and their commercial HPP products

Food company	HPP product
Urban Remedy	Cold-pressed juices
Evolution Fresh	Cold-pressure daily probiotics, juices, and smoothies
Suja Life	Organic juices
Ripe Craft	Cold-pressed juices
Fruity Line	Juices, smoothies
Coldpress Juices	Fruit and nut drinks, coconut water, smoothies, fruit juices, and fruit sparkling waters
Teresa's Juicery	Juices, purees
So Natural	Juices
Rakyan Beverages	Fruit juices
Good Nature	Cold-pressed juices
Genesis Juice	Raw and organic juices, smoothies, teas, and lemonade
Zula Juice	Organic cold-pressed juices
Hoogesteger	Fruit and vegetable juices, oatmeal smoothies, infused waters, boosters, and raw lemonades

latest HPP machine with the largest volume (1050 L) for large-scale production of beverages with the lowest processing cost and minimum energy use. This HPP machine allows processing of beverages in bulk before bottling at a delivery rate of 10,000 L/h. Another benefit of this bulk processing is use of any packaging material after HPP treatment, regardless of design or size.

Hydrogen peroxide is usually used for aseptic beverages and also for sterilization of high-pressure valves and pipes that connect the processing chamber to the storage tank in each cycle. With the introduction of this innovative equipment, the HPP process is simplified with fewer stages, leading to higher productivity (Fig. 1.4) (Huang et al., 2017).

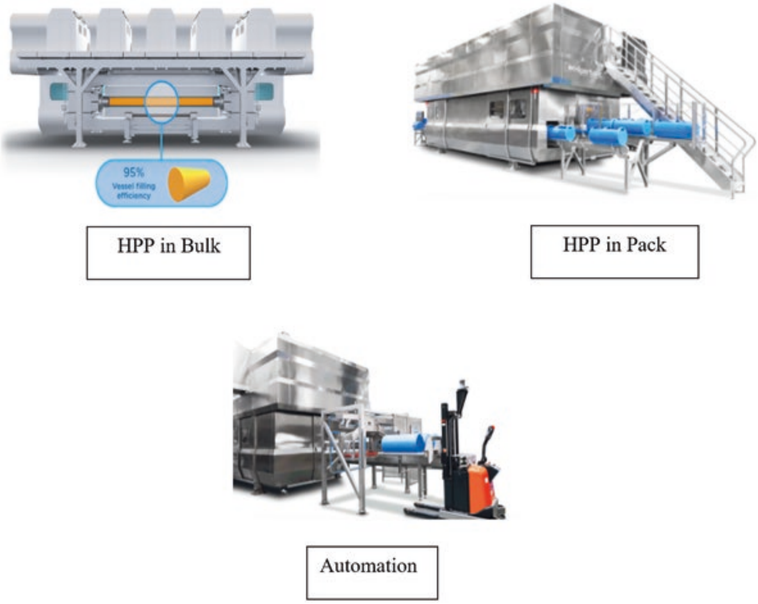


Fig. 1.4 Several types of HPP equipment (batch to continuous processing)

Market-available machines from Hiperbaric and JBT/Avure are horizontal. The only vertical machine available is from JBT/Avure for processing of seafood. Horizontal models of Avure are also available for seafood. Horizontal machines are used for higher volumes. AV-70X is the highest volume machine of JBT/Avure, with the ability to process 70 million pounds of product per year under suitable conditions.

1.4 Types of Packaging Material Used for HPP Foods

HPP is primarily an in-package food processing technology in which food (in final form) and packaging are processed together and the food content remains protected until the product is opened by the customer (Fig. 1.5) (Hogan et al., 2015). Packaging elasticity allows transmission of pressure to the processed product. When used with HPP processing, the packaging material must possess a high sealing capability as well as the ability to return to its original size and shape after a 15% drop in volume (Hogan et al., 2015).

The most suitable packaging materials for HPP are polymers and copolymers (Elamin et al., 2015). As copolymer packaging films have suitable barrier properties, they are ideal for HPP treatment. HPP processing of various materials has not shown any significant changes in their properties, including tensile strength, vapor barrier permeability, oxygen permeability, heat seal strength, or aroma permeability.

Fig. 1.5 Packaging of foods before HPP processing

Pressure also did not have a significant impact on their thermal properties (Le-Bail et al., 2006). The direct and indirect effects of high pressure on packaging materials were studied (Fleckenstein et al., 2010, 2014). EVOH-based (nylon-based ethylenevinyl-alcohol-copolymer) packaging material performed well due to package integrity and low oxygen permeability. Polyethylene, aluminum foil, and polyolefin (a combination three-layered system) showed good results for high-pressure thermal sterilization (HPTS) between 105 and 121 °C at 700 MPa (Juliano et al., 2010). In one study, different packaging materials were processed to evaluate HPP's influence on the barrier properties of flexible multilayer packaging and results showed that HPP had minimum effects on the properties of packaging material (Júnior et al., 2020).

The shape of a package should be in the form of a bottle with a simple sidewall design, a rigid bottom, and top shoulders. Cylindrical or round corner sidewalls are preferred as they provide a symmetrical area to compensate for volumetric package reduction. The package should have a minimum headspace to help reduce permanent deformation. Wide seals should be used to maintain package integrity. The lid film should be thick in order to withstand high pressures. Recyclable packaging material can be used to make the package environmentally friendly (Marangoni Júnior et al., 2019).

Different packaging materials are currently used for different HPP foods. For example, bottles with screw caps made of polyethylene terephthalate (PET) and polyethylene (PE) are used for HPP fruit and vegetable juices. Trays covered with a top skin film are used for HPP-treated sausages. Cooked sliced meat and sliced pork meat are packed in PE and polypropylene (PP) (Juliano et al., 2015). Photos of some HPP products are shown in Fig. 1.6.

Fig. 1.6 Different types of HPP food packaging

Since pressure is applied equally from all directions, no package damage or re-shaping of the food packaging unit occurs (Shahbaz et al., 2018).

To limit oxidation reactions, the packaging headspace must be small (Balasubramaniam et al., 2015). This can be achieved through vacuum sealing. Meal, Ready-to-eat pouches (used by the food industry for ketchup, soups, sauces, fish foods, and vegetable and fruit purees) are placed in high-pressure treatment baskets in order to maximize filling efficiency.

The European Union aims to make all packaging materials 100% recyclable by 2030 in order to maintain sustainability and economy. The alternative materials that have the aforementioned attributes are being searched. Packaging designs with two layers of the same material are attractive. Using one material with two layers can increase recycling while ensuring product quality and safety. There are many studies focused on developing novel and green packaging based on green platform chemicals, such as polylactides (PLA), hydroxy-hydroxymethylfurfural (HMF), or starch.

References

Abera, G. (2019). Review on high pressure processing of foods. *Cogent Food & Agriculture, 5*(1), 1–23.

Allied Market Research. (2021). *Global high pressure processing equipment market to reach $1.23 Billion by 2030*. Allied Market Research.

Balasubramanian, S., & Balasubramaniam, V. M. (2003). Compression heating influence of pressure transmitting fluids on bacteria inactivation during high pressure processing. *Food Research International, 36*, 661–668.

Balasubramaniam, V. M., Martínez-Monteagudo, S. I., & Gupta, R. (2015). Principles and application of high pressure-based technologies in the food industry. *Annual Review of Food Science and Technology, 6*, 435–462.

Bansal, V., Siddiqui, M., & Rahman, M. (2015). Minimally processed foods: Overview. In M. W. Siddiqui & M. S. Rahman (Eds.), *Minimally processed foods* (pp. 1–15). Springer.

Benet, G. U. (2005). *High-pressure low-temperature processing of foods: impact of metastable phases on process and quality parameters*. PhD dissertation, Department of Food Biotechnology and Food Process Engineering, Berlin University of Technology.

Boel, H., Sonne, A., Grunert, K. G., & Banati, D. (2009). Consumer perception of the use of high-pressure processing and pulsed electric field technologies in food production. *Appetite, 52*, 115–126.

Bolumar, T., Georget, E., & Mathys, A. (2015). High pressure processing (HPP) of foods and its combination with electron beam processing. In *Electron beam pasteurization and complementary food processing technologies* (pp. 127–155). Woodhead Publishing.

Danyluk, M. D., Goodrich-Schneider, R. M., Schneider, K. R., Harris, L. J., & Worobo, R. W. (2012). *Outbreaks of foodborne disease associated with fruit and vegetable juices, 1922–2010*. Institute of Food and Agricultural Sciences, University of Florida.

Elamin, W. M., Endan, J. B., Yosuf, Y. A., Shamsudin, R., & Ahmedov, A. (2015). High pressure processing technology and equipment evolution: A review. *Journal of Engineering Science and Technology Review, 8*(5), 75–83.

Felckenstein, B., Sterr, J., & Langowski, H. C. (2010). Effect of high-pressure food processing on the mass transfer properties of selected packaging materials. *Packaging and Technological Science, 23*(5), 253–266.

Fleckenstein, B., Sterr, J., & Langowski, H. C. (2014). The effect of high pressure processing on the integrity of polymeric packaging – Analysis and categorization of occurring. *Packaging and Technological Science, 29*(2), 399–412.

Hiperbaric. (2017). Hiperbaric 1050 Bulk, *Hiperbaric, 1*, 1.

Hiperbaric. (2020). *Asia-Pacific market, the great growth engine for HPP products*. https://www.hiperbaric.com/. Accessed Nov 2021.

Hite, B. H. (1899). The effect of pressure in the preservation of milk. *West Virginia University Agriculture Experimental Station, 58*, 15–35.

Hite, B. H., Giddings, N. J., & Weakley, C. E. (1914). Effect of pressure on certain micro-organisms encountered in the preservation of fruits and vegetables. *West Virginia University Agricultural Experiment Station, 146*, 2–67.

Hogan, E., Kelly, A. L., & Sun, D. W. (2005). High pressure processing of foods: An overview. In *Emerging technologies for food processing* (pp. 3–32). Academic.

Hogan, E., Kelly, A. L., & Sun, D. W. (2015). High pressure processing of foods: An overview. In D.-W. Sun (Ed.), *Emerging Technologies for Food Processing* (pp. 3–24). London, UK: Elsevier Academic, 2014.

Huang, H., Wu, S., Lu, J., Shyu, Y., & Wang, C. (2017). Current status and future trends of high-pressure processing in food industry. *Food Control, 72*, 1–8.

Huang, H. W., Hsu, C. P., & Wang, C. Y. (2020). Healthy expectations of high hydrostatic pressure treatment in food processing industry. *Journal of Food and Drug Analysis, 28*, 1–13.

Jaeger, H., Reineke, K., Schoessler, K., & Knorr, D. (2012). Effects of emerging processing technologies on food material properties. In *Food materials science and engineering* (pp. 222–262). Wiley-Blackwell.

Jaeger, H., Knorr, D., Szabo, E., Hamori, J., & Banati, D. (2015). Impact of terminology on consumer acceptance of emerging technologies through the example of PEF technology. *Innovative Food Science and Emerging Technologies, 29*, 87–93.

Jermann, C., Koutchma, T., Margas, E., Leadley, C., & Ros-Polski, V. (2015). Mapping trends in novel and emerging food processing technologies around the world. *Innovative Food Science and Emerging Technologies, 31*, 14–27.

Juliano, P., Koutchma, T., Sui, Q., Barbosa-Cánovas, G. V., & Sadler, G. (2010). Polymeric-based food packaging for high-pressure processing. *Food Engineering Reviews, 2*(4), 274–297.

Juliano, P., Richter, T., & Buckow, R. (2015). Food packaging for high pressure processing. In *Functional polymers in food sciences*. Scrivener Publishing.

Júnior, B. R. D. C. L., Tribst, A. A. L., Ribeiro, L. R., & Cristianini, M. (2019). High pressure processing impacts on the hydrolytic profile of milk coagulants. *Food Bioscience, 31*, 100–449.

Júnior, L. M., de Oliveira, L. M., Dantas, F. B. H., Cristianini, M., Padula, M., & Anjos, C. A. R. (2020). Influence of high-pressure processing on morphological, thermal and mechanical properties of retort and metallized flexible packaging. *Journal of Food Engineering, 273*, 109–812.

Knorr, D. (1993). Effects of high-hydrostatic-pressure processes on food safety and quality. *Food Technology, 47*, 156–161.

Knorr, D. (1995). Hydrostatic pressure treatment of food: Microbiology. In G. W. Gould (Ed.), *New methods of food preservation* (pp. 159–175). Springer.

Knorr, D., Heinz, V., & Buckow, R. (2006). High pressure application for food biopolymers. *Proteins and Proteomics, 1764*(3), 619–631.

Lavilla, M., & Gaya, E. (2018). Consumer acceptance and marketing of foods processed through emerging technologies. In *Innovative technologies for food preservation* (pp. 233–253). Academic.

Le-Bail, A., Hamadami, N., & Bahuaud, S. (2006). Effect of high-pressure processing on the mechanical and barrier properties of selected packaging. *Packaging and Technological Science, 19*, 237–243.

Lee, P. Y., Lusk, K., Mirosa, M., & Oey, I. (2015). Effect of information on Chinese consumers, perceptions and purchase intention for beverages processed by high pressure processing, pulsed-electric field and heat treatment. *Food Quality and Preference, 40*, 16–23.

Li, B. S., & Wang, B. S. (2019). Structural changes in the interactions between proteins and other macromolecules induced by HPP. In *Reference module in food science*. Elsevier.

Matser, A. M., Krebbers, B., Van Den Berg, R. W., & Bartels, P. V. (2004). Advantages of high pressure sterilisation on quality of food products. *Trends in Food Science and Technology, 15*, 79–85.

Mireaux, M., Cox, D. N., Cotton, A., & Evans, G. (2007). An adaptation of repertory grid methodology to evaluate Australian consumers' perceptions of food products produced by novel technologies. *Food Quality and Preference, 18*, 834–848.

Mújica-Paz, H., Valdez-Fragoso, A., Samson, C. T., Welti-Chanes, J., & Torres, A. (2011). High-pressure processing technologies for the pasteurization and sterilization of foods. *Food and Bioprocess Technology, 4*, 969–985.

Palou, E., Lopez-Malo, A., Barbosa-Canovas, G. V., Welti-Chanes, J., & Swanson, B. G. (1997). High hydrostatic pressure as a hurdle for *Zygosaccharomyces bailii* inactivation. *Journal of Food Science, 62*, 855–857.

Palou, E., Lopez-Malo, A., Barbosa-Canovas, G. V., Welti-Chanes, J., & Swanson, B. G. (1999). Polyphenoloxidase activity and color of blanched and high hydrostatic. *Journal of Food Science, 64*, 42–45.

Poojary, M. M., Dellarosa, N., Roohinejad, S., Koubaa, M., Tylewicz, U., Gomez-Galindo, F., Saraiva, J. A., Rosa, M. D., & Barba, F. J. (2017). Influence of innovative processing on γ -aminobutyric acid (GABA) contents in plant food materials. *Comprehensive Reviews in Food Science and Food Safety, 16*, 895–905.

Pottier, L., Villamonte, G., & Lamballerie, M. D. (2017). ScienceDirect applications of high pressure for healthier foods. *Current Opinion in Food Science, 16*, 21–27.

Rastogi, N. (2013). Introduction. In *Recent developments in high pressure processing of foods* (pp. 1–7). Springer.

Rodrigues, F. M., Rosenthal, A., Tiburski, J. H., & Cruz, A. G. (2016). Alternatives to reduce sodium in processed foods and the potential of high pressure technology. *Food Science and Technology, 36*(1), 1–8.

Sánchez, L., Pérez, M. D., & Parrón, J. A. (2020). HPP in dairy products: Impact on quality and applications. In *Present and future of high pressure processing: A tool for developing innovative, sustainable, safe and healthy foods* (pp. 245–272). Elsevier.

Sevenich, R., Rauh, C., & Knorr, D. (2016). A scientific and interdisciplinary approach for high pressure processing as a future toolbox for safe and high quality products: A review. *Innovative Food Science and Emerging Technologies, 38*, 65–75.

Shahbaz, H. M., Jeong, B., Kim, J. U., Ha, N., Lee, H., Ha, S. D., & Park, J. (2018). Application of high pressure processing for prevention of greenish-gray yolks and improving the microbiological safety and shelf life of hard-cooked peeled eggs. *Innovative Food Science and Emerging Technologies, 45*, 10.

Tao, Y., Sun, D. W., Hogan, E., & Kelly, A. L. (2014). High-pressure processing of foods: An overview. In *Emerging technologies for food processing* (pp. 3–24). Elsevier.

Veflen, N., & Grunert, K. G. (2010). Consumer acceptance of high- pressure processing and pulsed-electric field: A review. *Trends in Food Science and Technology, 21*, 464–472.

Visiongain. (2015). *The food high pressure processing (HPP) technologies market forecast 2015–2015*. Pascalization & Bridgmanization.

Xia, Q., Wang, L., Xu, C., Mei, J., & Li, Y. (2017). Effects of germination and high pressure processing on mineral elements, amino acids, and antioxidants in vitro bioaccessibility, as well as starch digestibility in brown rice (*Oryza sativa* L.). *Food Chemistry, 214*, 533–542.

Yordanov, D., & Angelova, G. (2010). High pressure processing for foods preserving. *Biotechnology & Biotechnological Equipment, 24*, 1940–1945.

Chapter 2
Applications of HPP for Microbial Food Safety

Abstract HPP has shown potential for inactivation of pathogenic and spoilage microorganisms in different food products and can achieve up to 5-log reductions in microbial counts, as required by the FDA, for an inactivation treatment with minimum impact on the nutritional and sensory qualities of food products. A variety of factors affect HPP inactivation, including pressure, time, temperature, and microorganism type.

Keywords HPP · Microbial inactivation · HPP processing conditions

2.1 Microbial Inactivation by HPP

The effect of HPP on the inactivation of microbial pathogens in different food commodities is summarized in Table 2.1. Table 2.1 showed that HPP has achieved 4.0–6.5 log CFU/g reductions in counts of microorganisms in several fruit juices, including apple, mango, and grape, and in other food products (Table 2.1). A number of studies showed that the inactivation of microbes by HPP did not adversely affect the nutritional and sensory characteristics of foods (Barba et al., 2012, 2015; Evelyn & Silva, 2019; Gong et al., 2015; Marszalek et al., 2017; Sevenich et al., 2020).

The National Advisory Committee on Microbiological Criteria for Foods (NACMCF) has redefined pasteurization as protection of products from lethal agents using pressure and electric fields. Under normal distribution and storage conditions, pasteurization can also be defined by the NACMCF as any process, treatment, or combination that improves food quality by reducing the number of disease-causing microbes (NACMCF, 2006). High-pressure pasteurization involves application of pressures and temperatures in the ranges of 300–600 MPa and less than 45 °C, respectively (Lau & Turek, 2007). HPP effectively inactivates different pathogenic and spoilage microbes, including bacteria, yeasts and molds, and viruses. Fruit and vegetable juices (France, Japan, USA, Portugal, UK, Italy), acidified

H. Muhammad Shahbaz et al., *Advances in Food Applications for High Pressure Processing Technology*, SpringerBriefs in Food, Health, and Nutrition,
https://doi.org/10.1007/978-3-031-33643-0_2

Table 2.1 Effect of HPP treatment for inactivation of microbes in food products

Product	HPP treatment parameter	Target microorganism	Microbial reductions $\log_{10}$ CFU/g	References
Red grape fruit juice	500 MPa/10 min/25 °C	Total plate count/yeasts and molds	4.8/4.1	Gao et al. (2015)
Mango juice	400 MPa/10 min/25 °C	*E. coli* O157:H7	6.0	Hiremath and Ramaswamy (2012)
Apple juice	600 MPa/10 min/75 °C	*Neosartorya fischeri* ascospores	3.0	Kim and Silva (2016)
Orange, apple, apricot, and cherry juices	350 MPa/5 min/40 °C	*E. coli* O157:H7, *Salmonella* Enteritidis, *S. aureus*	Below the detection limit	Bayındırlı et al. (2006)
Grapefruit juice	402 MPa/3 min/31.8 °C	*Total plate count/yeasts and molds*	No microbial growth for 28-day storage at 4 °C	Uckoo et al. (2013)
Orange juice	400 MPa/3 min/25 °C	*E. coli* O157:H7	6.5	Torres et al. (2016)
Strawberry puree	450 MPa/2 min/21 °C	*E. coli* O157:H7	Below the detection limit	Huang et al. (2014, b)
Hami melonjuice	464 MPa/12.8 min/54.61 °C	*Bacillus subtilis* Spores	5.0	Chen et al. (2015)
Ground chicken	450 MPa/10 min/6–10 °C	*Salmonella* spp.	>5.0	Sheen et al. (2015)
Chicken breast	HPP 500 MPa/1 min/18 °C, coupled with an essential oil-based active packaging	*Listeria monocytogenes*	Below the detection limit throughout 60-day storage at 4 °C	Stratakos et al. (2015)
Ready-to-eat tomatoes	UV-TiO_2 photocatalysis as pre-washing and HPP as post-package treatment, 500 MPa/1 min/25 °C	*Salmonella* Typhimurium	>5.0 log through synergistic effect	Shahbaz et al. (2018)

avocado purée (guacamole) and salsa dips (USA), sliced cured cooked and raw-cooked hams, tapas, and other processed meats and poultry products (Spain, USA), seafood, including oysters, clams, mussels, scallops, shrimps, crabs, and squid (USA, Japan), beverage blends (USA), rice cakes (Japan), jams, jellies, tropical fruits, fruit sauces, and fruit desserts (Japan, USA), yogurt (Japan), and smoothies

(UK) are different commercial HPP products available worldwide (Sáiz et al., 2008). The microbial efficacy of pressure pasteurization differs depending on the type of food to be processed. Several microbes, including *Salmonella, E. coli* O157:H7*, L. monocytogenes,* and *Vibrio parahaemolyticus,* are of common public health concern in a variety of foods, such as eggs, fruit juices, meat, and seafood. For elimination (a 5-log reduction), an adequate pressure treatment is required (NACMCF, 2006, 2010).

Other terms used for microbial inactivation achieved through high pressure are pressure-assisted thermal processing (PATP) and pressure-assisted thermal sterilization (PATS). Both are viable alternatives for production of sterile, shelf-stable, low-acid foods. Pressure-assisted thermal processing of potato products was accepted by the US Food and Drug Administration (FDA) in 2009. The combined effects of pressure and heat achieve inactivation of different bacterial spores and thermophilic microbes. A combination of increased pressure (500–700 MPa) and temperature (90 °C) is applied to food during PATP (Daryaei et al., 2012). The benefits of this technique are an increase in the temperature of treated foods and, after depressurization, expansion cooling of products. Food color, flavor, texture, and nutritional values can be better preserved through PATP than thermal sterilization. Spores of *Clostridium sporogenes* in beef showed a higher degree of inactivation during a short time at low temperature using high pressure (700–900 MPa) than using thermal processing (Zhu et al., 2008). *Bacillus amyloliquefacie*ns has been regarded as a pressure-thermal-resistant, non-pathogenic indicator organism (Daryaei et al., 2012). The FDA approved a no-objection certificate for pasteurization of low-acid products using PATP (IFT News, 2009). HPTS is also useful for enhancement of food quality parameters (Table 2.2). Pokhrel et al. (2019) found that application of HPP at 500 MPa with a mild thermal treatment of 35 °C and 25 ppm nisin achieved approximate 7-log CFU reductions in *Listeria innocua* and *E. coli* counts in carrot juice after 28 days under refrigerated storage, suggesting that clean, safe, good-quality juices can be produced using HPP with a combination of mild heat and nisin.

In a process termed high pressure-assisted thermal processing, approved by the United States' Food and Drug Administration (FDA), pressure is used in combination with a temperature of 70 °C to achieve inactivation of *Alicyclobacillus acidoterrestris* spores, and the spores germinate into vegetative cells more easily. Subsequent application of heat-shock (80 °C/10 min) caused inactivation of the germinated *A. acidoterrestris* spores (Ribeiro & Cristianini, 2020).

As lasagna contains beef, it has the potential for cross-contamination. The aerobic counts of lasagna inoculated with *S. aureus* and *L. monocytogenes* were reduced by 31% and 41%, following treatment at 500 and 600 MPa, respectively. The HPP process was also used to extend the shelf life of raw milk. HPP treatment of 600 MPa for 3 min prolonged the shelf life by decreasing total viable counts of *Enterobacteriaceae*, lactic acid bacteria, and *Pseudomonas* spp. and maintained nutritional quality attributes similar to unprocessed milk (Stratakos et al., 2019).

In the dairy industry, *L. monocytogenes* is a serious concern. Cheese made without rennet is high in pH and water activity values, high in moisture, and low in salt,

Table 2.2 Effect of HPP/HPTS for improving shelf life and quality parameters of food products

Product	HPP parameter	Quality parameter	References
Aloe vera-litchi mixed beverage	600 MPa/15 min/56 °C	Total color difference and browning index of beverage samples were increased; inactivation of pectinmethylesterase (PME), polyphenoloxidase (PPO), and peroxidase (POD) enzymes; shelf life of 100 days compared with 80 days for heat-treated beverage	Hulle and Rao (2016)
Carrot puree	400–500 MPa/15 min/20 °C	Increase in total carotenoids	Patras et al. (2009)
Granny Smith apple purée product	400 and 600 MPa/5 min/20 °C	Total vitamin C and ascorbic acid contents and nutritional quality remained unaffected at 400 MPa compared with mild conventional pasteurization	Landl et al. (2010)
Red wine	650 MPa/2 h/18 °C	Significant reduction in the intensities of sour and fruity odors of wine; affected physicochemical and sensorial properties	Tao et al. (2012)
Chevon goat meat	300 MPa and 600 MPa/5 and 10 min/28 ± 2 °C	Significant increase in non-heme iron and TBARS values; improved shelf life	Reddy et al. (2015)
Hilsa fish fillets	350 MPa/10 min/27 °C compared with heat treatment (75 °C for 8 min)	Higher L* and b* values with lower a* values compared to controls; texture improvement; shelf-life extension of 25 days	Chouhan et al. (2015)
Yellowfin tuna chunks	100, 200, and 300 MPa/5 min/25 °C; chunks were packed in ethyl vinyl alcohol film	Enterobacteriaceae level decreased with increasing pressure; 200 MPa treated samples were the most sensory acceptable after 30 days of storage	Kamalakanth et al. (2011)
Chilled Chilean jack mackerel	550 MPa/4 min/20 °C	Delayed microbial growth and trimethylamine production during refrigerated storage; microbiological shelf life was significantly extended from 6 to 40 days	Reyes et al. (2015)
Squid muscles	200 MPa/10 min/25 °C	Improved flavor compounds contributing to the taste of squid during refrigerated storage	Yue et al. (2016)
Ready-to-use egg product	HPP as post-package pasteurization at 550 MPa/5 min/25 °C	Significantly higher sensory preference of quality attributes of HPP post-processed eggs compared with steam heat post-processed eggs	Shahbaz et al. (2018)
Korean red ginseng	200–600 MPa/1 min/25 °C	A 45% higher level of total major ginsenosides in HPP-pretreated red ginseng than conventionally prepared red ginseng	Kim et al. (2007)

which are ideal growth conditions for *L. monocytogenes* (Evert-Arriagada et al., 2018). HPP reduced the microbial count in cheese. HPP was found to be effective in maintaining camembert cheese quality and mitigating the risk of *L. monocytogenes* infection associated with bloomy rind cheese (Batty et al., 2019). Inoculated with different strains of Listeria (*L. innocua, L. monocytogenes* CECT 4031, or *L. monocytogenes* Scott A) and inoculum levels (3–5 log CFU/g or 6–7 log CFU/g), starter-free fresh cheese was then treated at pressures of 300, 400, 500, or 600 MPa for 5 min to examine how HPP affects the load of microbes (Evert-Arriagada et al., 2018). Microbial counts were below the quantification limit (1-log CFU/g) for all samples inoculated with *L. innocua L. monocytogenes* CECT 4031 at 3–4 log CFU/g. The *L. monocytogenes* Scott A strain showed more resistance to treatment, and counts below the detection limits were only observed after 600 MPa of pressure was applied.

Rifna et al. (2019) reviewed the role of HPP to examine microbial safety in powdered foods. Corn flour, fennel powder, and Chinese herbs inoculated with *Bacillus cereus* were treated with HPP. Heat-resistant spore colony counts declined to nearly the detection level when the compaction rate was above 3 with a linear press force of 700 MPa. Inactivation of *Bacillus cereus* spores was also studied in combined olive powder using HPP. At 200 and 500 MPa, inactivation of *Bacillus cereus* was largely achieved, and at a pressure of 400 MPa, inactivation of *Bacillus cereus* was reduced (Marco et al., 2011). The olive powder, therefore, had an additive effect with storage temperature and HHP processing and could act as an additional control hurdle during the shelf life of products pasteurized by HHP technologies or in the case of cold-chain breakage. Inactivation of *Cronobacter sakazakii* in infant formula was achieved using HPP. Inactivation levels of 3 and 6 $\log_{10}$ cycles were obtained at 600 MPa (Gonzalez & Barrett, 2010).

2.2 Factors Affecting Microbial Inactivation

HPP microbial inactivation is affected by several factors, including process parameters of pressure and time. Characteristics of the microorganisms and the substrate in which they are treated are also important (Georget et al., 2015; Lee & Oey, 2018; Park et al., 2019; Shahbaz et al., 2016, 2018).

2.2.1 Process Parameters

The process parameters of pressure level, process temperature, and pressure holding time are the keys that influence the inactivation of microbes during HPP processing (Smelt et al., 2002). Although vegetative microbes were effectively killed at 600 MPa at 20 °C and 45 °C, they showed maximum resistance at room temperature (25 °C) (Barba et al., 2012).

In UHT milk treated at 600 MPa for 30 min at 20 °C, the *E. coli* O157:H7 strain was reduced by 2-logs, while the same strain was reduced by 8-logs with treatments at 200 MPa for 15 min at 60 °C or 700 MPa for 15 min at 40 °C (Reineke et al., 2013). High HPP microbial inactivation levels with heat were due to destruction of proteins (Georget et al., 2015). A reduction in the fluidity of the cell membrane was cited as the reason for the increased microbiological efficacy of pressure treatment at a reduced temperature (<20 °C) (Molina-Höppner et al., 2013).

2.2.2 Microbial Characteristics

Vegetative cells are easily destroyed by high pressure. Bacterial spores are not. The microbe genus, species, and strain affected the sensitivity of cells to HPP (Patterson, 2014). More physiological changes occur in Gram-negative than in Gram-positive bacteria under high pressure due to a more complex Gram-negative cell membrane (Smelt, 1998). The inactivation of rod-shaped bacteria was easily achieved by high pressure, whereas the inactivation of spherical bacteria was difficult. *Lactoccoci* inoculated with 10% (v/v) reconstituted skim milk were found to be more susceptible to high-pressure treatment (100–350 MPa) than *Lactobacilli*.

Inactivation of virus particles by HPP has been demonstrated, in which pressure affects proteins present in the viral capsid (Kingsley, 2013; Lou et al., 2015).

2.2.3 Influence of Substrate Composition, pH, and Water Activity for Inactivation of Microorganisms

HPP inactivation of microorganisms can be affected by many factors, including substrate, pH, and water activity. Various food constituents, including proteins, carbohydrates, lipids, and minerals, have been shown to protect microbial inactivation by HPP (baroprotective effect) (Daryaei et al., 2012). Water activity is reduced due to the baroprotective effect of sugar and salt solutes at high concentrations on vegetative microbes, and a reduction in water activity causes cell shrinkage and thickening that leads to decreased cell size, membrane permeability, and fluidity (Daryaei et al., 2012). A higher degree of HPP microorganism inactivation occurs when the medium pH is reduced due to a transient pH shift or addition of acids. This occurs because high pressure can cause a transient acidic pH shift by increasing the ionic dissociation of water and weak acids. At depressurization, the pH shifts back to the initial value. Thus, growth of microbes during storage can be prevented due to a pH decrease. A decrease in pH has been found to increase HPP inactivation levels for foodborne vegetative pathogens, including *L. monocytogenes* (Mackey et al., 1995; Stewart et al., 1997; Alpas et al., 2000) and *Streptocoocus aureus*, *E. coli*, *Salmonella Enteritidis*, and *S. Typhimurium* (Alpas et al., 2000). More *Bacillus coagulans* and *Clostridium sporogenes* spore inactivation at pH 4.0 than at pH 7.0 has been reported through HPP at moderate process temperatures (Daryaei et al., 2012).

2.2.4 Species and Strain Variation Effects on Microbial Inactivation

Different microorganisms have shown different responses to HPP treatment (Table 2.3). Eukaryotic cells showed more sensitivity than prokaryotes. The most sensitive microorganisms to high pressure were yeasts, which showed a 6-log reduction as a result of treatments at 300–400 for MPa for a few min at 20 °C. Mold spores are more resistant than vegetative forms. Gram-positive bacteria are less sensitive to high pressure than Gram-negative bacteria, which have a complex cell membrane structure that is more susceptible to environmental changes. However, strains of the Gram-negative bacterium *E. coli* O157:H7 have shown resistance to pressure (Patterson, 2014).

Bacterial spores are very resistant to pressure treatments applied to foods, regardless of the species and strain (Table 2.3). *Bacillus* spores are less pressure-resistant than the spores of *Clostridium spp*. For effective inactivation of bacterial spores through HPP, a combination of other preservation techniques, such as HPTS, is required. Direct inactivation of spores requires extremely high pressure.

Low pressure (usually less than 400 MPa) helps spores to germinate including L-alanine, adenosine, and inosine. The germinative effect of pressure is effectively enhanced with a mild temperature for inactivation of spores, especially in low-acid foods (Patterson, 2014).

Table 2.3 presents information on the HPP inactivation of viruses. Hepatitis A, which is present in contaminated oysters, is pressure sensitive like many vegetative bacteria. For 1 min treatments at 350, 375, and 400 MPa, respectively, within a temperature range of 8.7–10.3 °C, the Hepatitis A virus showed reductions of >1, >2, and >3 log10 plaque-forming units (PFU). Using a 5-min treatment at 5 °C, norovirus in oyster tissue was inactivated to a level of 4.05 log10 PFU (Patterson, 2014).

The stationary phase of cell growth is generally more resistant to pressure than cells in the exponential phase. As bacteria enter the stationary phase, they synthesize new proteins that protect them from a variety of adverse environmental conditions, such as high salt concentrations, elevated temperatures, and oxidative stress.

2.2.5 Substrate Composition

The response of bacteria to pressure depends on the chemical composition of the substrate. The presence of proteins, carbohydrates, and lipids can protect microorganisms against pressure. A rich medium provides the necessary amino acids and vitamins to stressed cells. Greater microbial inactivation has been shown in buffer solutions than in foods, while certain foods provide more protection than others. When *E. coli* O157:H7 was treated with 375 MPa for 30 min at 20 °C in a phosphate buffer (pH 7.0), it was inactivated by 6 logs, but the same treatment reduced *E. coli*

Table 2.3 Sensitivity of microorganisms to high pressure in different food products

Microorganisms	Substrate	Treatment conditions	Inactivation (log_{10} units of reduction)
Vegetative bacteria			
Campylobacter jejuni	Pork slurry	300 MPa, 10 min, 25 °C	6
	Poultry puree	400 MPa, 10 min, 25 °C	>8
Citrobacter freundii	Minced meat	300 MPa, 20 min, 20 °C	>5
E. coli (nonpathogenic)	Goat's cheese	400 MPa, 10 min, 25 °C	>7
E. coli O157:H7	UHT milk	800 MPa, 10 min, 20 °C	<2
	Poultry meat	700 MPa, 30 min, 20 °C	5
L. monocytogenes	UHT milk	340 MPa, 80 min, 23 °C	6
	Raw milk	340 MPa, 60 min, 23 °C	6
	Cold-smoked salmon	450 MPa, 5 min, 12 °C	Approx. 2
Yersinia enterocolitica	Pork slurry	300 MPa, 10 min, 25 °C	6
Spore-forming bacteria			
Bacillus coagulans spores	PBS (100 mmol l^{-1}) pH 8.0400	400 MPa, 30 min, 45 °C plating out immediately after pressurizing	2
Clostridium botulinum type A spores	Rich medium	250 MPa, 60 min, 70 °C	6
Yeasts and molds			
Candida utilis	Pork slurry	300 MPa, 10 min, 25 °C	2
Saccharomyces cerevisiae	Apple juice, pH 3.8	500 MPa, 1 min, 5 °C	Approx. 6
Zygosaccharomyces bailii	Mosca wine, pH 3.0	400 MPa, 2 min, 20 °C	6
Viruses			
Hepatitis A virus	Green onions	375 MPa, 5 min, 21 °C	4.75 [a]PFU g^{-1}
Norovirus	Oyster tissue	400 MPa, 5 min, 5 °C	4.05 [a]PFU g^{-1}
Parasites			
Cryptosporidium parvum	Apple juice	530 MPa, 1 min, 20 °C	>4 log reduction of oocysts

Patterson (2014)
[a]*PFU* Plate forming unit

O157:H7 in poultry meat by 2.5 logs and in milk by 1.75 logs. *S. typhimurium* was reduced by 6 logs in pork slurry when pressurized at 300 MPa for 10 min and by 2 logs in baby food chicken when pressurized at 340 MPa for 10 min. These differences were attributed to different substrates (Patterson, 2014).

Cells can be protected by a reduction in water activity (a_w) during pressurization. In the presence of sucrose, glucose, fructose, and sodium chloride, *Rhodotorula rubra* was treated at 25 °C and 400 MPa for 15 min to achieve a range of water activities. Due to protective effects, yeast was not inactivated below 0.92 a_w. At a_w value of 0.96, cell counts decreased by log 7 (Considine et al., 2008). Spores' pressure resistance can be affected by the nature of their solutes. *Bacillus coagulans* is better protected by ionic solutes, such as NaCl and $CaCl_2$, than by nonionic solutes, such as sucrose and glycerol. A high ionic concentration was shown to protect spores more than a low aw value, especially above 0.96 (Considine et al., 2008). Electrostriction causes the pH of aqueous solutions to decrease with increasing pressure, making it difficult to measure how much the pH has changed. It is expected that fruit juices, which are often acidic, will undergo a pH shift towards higher acidity at 500 MPa. After pressure is released, the pH increases. *L. monocytogenes* became increasingly sensitive to pressure at 23–24 °C as pH decreased. Complete survival was observed after 10 min at 300 MPa at pH 7.1, whereas under the same treatment conditions, numbers of *L. monocytogenes* were decreased by log 1.8 at pH 5.3. The pressure was more sensitive to *B. coagulans* spores at low pH and high temperature. A 4-log decrease was observed in pH 7.0 buffer samples treated at 400 MPa for 30 min at 70 °C, compared with a 6-log decrease in pH 4.0 buffer samples (Mathys et al., 2008). Pressure resistance is also affected by the presence of food additives. Potassium sorbate and butylated hydroxyanisole (BHA) increased pressure-related inactivation of *L. monocytogenes*, while sodium ascorbate and BHT did not. Therefore, it is important to understand food processing conditions rather than simply relying on substrate data (Patterson, 2014).

2.2.6 Effect of Temperature

It is important to maintain temperature during pressurization for vegetative microbes to survive. Microbes are generally inactivated at both below- and above-ambient temperatures. Increased lethal effects have been observed in several reports when pressurizing at −20 °C compared with +20 °C (Li et al., 2020; Podolak et al., 2020). Pressure inactivation can be enhanced under refrigeration temperatures. When ewe and goat milk was pressurized at 2 °C and 10 °C, microbial numbers were reduced more than when milk was treated at 25 °C. At 600 MPa applied with mild heating at 40 °C, certain strains of *E. coli* O157:H7 and *S. aureus* were inactivated. Heat during pressurization is not more effective for inactivation of spores than a preheating treatment. There was no inactivation of *Clostridium sporogenes* spores with 600 MPa at 60 °C for 60 min, but a 2-log reduction was observed with a mild pressure treatment followed by preheating (80 °C for 10 min followed by 400 MPa at 60 °C for 30 min) (Considine et al., 2008).

Harmful pathogens, including *E. coli* O157:H7*, Salmonella,* and *L. monocytogenes*, as well as vegetative spoilage microorganisms such as yeasts, Pseudomonas, and lactic acid bacteria, were inactivated in a variety of meat products through applications of HPP (Kamenik et al., 2015). The effect of HPP on microbes can be observed using both scanning (SEM) and transmission electron microscopy (TEM) (Figs. 2.1a, 2.1b, and 2.1c).

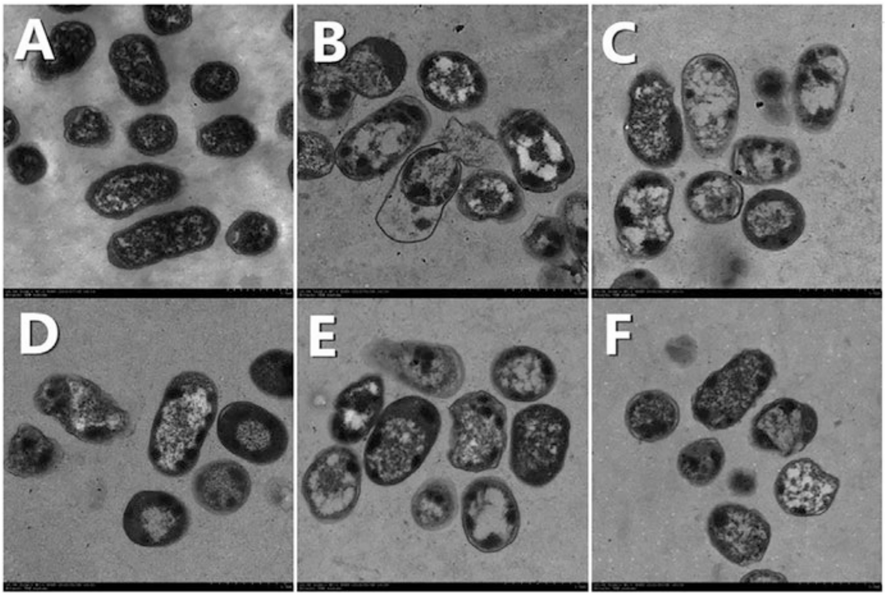


Fig. 2.1a Scanning electron microscope (SEM) micrographs of *E. coli* O157:H7. (**a**) Cells without HPP treatment; (**b**) cells treated with 400 MPa for 5 min; (**c**) HPP-treated samples for 6 h; (**d**) HPP-treated samples for 12 h; (**e**) HPP-treated samples for 18 h; and (**f**) HPP-treated samples for 24 h

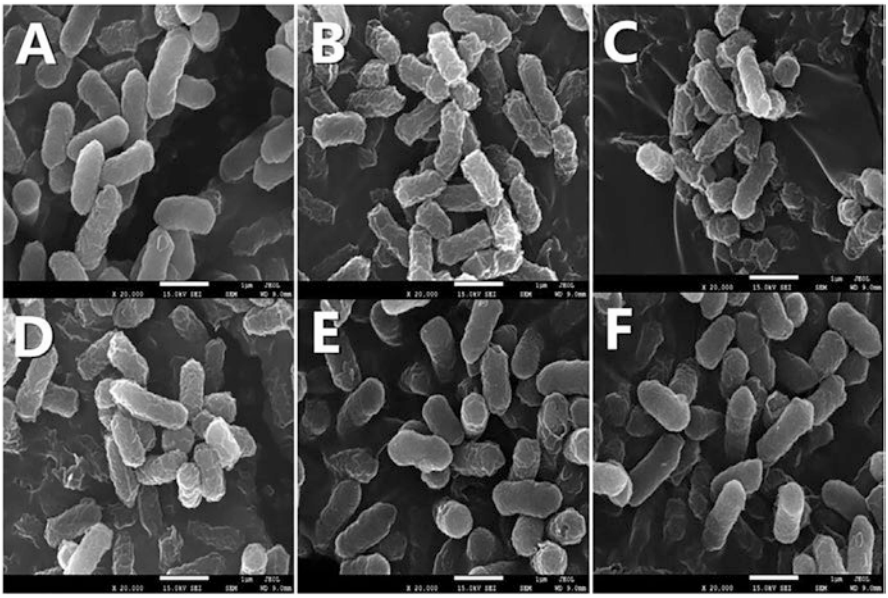


Fig. 2.1b Transmission electron microscope (TEM) micrographs of *E. coli* O157:H7. (**a**) Cells without HPP treatment cells; (**b**) samples treated with HPP for 0 h at 400 MPa for 5 min; (**c**) samples treated with HPP for 6 h; (**d**) samples treated with HPP for 12 h; (**e**) samples treated with HPP for 18 h; and (**f**) samples treated with HPP for 24 h. (Reproduced by Ma et al., 2019)

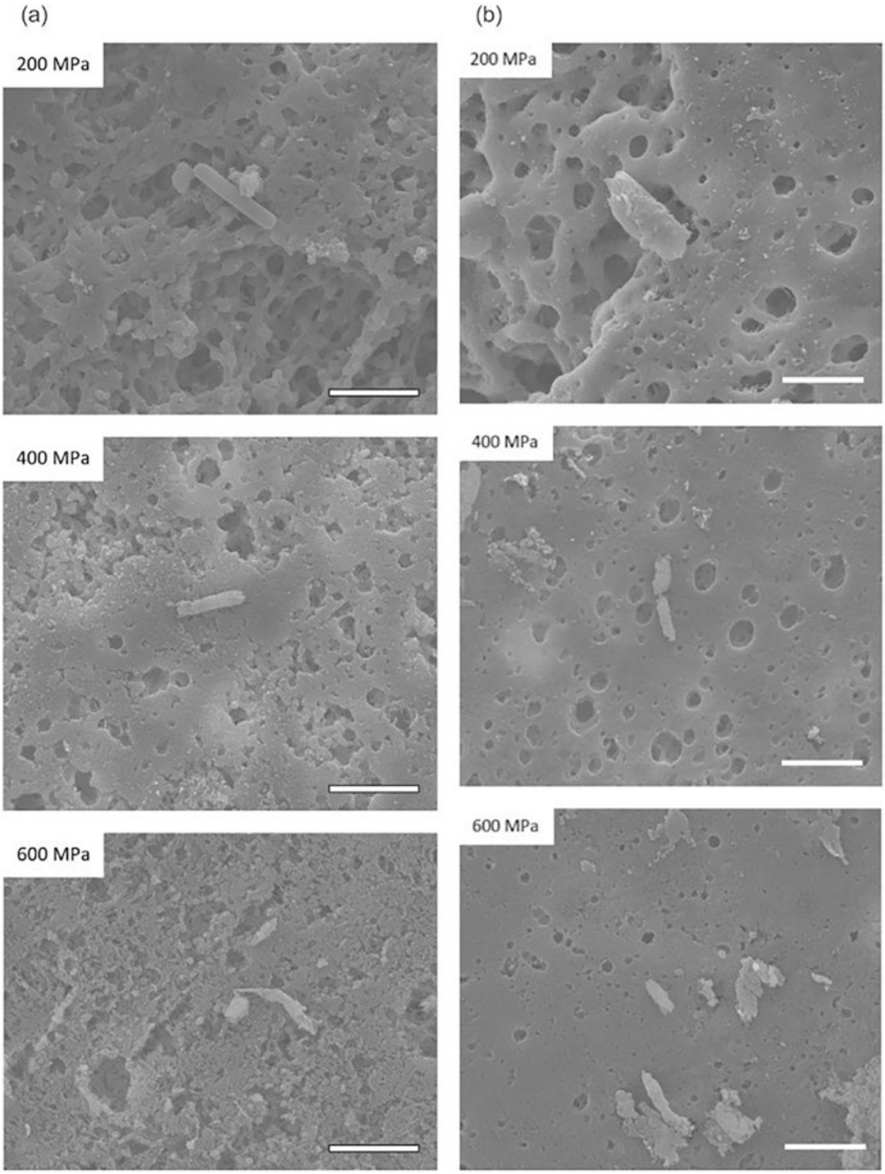


Fig. 2.1c Scanning electron micrographs of *Listeria monocytogenes* processed at 200, 400, and 600 MPa for (**a**) 5 min and (**b**) 20 min. (Reproduced by Tomasula et al., 2014)

References

Alpas, H., Kalchayanand, N., Bozoglu, F., & Ray, B. (2000). Interactions of high hydrostatic pressure pressurization temperature and pH on death and injury of pressure-resistant and pressure-sensitive strains of foodborne pathogens. *Intenational Journal of Food Microbiology, 60*, 33–42.

Barba, F. J., Esteve, M. J., & Frígola, A. (2012). High pressure treatment effect on physicochemical and nutritional properties of fluid foods during storage: A review. *Comprehensive Reviews in Food Science and Food Safety, 11*, 307–322.

Barba, F. J., Terefe, N. S., Buckow, R., Knorr, D., & Orlien, V. (2015). New opportunities and perspectives of high pressure treatment to improve health and safety attributes of foods. A review. *Food Research International, 77*, 725–742.

Batty, D., Meunier-Goddik, L., & Waite-Cusic, J. G. (2019). Camembert-type cheese quality and safety implications in relation to the timing of high-pressure processing during aging. *Journal of Dairy Science, 102*, 8721–8733.

Bayındırlı, A., Alpas, H., Bozoğlu, F., & Hızal, M. (2006). Efficiency of high pressure treatment on inactivation of pathogenic microorganisms and enzymes in apple, orange, apricot and sour cherry juices. *Food Control, 17*(1), 52–58.

Chen, J., Zheng, X., Dong, J., Chen, Y., & Tian, J. (2015). Optimization of effective high hydrostatic pressure treatment of *Bacillus subtilis* in Hami melon juice. *Food Science and Technology, 60*, 1168–1173.

Chouhan, A., Kaur, B. P., & Rao, P. S. (2015). Effect of high pressure processing and thermal treatment on quality of hilsa (*Tenualosa ilisha*) fillets during refrigerated storage. *Innovative Food Science and Emerging Technologies, 29*, 151–160.

Considine, K. M., Kelly, A. L., Fitzgerald, G. F., Hill, C., & Sleator, R. P. (2008). High- pressure processing effects on microbial food safety and food quality. *FEMS Microbiology Letters, 281*, 1–9.

Daryaei, H., Balasubramaniam, V. M., & State, T. O. (2012). Microbial decontamination of food by high pressure processing. In *Microbial decontamination in the food industry: Novel methods and applications* (pp. 371–406). Woodhead Publishing Ltd.

Evelyn, & Silva, F. V. M. (2019). Heat assisted HPP for the inactivation of bacteria, moulds and yeasts spores in foods: Log reductions and mathematical models. *Trends in Food Science and Technology, 88*, 143–156.

Evert-Arriagada, K., Trujillo, A. J., Amador-Espejo, G. G., & Hernández-Herrero, M. M. (2018). High pressure processing effect on different Listeria spp. in a commercial starter-free fresh cheese. *Food Microbiology, 76*, 481–486.

Gao, G., Zhao, L., Ma, Y., Wang, Y., Sun, Z., & Liao, X. (2015). Microorganisms and some quality of red grapefruit juice affected by high pressure processing and high temperature short time. *Food and Bioprocess Technology, 8*(10), 2096–2108.

Georget, E., Sevenich, R., Reineke, K., Mathys, A., Heinz, V., Callanan, M., Rauh, C., & Knorr, D. (2015). Inactivation of microorganisms by high isostatic pressure processing in complex matrices: A review. *Innovative Food Science and Emerging Technologies, 27*, 1–14.

Gong, Y., Jian-Yong, Y., Ping, Q., Jun, M., Xiao-Juan, Z., & Rong-Rong, L. (2015). Comparative study of the microbial stability and quality of carrot juice treated by high pressure processing combined with mild temperature and conventional heat treatment. *Journal of Food Process Engineering, 38*, 395–404.

Gonzalez, M. E., & Barrett, D. M. (2010). Thermal, high pressure, and electric field processing effects on plant cell membrane integrity and relevance to fruit and vegetable quality. *Journal of Food Science, 75*(7), 121–130.

Hiremath, N. D., & Ramaswamy, H. S. (2012). High-pressure destruction kinetics of spoilage and pathogenic microorganisms in mango juice. *Journal of Food Processing and Preservation, 36*(2), 113–125.

Huang, H. W., Hsu, C. P., Yang, B. B., & Wang, C. Y. (2014). Potential utility of high-pressure processing to address the risk of food allergen concerns. *Comprehensive Reviews in Food Science and Food Safety, 13*(1), 78–90.

Huang, R., Li, X., Huang, Y., & Chen, H. (2014). Strategies to enhance high pressure inactivation of murine norovirus in strawberry puree and on strawberries. *International Journal of Food Microbiology, 185*, 1–6.

Hulle, N. R. S., & Rao, P. S. (2016). Effect of high pressure and thermal processing on quality changes of aloe vera-litchi mixed beverage (ALMB) during storage. *Journal of Food Science and Technology, 53*(1), 359–369.

IFT News. (2009). Institute of Food Technologists announces. *Innovation Award winners*. Available from: http://www.ift.org/newsroom/news-releases/(2009),/june/07/(2009),-innovation-award-winners.aspx. Accessed 25 July 2011

Kamalakanth, C. K., Ginson, J., Bindu, J., Venkateswarlu, R., Das, S., Chauhan, O. P., & Gopal, T. K. S. (2011). Effect of high pressure on K-value, microbial and sensory characteristics of yellowfin tuna (*Thunnus albacares*) chunks in EVOH films during chill storage. *Innovative Food Science and Emerging Technologies, 12*(4), 451–455.

Kamenik, J., Salakova, A., Hulankova, R., & Borilova, G. (2015). The effect of high pressure on the microbiological quality and other characteristics of cooked sausages packed in a modified atmosphere or vacuum. *Food Control, 57*, 232–237.

Kim, H. J., & Silva, F. V. M. (2016). Modeling the inactivation of Neosartorya fischeri ascospores in apple juice by high pressure, power ultrasound and thermal processing. *Food Control, 59*, 530–537.

Kim, S. O., Park, C. W., Moon, S., Lee, H. A., Kim, B., Lee, D. U., Lee, J. H., & Park, J. (2007). Effects of high-hydrostatic pressure on ginsenoside concentrations in Korean red ginseng. *Food Science and Biotechnology, 16*(5), 848–853.

Kingsley, D. H. (2013). High pressure processing and its application to the challenge of virus-contaminated foods. *Food Environmental Virology, 5*, 1–12.

Landl, A., Abadias, M., Sárraga, C., Viñas, I., & Picouet, P. A. (2010). Effect of high pressure processing on the quality of acidified Granny Smith apple purée product. *Innovative Food Science and Emerging Technologies, 11*(4), 557–564.

Lau, M. H., & Turek, E. J. (2007). Determination of quality differences in low-acid foods sterilized by high pressure versus retorting. In C. Doona & F. Feeherry (Eds.), *High pressure processing of foods* (pp. 195–217). Blackwell Publishing.

Lee, P. Y., & Oey, I. (2018). Sensory properties of high-pressure treated fruit and vegetable juices. In M. Houška & F. V. M. Silva (Eds.), *High pressure processing of fruit and vegetable products* (pp. 121–133). CRC Press.

Li, Y., Zheng, Z., Zhu, S., Ramaswamy, H. S., & Yu, Y. (2020). Effect of low-temperature-high-pressure treatment on the reduction of *Escherichia coli* in milk. *Foods, 9*, 17–42.

Lou, F., Neetoo, H., Chen, H., & Li, J. (2015). High hydrostatic pressure processing: A promising nonthermal technology to inactivate viruses in high-risk foods. *Annual Review of Food Science and Technology, 6*, 389–409.

Ma, J., Wang, H., Yu, L., Yuan, W., Fu, W., Gao, F., & Jiang, Y. (2019). Dynamic self-recovery of injured *Escherichia coli* O157: H7 induced by high pressure processing. *LWT Food Science and Technology, 113*, 108–308.

Mackey, B. M., Forestière, K., & Isaacs, N. (1995). Factors affecting the pressure resistance of Listeria monocytogenes to high hydrostatic pressure. *Food Biotechnology, 9*, 1–11.

Marco, A., Ferrer, C., Velasco, L. M., Rodrigo, D., Muguerza, B., & Martínez, A. (2011). Effect of olive powder and high hydrostatic pressure on the inactivation of bacillus cereus spores in a reference medium. *Foodborne Pathogens and Disease, 8*(6), 681–685.

Marszalek, K., Wozniak, L., Skapska, S., & Mitek, M. (2017). High pressure processing and thermal pasteurization of strawberry purée: Quality parameters and shelf life evaluation during cold storage. *Journal of Food Science and Technology, 54*, 832–841.

Mathys, A., Reineke, K., Heinz, V., & Knorr, D. (2008). High pressure sterilisation – Development and application of temperature controlled spore inactivation studies. *High Pressure Research, 29*, 3–7.

Molina-Höppner, A., Doster, W., Vogel, R. F., & Ga, M. G. (2013). Protective effect of sucrose and sodium chloride for Lactococcus lactis during sublethal and lethal high-pressure treatments. *Applied and Environmental Microbiology, 70*(4), 2013–2020.

National advisory committee on microbiological criteria for foods (NACMCF). (2006). Requisite scientific parameters for establishing the equivalence of alternative methods of pasteurization. *Journal of Food Protection, 69*(5), 1190–1216.

National advisory committee on microbiological criteria for foods (NACMCF). (2010). Parameters for determining inoculated pack/challenge study protocols. *Journal of Food Protection, 73*(1), 140–202.

Park, I., Kim, J. U., Shahbaz, H. M., Jung, D., Jo, M., Lee, K. S., Lee, H., & Park, J. (2019). High hydrostatic pressure treatment for manufacturing of garlic powder with improved microbial safety and antioxidant activity. *International Journal of Food Science and Technology, 54*, 325.

Patras, A., Brunton, N., Da Pieve, S., Butler, F., & Downey, G. (2009). Effect of thermal and high pressure processing on antioxidant activity and instrumental colour of tomato and carrot purées. *Innovative Food Science and Emerging Technologies, 10*(1), 16–22.

Patterson, M. (2014). High-pressure treatment of foods. In *Encyclopedia of food microbiology* (Vol. 2, pp. 206–1212).

Podolak, R., Whitman, D., & Black, D. G. (2020). Factors affecting microbial inactivation during high pressure processing in juices and beverages: A review. *Journal of Food Protection, 83*(9), 1561–1575.

Pokhrel, P. R., Toniazzo, T., Boulet, C., Oner, M. E., Sablani, S., Tang, J., & Barbosa-Cánovas, G. V. (2019). Inactivation of *Listeria innocua* and *Escherichia coli* in carrot juice by combining high pressure processing, nisin, and mild thermal treatments. *Innovative Food Science and Emerging Technologies, 54*, 93–104.

Reddy, K. J., Jayathilakan, K., Chauhan, O. P., Pandey, M. C., & Radhakrishna, K. (2015). Effect of high-pressure processing on physico-chemical and microbial quality characteristics of chevon (*Capra aegagrus hircus*). *Food and Bioprocess Technology, 8*(12), 2347–2358.

Reineke, K., Mathys, A., Heinz, V., & Knorr, D. (2013). Mechanisms of endospore inactivation under high pressure. *Trends in Microbiology, 21*, 296–304.

Reyes, J. E., Tabilo-Munizaga, G., Pérez-Won, M., Maluenda, D., & Roco, T. (2015). Effect of high hydrostatic pressure (HHP) treatments on microbiological shelf-life of chilled Chilean jack mackerel (Trachurus murphyi). *Innovative Food Science and Emerging Technologies, 29*, 107–112.

Ribeiro, L. R., & Cristianini, M. (2020). Effect of high pressure processing combined with temperature on the inactivation and germination of Alicyclobacillus acidoterrestris spores: Influence of heat-shock on the counting of survivors. *Food Science and Technology, 118*, 108–781.

Rifna, E. J., Singh, S. K., Chakraborty, S., & Dwivedi, M. (2019). Effect of thermal and non-thermal techniques for microbial safety in food powder: Recent advances. *Food Research International, 126*, 108–654.

Sáiz, A. H., Mingo, S. T., Balda, F. P., & Samson, C. T. (2008). Advances in design for successful commercial high pressure food processing. *Food Australia, 60*(4), 154–156.

Sevenich, R., Rauh, C., & Knorr, D. (2020). Overview of research needs, future and potential applications of high-pressure processing. In *Reference in module science*. Elsevier.

Shahbaz, H. M., Akram, K., Ahn, J. J., & Kwon, J. H. (2016). Worldwide status of fresh fruits irradiation and concerns about quality, safety, and consumer acceptance. *Critical Reviews in Food Science and Nutrition, 56*, 1790–1807.

Shahbaz, H. M., Jeong, B., Kim, J. U., Ha, N., Lee, H., Ha, S. D., & Park, J. (2018). Application of high pressure processing for prevention of greenish-gray yolks and improving the microbiological safety and shelf life of hard-cooked peeled eggs. *Innovative Food Science and Emerging Technologies, 45*, 10.

Shahbaz, H. M., Kim, S., Kim, J. U., Park, D., Lee, M., Lee, D. U., & Park, J. (2018). Inactivation of *Salmonella Typhimurium* in fresh cherry tomatoes using combined treatment of UV-TiO_2 photocatalysis and high hydrostatic pressure. *Food Science and Biotechnology, 27*, 1531–1539.

Sheen, S., Cassidy, J., Scullen, B., Uknalis, J., & Sommers, C. (2015). Inactivation of *Salmonella* spp. in ground chicken using high pressure processing. *Food Control, 57*, 41–47.

Smelt, J. P. P. M. (1998). Recent advances in the microbiology of high pressure processing. *Trends in Food Science and Technology, 9*, 152–158.

Smelt, J. P., Hellemons, J. C., & Patterson, M. (2002). Effects of high pressure on vegetative microorganisms. In M. E. G. Hendrickx & D. W. Knorr (Eds.), *Ultra high pressure treatments of foods* (pp. 55–76). Kluwer Academic/Plenum Publishers.

Stewart, C. M., Jewett, F. F., Dunne, C. P., & Hoover, D. G. (1997). Effect of concurrent high hydrostatic pressure acidity and heat on the injury and destruction of *Listeria monocytogenes*. *Journal of Food Safety, 17*, 23–26.

Stratakos, A. C., Delgado-Pando, G., Linton, M., Patterson, M. F., & Koidis, A. (2015). Synergism between high-pressure processing and active packaging against *Listeria monocytogenes* in ready-to-eat chicken breast. *Innovative Food Science and Emerging Technologies, 27*, 41–47.

Stratakos, A. C., Inguglia, E. S., Linton, M., Murphy, L., Corcionivoschi, N., & Tiwari, B. K. (2019). Effect of high pressure processing on the safety, shelf life and quality of raw milk. *Innovative Food Science and Emerging Technologies, 52*, 325–333.

Tao, Y., Sun, D. W., Górecki, A., Błaszczak, W., Lamparski, G., Amarowicz, R., & Jeliński, T. (2012). Effects of high hydrostatic pressure processing on the physicochemical and sensorial properties of a red wine. *Innovative Food Science and Emerging Technologies, 16*, 409–416.

Tomasula, P. M., Renye, J. A., Van Hekken, D. L., Tunick, M. H., Kwoczak, R., Toht, M., Leggett, L. N., Luchansky, J. B., Porto-Fett, A. C. S., & Phillips, J. G. (2014). Effect of high-pressure processing on reduction of Listeria monocytogenes in packaged Queso Fresco. *Journal of Dairy Science, 97*(3), 1281–1295.

Torres, E. F., González-M, G., Klotz, B., & Rodrigo, D. (2016). Effects of high hydrostatic pressure and temperature increase on *Escherichia coli* spp. and pectin methyl esterase inactivation in orange juice. *Food Science and Technology International, 22*(2), 173–180.

Uckoo, R. M., Jayaprakasha, G. K., Somerville, J. A., Balasubramaniam, V. M., Pinarte, M., & Patil, B. S. (2013). High pressure processing controls microbial growth and minimally alters the levels of health promoting compounds in grapefruit (*Citrus paradisi Macfad*) juice. *Innovative Food Science and Emerging Technologies, 18*, 7–14.

Yue, J., Zhang, Y., Jin, Y., Deng, Y., & Zhao, Y. (2016). Impact of high hydrostatic pressure on non-volatile and volatile compounds of squid muscles. *Food Chemistry, 194*, 12–19.

Zhu, S., Naim, F., Marcotte, M., Ramaswamy, H., & Shao, Y. (2008). High pressure destruction kinetics of Clostridium sporogenes spores in ground beef at elevated temperatures. *International Journal of Food Microbiology, 126*, 86–92.

Chapter 3
Applications of HPP for Improving the Shelf Life and Quality of Food Products

Abstract HPP technology is mainly used for processing fruit juices and other beverages. Applications have been expanded to other products, including meat, ready-to-eat meals, vegetables and fruits, avocado, dairy, dips and condiments, wet salads and sandwich fillings, fermented products, and baby and infant foods.

Keywords HPP · Meat products · Fermented products · Dairy products · Baby foods

In recent years, applications of HPP technology for many food products have been reported. HPP technology has wide applications in production of meat products, dairy products, marine products, vegetable and fruit products, and beverage products.

3.1 Fruit and Vegetable Products

HPP has been used to maintain the prebiotic properties of cranberry juice. Prebiotic cranberry juice fortified with fructooligosaccharides (FOS) was processed using HPP in duplicate with a triplicate ultrasound cycle. In addition to HPP treatment at 450 MPa for 5 min, ultrasound treatment at 600 and 1200 watt/liter (W/L) for 5 min was followed by HPP treatment at the same pressure for 5 min. Analysis of the juice after treatments did not indicate any significant changes in color, pH, soluble solid content, organic acids, bioactive compounds, or antioxidant capacity (Ávila et al., 2016).

HPP was also used to extend the shelf life of diluted apple juice concentrate by reducing the water activity and increasing the pH, resulting in prevention of fungal spoilage (Buerman et al., 2020). HPP at 630 MPa for 6 min was used to inactivate enzymes for assessment of the physicochemical, microbiological, and antioxidant stability of a fruit and vegetable smoothie at a storage temperature of 25 °C. The

H. Muhammad Shahbaz et al., *Advances in Food Applications for High Pressure Processing Technology*, SpringerBriefs in Food, Health, and Nutrition,
https://doi.org/10.1007/978-3-031-33643-0_3

activity of the enzymes pectin methylesterase, peroxidase (POD), and polyphenol oxidase was decreased by HPP treatment. An HPP-treated fruit and vegetable smoothie was physiochemically and microbiologically stable and had an antioxidant activity similar to the fresh product (Fernandez et al., 2019).

Korla pear, known for its delicious taste, is commonly grown in China (Zhou et al., 2018). The properties of Korla pear juice were compared after ultrafiltration with HPP at 400 and 500 MPa for 2, 6, and 10 min and HTST (high-temperature short-time) at 110 °C for 8.6 s (Zhao et al., 2016). Ultrafiltration is the process of filtration in which small particles can easily pass through a membrane and permeate while large molecules are retained. It is possible, however, for some small particles to be retained in the retentates, resulting in a loss of nutrients and vitamins in the permeate. A reduction in microbial loads of ultra-filtered samples using HPP at 500 MPa or HTST was observed (<10 CFU/mL) (Zhao et al., 2016). HTST decreased the phenolic and ascorbic acid contents in juice samples by 5% and 13%, respectively. After ultrafiltration combined with HPP, the total phenolic and ascorbic acid content remained unchanged.

There is a lot of provitamin A in carrot juice. It has a short shelf life of 48 h. The quality attributes of thermally processed carrot juice (110 °C for 8.6 s) as well as non-thermally processed carrot juice (550 MPa for 2, 4, 6, 8, or 10 min) have been compared (Zhang et al., 2016). According to results from pressurized samples, the sugar, glucose, and fructose contained in juice remained similar to those in untreated juice. However, Maillard reactions reduced glucose and fructose contents by 16% and 26%, respectively, in thermally treated samples. The total phenolic contents were also maintained in HPP samples, whereas they were decreased significantly (12%) in thermally treated samples.

Functional foods show beneficial effects on health along with normal nutritional effects (Crowe & Francis, 2013). In addition to dairy products, there is an increasing demand for non-dairy functional foods, such as juice. Cranberry juice with fructooligosaccharides (FOS) (containing 3–7% glucose and 5% fructose) is an example of a functional food juice. The combination of HPP treatment at 450 MPa for 5 min with ultrasound treatment at 600 and 1200 W/L for 5 min was compared with HPP treatment at 450 MPa for 5 min (Gomes et al., 2017). Both treatments resulted in slight changes in the FOS profile. The color and pH of all samples were maintained, regardless of processing. HPP alone maintained the antioxidant capacity, but US + HPP treatment decreased it by 42%.

Orange juice with FOS (7 g/100 g) is an example of a functional product juice. HPP treatment of 450 MPa for 5 min was applied to this juice, and then the thermally treated samples were compared (Almeida et al., 2017). Degradation of FOS was greater in thermally treated samples. The lightness of HPP-treated juices was significantly enhanced (Almeida et al., 2017). Thus, FOS can be preserved better by high-pressure treatment than by thermal treatment (Lawrence & Jung, 2020).

Similarly, the impact of HPP on the carotenoid profile, color, and microbial and enzymatic stability of fresh carrot juice was studied. Higher pressures resulted in the least amount of carotenoid degradation. However, peroxidases were more resistant to high pressure than polyphenol oxidases, and HPP extended the shelf life of carrot juice up to 14 weeks (Stinco et al., 2019) (Fig. 3.1).

Fig. 3.1 HPP commercial natural beverages

There is increasing demand for tropical fruits due to rising incomes, population growth, urbanization, and increased health consciousness. Due to their high perishability, most tropical fruits have a limited post-harvest life. Mechanical, physiological, and pathological factors are the causes of post-harvest losses in all crops. Poor post-harvest management and lack of proper processing facilities also increase these problems. Tropical fruits are considered to be ideal subjects for HPP processing for preservation of natural attributes, as these fruits have specific flavors, colors, freshness, and nutritional contents (Lopes et al., 2010).

Popular purees marketed in large quantities by multi-national companies include carrot, pea, pumpkin, and butternut squash purees. Traditional thermal processes are used for sterilization. Contents of heat-sensitive nutrients, including vitamin C, are reduced during thermal sterilization because of excessive heat applied for a long time (Zhang et al., 2019). Color and texture changes also occur due to excessive heat (Patel et al., 2019). Natural color pigments are also influenced by heat, as they have complex chemical structures giving each product a unique color. However, HPP has preserved the nutrient contents and quality attributes of fruits and vegetables (Al-Ghamdi et al., 2020).

Kiwiberries are attractive to consumers because they have health-promoting potential and a rich aromatic flavor (Starowicz et al., 2022). Kiwiberries contain mostly esters, aldehydes, alcohols, and monoterpenes as volatile organic compounds. As a result of the preservation of bioactive food constituents in HHP, products with prolonged shelf life and high nutritional content can be produced (Jeż et al., 2020). Zhao et al. (2021) reported that a fresh kiwifruit sample and kiwifruit juice exposed to 500 MPa for 10 min showed similar volatile profiles. The fruity, ethereal aromas of ethyl acetate in kiwifruit pulp did not change after HPP processing (400–500–600 MPa/5–10–15 min), as reported by Chen et al. (2020) (Fig. 3.2).

Fig. 3.2 HPP commercial fruit and vegetable products

3.2 Meat Products

HPP can also be applied to meat products. The combined effect of HPP with cinnamon oil (7–17%) incorporated into active packaging (plasticizer polylactide (PLA) and polyethylene glycol (PEG) (80:20)) was studied with chicken meat to inactivate *Listeria monocytogenes* and *Salmonella typhimurium*. PLA/PEG film containing 17% cinnamon oil, followed by treatment at 300 MPa for 10 min, completely inhibited both pathogens for 3 weeks in refrigerated storage (Ahmed et al., 2017).

Zhang et al. (2018) studied the application of HPP to prevent rigor in pork. HPP at 400 MPa for 10 min inhibited the process of rigor with decreased calpain and calpastatin activities, resulting in an increase in total calpains in pressurized muscle. HPP-treated meat showed significant increases in tenderness, hardness, chewiness, and gumminess. Similarly, the efficacy of HPP to accelerate marinade absorption in pork chops was studied, and the effects on different sample characteristics were observed. HPP increased marinade absorption, ultimately enhancing the flavor acceptability of marinated pork chops. The marinade masked the discoloration effect of HPP and increased the tenderness and shelf life of the pork chops during storage (O'Neill et al., 2019).

A consumer's purchasing choice is influenced by the color of the meat (Banović et al., 2012). Following HPP at 600 MPa for 3 min and 450 MPa for 6 min, ground beef packaged in modified atmosphere packaging for 2 days at 4 °C was analyzed after refrigerated vacuum packaging for 21 days. According to Gupta et al. (2018), pressurized samples' lightness (L*) increased more than controls (29% at 450 MPa and 31% at 600 MPa). As compared to control samples (modified atmosphere package only), redness was reduced by only 6% in pressurized samples (600 MPa for 6 min) when stored compared to control samples (27% reduction). The extraction of amino acids from meat is affected by HPP. Pressure level, muscle type, and free amino acid content influence extraction (Tao et al., 2014). When HPP was done at 200, 300, and 500 MPa for 5 min, there was no direct release of amino acids from meat, but the release was modified during storage for 14 days (Guyon et al., 2018).

By using HPP, beef and beef-based meals could be improved in terms of quality attributes. Various HPP levels (200, 300, 400, and 500 MPa) were applied to heated beef muscles for 20 min before being cooked with gravy (Sorenson et al., 2011). The best organoleptic properties were exhibited by samples treated at 200 MPa with an 18% increase in juiciness compared with controls. Juiciness decreased as the pressure level increased. Flavor was enhanced by 15% and 7% in 200 MPa and 300 MPa treated samples, respectively, compared with controls.

Blue crab (*Callinectes sapidus*) is exported from Canada to northern Argentina. In order to extract crab meat, boiling is the most commonly used process, but thermal processes reduce the moisture content of the product by up to 10% and affect the overall quality (McDermott et al., 2018). Martnez et al. (2017) examined the water-holding capacity and crab meat yield by using HPP at 100, 300, and 600 MPa for 5 min. In comparison to controls, pressure levels significantly impacted meat extraction efficiency, with 30% and 50% increases at 300 and 600 MPa, respectively. As a result of HPP, proteins can hold more water (increase their moisture content), which is significant economically (Lawrence & Jung, 2020) (Fig. 3.3).

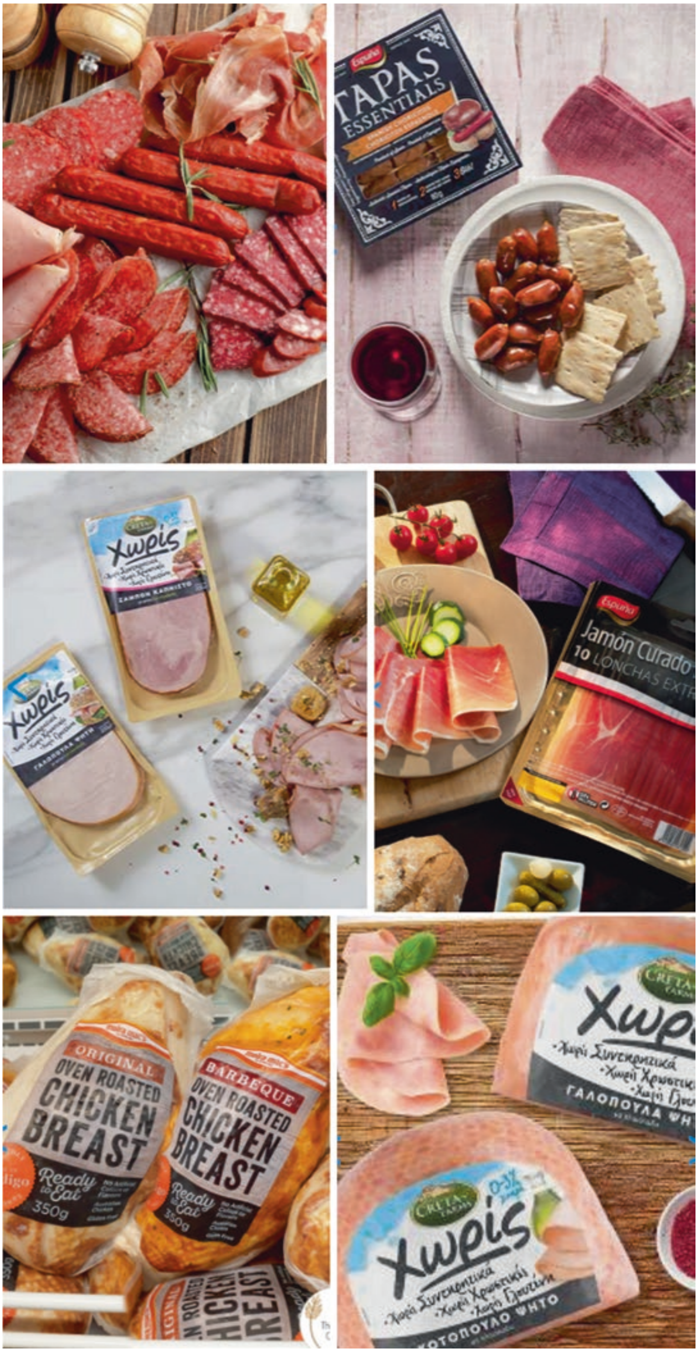


Fig. 3.3 HPP commercial meat products

3.3 Dairy Products

HPP is also known to improve the hydrolytic profile and specific activity of milk coagulants. Milk clotting enzymes were processed using HPP under optimum conditions (212 MPa/5 min/10 °C) and added to casein to evaluate the degree of hydrolysis. HPP-processed samples exhibited faster hydrolysis than non-processed samples (Júnior et al., 2019).

Various cheese products are available, depending on the consumer's convenience. Cut or sliced cheese products have a larger surface area, which increases their susceptibility to deterioration or spoilage. In order to avoid post-processing contamination during handling (for example, slicing, cutting, and shredding) and packaging, HPP can be considered an effective post-processing non-thermal decontamination option (Papadopoulou et al., 2022). A study showed the effectiveness of Na-alginate edible films in delivering lactic acid bacteria (LAB) to sliced cheese with and without high-pressure processing (HPP). HPP treatment reduced the indigenous microbiota population by approximately 1–1.5 log CFU/g in cheeses, and without HPP treatment, mostly mesophilic LAB and lactococci (>7.0 log CFU/g) were present. The HPP-LAB edible films (LEF) samples exhibited the best organoleptic characteristics, while the LEF samples without HPP had a slightly more acidic taste. The results of the study are promising since the edible films were successful in delivering functional LAB strains to the products (Papadopoulou et al., 2022).

HPP treatments at pressure levels of 200–500 MPa at 14 °C for 10 min were applied to semi-hard cheeses to control butyric acid fermentation caused by strains of *Clostridium tyrobutyricum* and the late blowing defect (butyric acid fermentation) in cheeses. Pressure at ≥300 MPa was effective in preventing butyric acid fermentation and the late-blowing defect in cheeses for 60 days. However, production of organic acids remained unaffected by HPP (Ávila et al., 2016). Similarly, Ribeiro et al. (2018) used HPP 600 MPa for 5 min at 25 °C to extend the shelf life of ultrafiltered cheese made from recombinant chymosin or bovine renin and stored at 7 °C for 56 days. HPP produced cheese with a firmer texture and did not cause a significant change in the cheese color. The proteolytic activity was significantly reduced to 42.8% and 52.5% in ultrafiltered cheese made from recombinant chymosin and bovine renin, respectively, compared with controls, thus extending the shelf life of the cheeses (Batty et al., 2019).

HPP can also change the quality attributes of cheese. In reduced-sodium, low-moisture, part-skim mozzarella cheese, calcium dissolves during aging, resulting in changes in its machinability and baking properties. The solubilization of calcium increased after treatment at 500 and 600 MPa for 3 min, and pH increased by 2% (Ozturk et al., 2018).

Trapped pockets of heated air and steam are known as blisters that may be preferentially scorched during baking. Cheese shreds are melted and fused during the baking of mozzarella cheese on a pizza base. The impedance of moisture loss occurs when the protein matrix collapses and fat globules melt to form free oil, which is released from the cheese. Moisture in cheese that is converted to steam has a force sufficient to lift the cheese and counteract the internal elastic and stretching resistances of the cheese. A balance between the force of the steam and the elastic and stretching resistances of the cheese causes gas pockets to grow bigger. Moisture evaporates more easily from the top when free oil flows from the top of each bubble. Scorching occurs at the top of bubbles, known as blisters (Ma et al., 2013). A 42% increase in blister quantity was observed in control samples after 20 days. However, blister quantities remained stable after treatment at 600 MPa, which was desirable for good-quality pizza (Ma et al., 2013) (Fig. 3.4).

3.4 Fermented Food Products

HPP improved the microbiological, antioxidant, and sensorial stability of fermented beverages during storage (Rios-Corripio et al., 2020). Similarly, HPP applied to avocado products (halves, chunks, puree, guacamole, salsas, and sauces) improved shelf life. Currently, there are several avocado-processing HPP units in Australia, Chile, Peru, Spain, New Zealand, and the United States (Purroy et al., 2011).

HPP maintains the natural green color of avocado products by inactivating the enzyme polyphenol oxidase (PPO), which is responsible for browning. Through HPP, the natural green color of avocado remains stable for a long time and the nutritional profile remains unchanged (Jacobo-Velazquez & Hernandez-Brenes, 2010) (Fig. 3.5).

3.5 Baby Food Products

HPP is also being used for processing of baby foods and infant milk formulas (Bravo et al., 2015). HPP and HPTS can be used in mitigation of contaminants in infant and baby foods. Production of food processing contaminants, including furan and mono-chlorpropandiol-esters, in baby foods, canned vegetables, and meat products was reduced using HPP (Sevenich et al., 2014, 2015; Barba et al., 2015; Palmers et al., 2015; Sevenich, 2016; Javed et al., 2021). Holding times, thermal loads, pressure treatments, positive-specific reaction volumes, and amounts of furan were decreased up to 81–96% in baby food puree using HPTS at 600 MPa at 115 °C for 28 min and 121 °C for 7 min, compared to retorting at 115 °C for 28 min (Sevenich et al., 2014; Barba et al., 2015). Spinach puree contained minute levels of furan (1–2 ng/g) when treated with HPTS at 117 °C and 600 MPa, compared to thermally treated puree (7–8 ng/g) at the same temperature (Palmers et al., 2015).

Sevenich et al. (2015) concluded that in a baby food puree, the maximum reduction of furan was between 71% and 98% using HPTS at 115 °C, 0.45 min, 600 MPa, compared with retorting at 115 °C for 28 min. The pilot scale and lab scale results were related. HPTS can be used for industrial food applications based on the scale-up procedure reported by Sevenich et al. (2015).

HPTS resulted in a decrease in furan concentrations during the processing of canned fish (71–97%) and baby food puree (86–97%) compared with conventional

Fig. 3.4 HPP commercial dairy products

Fig. 3.5 HPP commercial fermented products

thermal processing (Sevenich, 2016). However, commercial applications of HPTS are hindered due to operational challenges and industrial-level scale-up costs (Evelyn & Silva, 2019; Garcıa-Parra & Ramırez, 2019).

The furan concentration in all HPP-treated products reported by Patterson (2014) was below the limit of detection (1.0 ng/g), whereas in thermally processed vegetable-based infant formula, the level was 5.84 ng/g. Reductions in furan amounts in HPP-treated baby food samples were due to shorter processing times, which results in reduction in the heat intensity (Daryaei et al., 2012).

Different nutritious, healthy, commercially available HPP-treated baby foods from different companies include blends, boosters, and gluten-free products. For convenience and comfort, HPP products, including pureed fruits and vegetables, can be used as the main food components for babies for immediate consumption and have more market value than fresh products (Al-Ghamdi et al., 2020) (Fig. 3.6).

Fig. 3.6 HPP commercial baby foods

3.6 Human Donor Milk

When breastfeeding is unavailable for reasons such as shortage of the mother's milk or suffering from some disease, human donor milk is an alternative. Standard pasteurization, or holder pasteurization (HoP, heating milk at 62.5 °C for 30 min), is applied for human donor milk in a human milk bank to reduce microbial contamination (Picaud & Buffin, 2017). However, the important bioactive components of human milk, such as lactoferrin, lysozyme, lipase, immunoglobulins, lactoperoxidase, and xanthine oxidase, are reduced after HoP (Picaud & Buffin, 2017). HPP can be used as an alternative to HoP for the pasteurization of human donor milk. HPP has the potential to inactivate pathogens and preserve the quality of human milk (Zhang et al., 2022). In a study, the effect of HPP (350 MPa, 500 MPa, and 600 MPa for 8 min at <10 °C) was compared with HoP on the inactivation of cytomegalovirus and hepatitis A virus (HAV) inoculated human milk pools and culture media. Milk quality was assessed through the determination of macronutrient concentration and lactoferrin. Cytomegalovirus was reduced to more than 4.8-log PFU/mL and more than 0.9-log PFU/mL in culture medium and human milk by HPP and HoP, respectively. HAV was reduced by 3.4-log PFU/mL and 3.1-log PFU/mL in culture medium and human milk, respectively, by HoP. HAV was reduced by >5.7-log PFU/mL and >4-log PFU/mL in culture medium and human milk by HPP treatments of 500 MPa or 600 MPa, respectively. Both treatments did not affect the macronutrients (fat, total protein, and carbohydrate) and energy composition. HPP did not decrease the lactoferrin concentration, while it was reduced by 35% after HoP (Pitino et al., 2022). In another study, the effects of HPP (300, 400, 500, and 600 MPa for 5 min) compared to HoP treatments were analyzed on the macronutrients, acidity in Dornic, total coliforms, fatty acid composition, and the triacylglycerols profile of mature human milk. Both processes removed the microorganisms present, and the concentration of macronutrients and Dornic acidity did not show significant differences in methods (Manin et al., 2022).

Mank et al. (2021) studied the effect of different treatments, including HoP, HTST, thermoultrasonication, UV-C, and HPP, on the insulin concentration in human donor milk. Milk samples were collected from 28 non-diabetic mothers. The milk treated with HoP showed significantly lower insulin concentration than untreated milk. The other treatments, including thermoultrasonication, UV-C, and HPP, preserved insulin in human donor milk (Mank et al., 2021). The effect of different HPP treatments (400 MPa or 600 MPa for 3 min) was compared with that of HoP on the immune cells (leukocyte content) and immunoglobulins (IgM, IgA, and IgG). The original levels of immunoglobulins were maintained at 400 MPa for 3 min of breast milk, which is better than HoP (Contador et al., 2013). HPP achieved the microbiological safety of human donor milk. No bacteria were detected in human milk processed through HPP at 400 MPa for 5 min. The activities of a selection of bioactive components, including lysozyme, xanthine oxidase, lactoperoxidase, immunoglobulin A, lactoferrin, lipoprotein lipase, and bile salt-stimulated lipase, did not decrease significantly after HPP treatment. HPP showed better retention of milk nutrients and closer digestion behavior than HoP (Zhang et al., 2022).

Milk oligosaccharides (HMOs) or the formation of Maillard reaction products, which may be deleterious for preterm newborns, were assessed by HPP. HoP (62.5 °C for 30 min) or processed by HPP (350 MPa at 38 °C) was used to sterilize the human raw milk. The impact of HPP processing of human milk on 22 HMOs measured by liquid chromatography with fluorescence detection, and on furosine, lactuloselysine, carboxymethyl lysine, and carboxyethyl lysine measured by liquid chromatography with tandem mass spectrometric detection, was evaluated. Both treatments did not affect the concentration of HMOs, but HoP significantly increased the concentration of furosine, lactuloselysine, carboxymethyl lysine, and carboxyethyl lysine levels in milk. Maillard reaction product formation was restricted by HPP treatment and preserved HMOs. The study confirmed that HPP treatment of human milk provides safe milk with fewer detrimental effects on the biochemically active milk components than HoP (Marousez et al., 2022).

References

Ahmed, J., Mulla, M., & Arfat, Y. A. (2017). Application of high-pressure processing and polylactide/cinnamon oil packaging on chicken sample for inactivation and inhibition of *Listeria monocytogenes* and *Salmonella Typhimurium*, and post-processing film properties. *Food Control, 78*, 160–168.

Al-Ghamdia, S., Sonara, C. R., Patela, J., Albahra, Z., & Sablania, S. S. (2020). High pressure-assisted thermal sterilization of low-acid fruit and vegetable purees: Microbial safety, nutrient, quality, and packaging evaluation. *Food Control, 114*, 107–233.

Almeida, F. D. L., Gomes, W. F., Cavalcante, R. S., Tiwari, B. K., Cullen, P. J., Frias, J. M., & Rodrigues, S. (2017). Fructooligosaccharides integrity after atmospheric cold plasma and high-pressure processing of a functional or- ange juice. *Food Research International, 102*, 282–290.

Avila, M., Gomez-Torres, N., Delgado, D., Gaya, P., & Garde, S. (2016). Application of high pressure processing for controlling *Clostridium tyrobutyricum* and late blowing defect on semi-hard cheese. *Food Microbiology, 60*, 165–173.

Banović, M., Fontes, M. A., Barreira, M. M., & Grunert, K. G. (2012). Impact of product familiarity on beef quality perception. *Agribusiness, 28*(2), 157–172.

Barba, F. J., Terefe, N. S., Buckow, R., Knorr, D., & Orlien, V. (2015). New opportunities and perspectives of high pressure treatment to improve health and safety attributes of foods. A review. *Food Research International, 77*, 725–742.

Batty, D., Meunier-Goddik, L., & Waite-Cusic, J. G. (2019). Camembert-type cheese quality and safety implications in relation to the timing of high-pressure processing during aging. *Journal of Dairy Science, 102*, 8721–8733.

Bravo, F. I., Felipe, X., López-fandiño, R., & Molina, E. (2015). Skim milk protein distribution as a result of very high hydrostatic pressure. *Food Research International, 72*, 74–79.

Buerman, E. C., Worobo, R. W., & Padilla-Zakour, O. I. (2020). High pressure processing of spoilage fungi as affected by water activity in a diluted apple juice concentrate. *Food Control, 107*, 106–779.

Chen, Y., Feng, X., Ren, H., Yang, H., Liu, Y., Gao, Z., & Long, F. (2020). Changes in physicochemical properties and volatiles of kiwifruit pulp beverage treated with high hydrostatic pressure. *Foods, 9*, 485.

Contador, R., Delgado-Adámez, J., Delgado, F. J., Cava, R., & Ramírez, R. (2013). Effect of thermal pasteurisation or high pressure processing on immunoglobulin and leukocyte contents of human milk. *International Dairy Journal, 32*(1), 1–5.

Crowe, K. M., & Francis, C. (2013). Position of the academy of nutrition and dietetics: Functional foods. *Journal of the Academy of Nutrition and Dietetics, 113*(8), 1096–1103.

Daryaei, H., Balasubramaniam, V. M., & State, T. O. (2012). Microbial decontamination of food by high pressure processing. In *Microbial decontamination in the food industry: Novel methods and applications* (pp. 371–406). Woodhead Publishing Ltd.

Evelyn, & Silva, F. V. M. (2019). Heat assisted HPP for the inactivation of bacteria, moulds and yeasts spores in foods: Log reductions and mathematical models. *Trends in Food Science and Technology, 88*, 143–156.

Fernandez, M. V., Denoya, G. I., Jagus, R. J., Vaudagna, S. R., & Agüero, M. V. (2019). Microbiological, antioxidant and physicochemical stability of a fruit and vegetable smoothie treated by high pressure processing and stored at room temperature. *Food Science and Technology, 105*, 206–210.

Garcia-Parra, J., & Ramırez, R. (2019). New preservations technologies: Hydrostatic high pressure processing and high pressure thermal processing. In *Reference module in food science. Encyclopedia of food security and sustainability* (pp. 473–480). Elsevier.

Gomes, W. F., Tiwari, B. K., Rodriguez, Ó., de Brito, E. S., Fernandes, F. A. N., & Rodrigues, S. (2017). Effect of ultrasound followed by high pressure processing on prebiotic cranberry juice. *Food Chemistry, 218*, 261–268.

Gupta, J., Bower, C. G., Sullivan, G., & Cavender, G. (2018). Effect of differing ingredients and packaging technologies on the color of high-pressure processed ground beef. *Journal of Food Quality, 2018*, 20180605.

Guyon, C., Le Vessel, V., Meynier, A., & de Lamballerie, M. (2018). Modifications of protein-related compounds of beef minced minced meat treated by high pressure. *Meat Science, 142*, 32–37.

Jacobo-Velazquez, D. A., & Hernandez-Brenes, C. (2010). Biochemical changes during the storage of high hydrostatic pressure processed avocado paste. *Journal of Food Science, 75*(6), 264–270.

Javed, F., Shahbaz, H. M., Nawaz, A., Olaimat, A. N., Stratakos, A. C., Wahyono, A., Munir, S., Mueen-ud-din, G., Ali, Z., & Park, J. (2021). Formation of furan in baby food products: Identification and technical challenges. *Comprehensive Reviews in Food Science and Food Safety, 20*(3), 2699–2715.

Jez, M., Błaszczak, W., Penkacik, K., & Amarowicz, R. (2020). Quality parameters of juice obtained from hydroponically grown tomato processed with high hydrostatic pressure or heat pasteurization. *International Journal of Food Science, 2020*, 435–461.

Júnior, B. R. D. C. L., Tribst, A. A. L., Ribeiro, L. R., & Cristianini, M. (2019). High pressure processing impacts on the hydrolytic profile of milk coagulants. *Food Bioscience, 31*, 100–449.

Lawrence, I., & Jung, S. (2020). HPP as an innovation tool for healthy foods. In *Present and future of high pressure processing* (pp. 187–199). Elsevier.

Lopes, M. L. M., Mesquita, V. L. V., Chiaradia, A. C. N., Fernandes, A. A. R., & Fernandes, P. M. B. (2010). High hydrostatic pressure processing of tropical fruits: Importance for maintenance of the natural food properties. *Annals of the New York Academy of Sciences, 1189*, 6–15.

Ma, X., James, B., Balaban, M. O., Zhang, L., & Emanuelsson-Patterson, E. A. C. (2013). Quantifying blistering and browning properties of Mozzarella cheese. Part II: Cheese with different salt and moisture contents. *Food Research International, 54*, 917–921.

Manin, L. P., Rydlewski, A. A., Pizzo, J. S., da Cruz, V. H. M., da Silva Alves, E., Santos, P. D. S., Mikcha, J. M. G., Cristianini, M., Santos, O. O., & Visentainer, J. V. (2022). Effects of pasteurization and high-pressure processing on the fatty acids, triacylglycerol profile, Dornic acidity, and macronutrients in mature human milk. *Journal of Food Composition and Analysis, 115*, 104–918.

Mank, E., Kontopodi, E., Heijboer, A. C., van Elburg, R. M., Hettinga, K., van Goudoever, J. B., & van Toledo, L. (2021). Thermoultrasonication, ultraviolet-C irradiation, and high-pressure processing: Novel techniques to preserve insulin in donor human milk. *Clinical Nutrition, 40*(11), 5655–5658.

Marousez, L., Sprenger, N., De Lamballerie, M., Jaramillo-Ortiz, S., Tran, L., Micours, E., Gottrand, F., Howsam, M., Tessier, F. J., Ley, D., & Lesage, J. (2022). High hydrostatic pressure processing of human milk preserves milk oligosaccharides and avoids formation of Maillard reaction products. *Clinical Nutrition, 41*(1), 1–8.

Martínez, M. A., Velazquez, G., Cando, D., Núñez-Flores, R., Borderías, A. J., & Moreno, H. M. (2017). Effects of high pressure processing on protein fractions of blue crab (Callinectes sapidus) meat. *Innovative Food Science and Emerging Technologies, 41*, 323–329.

McDermott, A., Whyte, P., Brunton, N., Lyng, J., & Bolton, D. J. (2018). Increasing the yield of Irish brown crab (*Cancer pagurus*) during processing without adversely affecting shelf-life. *Foods, 7*(7), 99.

O'Neill, C. M., Cruz-Romero, M. C., Duffy, G., & Kerry, J. P. (2019). Improving marinade absorption and shelf life of vacuum packed marinated pork chops through the application of high pressure processing as a hurdle. *Food Packaging and Shelf Life, 21*, 100–350.

Ozturk, M., Govindasamy-Lucey, S., Jaeggi, J. J., Johnson, M. E., & Lucey, J. A. (2018). Investigating the properties of high-pressure-treated, reduced-sodium, low-moisture, part-skim Mozzarella cheese during refrigerated storage. *Journal of Dairy Science, 101*(8), 6853–6865.

Palmers, S., Grauwet, T., Celus, M., Kebede, B. T., Hendrickx, M. E., & Van Loey, A. (2015). Food Science and Technology Furan formation as a function of pressure, temperature and time conditions in spinach puree. *Food Science and Technology, 64*, 565–570.

Papadopoulou, O. S., Argyri, A. A., Bikouli, V. C., Lambrinea, E., & Chorianopoulos, N. (2022). Evaluating the quality of cheese slices packaged with Na-alginate edible films supplemented with functional lactic acid bacteria cultures after high-pressure processing. *Foods, 11*(18), 2855.

Patel, J., Al-Ghamdi, S., Zhang, H., Queiroz, R., Tang, J., & Yang, T. (2019). Determining shelf life of ready-to-eat macaroni and cheese in oxygen scavenger and high barrier packaging sterilized via microwave-assisted thermal sterilization. *Food and Bioprocess Technology, 12*(9), 1516–1526.

Patterson, M. (2014). High-pressure treatment of foods. In *Encyclopedia of food microbiology* (Vol. 2, pp. 206–1212).

Picaud, J. C., & Buffin, R. (2017). Human milk – Treatment and quality of banked human milk. *Clinics in Perinatology, 44*(1), 95–119.

Pitino, M. A., Unger, S., Gill, A., McGeer, A. J., Doyen, A., Pouliot, Y., Bazinet, R. P., Kothari, A., Mazzulli, T., Stone, D., & O'Connor, D. L. (2022). High pressure processing inactivates human cytomegalovirus and hepatitis A virus while preserving macronutrients and native lactoferrin in human milk. *Innovative Food Science and Emerging Technologies, 75*, 102–891.

Purroy, B. F., Tonello, C., Peregrina, R., & de Celis, C. (2011). *Industrial high pressure processing of avocado products: Emerging trends and implementation in new markets*. In Proceedings VII World Avocado Congress, pp. 1–5.

Ribeiro, L. R., de Castro Leite Júnior, B. R., & Cristianini, M. (2018). Effect of high-pressure processing on the char- acteristics of cheese made from ultrafiltered milk: Influence of the kind of rennet. *Innovative Food Science and Emerging Technologies, 50*, 57–65.

Rios-Corripio, G., Welti-Chanes, J., Rodríguez-Martínez, V., & Guerrero-Beltrán, J. Á. (2020). Influence of high hydrostatic pressure processing on physicochemical characteristics of a fermented pomegranate (*Punica granatum* L.) beverage. *Innovative Food Science and Emerging Technologies, 59*, 102–249.

Sevenich, R. (2016). High-pressure thermal sterilization. In *Reference module in food science* (pp. 1–10). Elsevier.

Sevenich, R., Kleinstueck, E., Crews, C., Anderson, W., Pye, C., & Riddellova, K. (2014). High-pressure thermal sterilization: Food safety and food quality of baby food puree. *Journal of Food Science, 79*, 230–237.

Sevenich, R., Bark, F., Kleinstueck, E., Crews, C., Pye, C., Hradecky, J., & Reineke, K. (2015). The impact of high pressure thermal sterilization on the microbiological stability and formation of food processing contaminants in selected fish systems and baby food puree at pilot scale. *Food Control, 50*, 539–547.

Sorenson, D., Henchion, M., Marcos, B., Ward, P., Mullen, A. M., & Allen, P. (2011). Consumer acceptance of high pressure processed beef-based chilled ready meals: The mediating role of food-related lifestyle factors. *Meat Science, 87*(1), 81–87.

Starowicz, M., Błaszczak, W., Ciska, E., & Latocha, P. (2022). Characterization of volatile organic compounds in kiwiberries (*Actinidia arguta*) exposed to high hydrostatic pressure processing by HS-SPME/GC-MS. *Molecules, 27*, 5914.

Stinco, C. M., Szczepańska, J., Marszałek, K., Pinto, C. A., Inácio, R. S., Mapelli-Brahm, P., Barba, F. J., Lorenzo, J. M., Saraiva, J. A., & Meléndez-Martínez, A. J. (2019). Effect of high-pressure processing on carotenoids profile, colour, microbial and enzymatic stability of cloudy carrot juice. *Food Chemistry, 299*, 125–112.

Tao, Y., Sun, D. W., Hogan, E., & Kelly, A. L. (2014). High-pressure processing of foods: An overview. In *Emerging technologies for food processing* (pp. 3–24). Elsevier.

Zhang, Y., Liu, X. C., Wang, Y., Zhao, F., Sun, Z., & Liao, X. (2016). Quality comparison of carrot juices processed by high-pressure processing and high-temperature short-time processing. *Innovative Food Science and Emerging Technologies, 33*, 135–144.

Zhang, H., Pan, J., & Wu, Z. (2018). Investigation of the effects of high pressure processing on the process of rigor in pork. *Meat Science, 145*, 455–460.

Zhang, H., Patel, J., Bhunia, K., Al-Ghamdi, S., Sonar, C., & Ross, C. (2019). Color, vitamin C, β-carotene and sensory quality retention in microwave-assisted thermally sterilized sweet potato puree: Effects of polymeric package gas barrier during storage. *Food Packaging and Shelf Life, 21*, 100–324.

Zhang, J., Lee, N. A., Duley, J. A., Cowley, D. M., Shaw, P. N., & Bansal, N. (2022). Comparing the effects of hydrostatic high-pressure processing vs holder pasteurisation on the microbial, biochemical and digestion properties of donor human milk. *Food Chemistry, 373*, 131–545.

Zhao, L., Wang, Y., Hu, X., Sun, Z., & Liao, X. (2016). Korla pear juice treated by ultrafiltration followed by high pressure processing or high temperature short time. *Food Science and Technology, 65*, 283–289.

Zhao, Y., Wang, P., Zhan, P., Tian, H., Lu, C., & Tian, P. (2021). Aroma characteristics of cloudy kiwifruit juices treated with high hydrostatic pressure and representative thermal processes. *Food Research International, 139*, 109–841.

Zhou, L., Li, C., Niu, J., Pei, M., Cao, F., & Quan, S. (2018). Identification of miRNAs involved in calyx persistence in Korla fragrant pear (*Pyrus sinkiangensis Yu*) by high-throughput sequencing. *Scientia Horticulturae, 240*, 344–353.

Chapter 4
Applications of HPP for Improved Functionality of Food Products

Abstract Recent applications of HPP are reviewed for allergenicity reduction in foods, preservation of essential fatty acids, and reduction of salt content. HPP has shown good potential to manipulate functionality, retain essential fatty acids, and reduce allergenicity in foods.

Keywords HPP · Allergenicity reduction · Retention of lipids · Salt reduction

4.1 Effect of HPP on Food Allergenicity

Food allergies in developed countries and some developing countries are increasing (Wang & Sampson, 2011). Allergenic proteins mostly originate from a plant family with almost the same allergic signs and symptoms that may render them allergenic (Radauer & Breiteneder, 2006). Bovine milk, eggs, apples, peanuts, shellfish, soy, and wheat are the most widely reported food allergy sources (Cianferoni & Spergel, 2009). Bovine milk proteins (whey proteins, including "-lactoglobulin" and "-lact-albumin"), egg whites (ovalbumin), birch pollens (BetV1), carrots (DauV1), celery (ApiG1), peanuts (AraH1), and others contain allergenic proteins (epitopes) (Barba et al., 2015).

Food allergens that can cause serious allergic reactions are members of the prolamin family, so-called lipid transfer proteins (LTPs). These allergens are heat stable. Among the apple and peanut allergens, Mal d 3 and Ara h 2 are reported to be the most dangerous to sensitized people in Spain and Italy, as well as the United States (Cianferoni & Spergel, 2009).

Food structure and functional changes during processing and storage occur that can reduce or increase the presence of food allergens (Maleki et al., 2003). Packaging and storage can decrease or increase food allergic activities. Among the apple and peanut allergens, Mal d 3 and Ara h 2 are reported to be the most dangerous to sensitized people in Spain and Italy, as well as the United States (Besler et al., 2001). HPP treatment can damage food structure or change the protein structure present in

H. Muhammad Shahbaz et al., *Advances in Food Applications for High Pressure Processing Technology*, SpringerBriefs in Food, Health, and Nutrition,
https://doi.org/10.1007/978-3-031-33643-0_4

Table 4.1 Effect of HPP on allergens in different foods

Food allergen source	HPP treatment condition	Observations	References
Apple	150–700 MPa, 20 °C, 10 min	Minor changes in structure and allergenicity of Mal d 1b occurred.	Johnson et al. (2010)
	700 MPa, 20 °C, 60 min	Significant reduction of Mal d amount.	Husband et al. (2011)
Celery	700 MPa, 118 °C, 10 min	Api g 1 allergenicity reduced.	Husband et al. (2011)
Milk	500 MPa, 40 °C, 30 min	Marked decrease in tryptic and chymotryptic hydrolysis of β-lg and α-lactalbumin (α-la).	Beran et al. (2009)
Sesame	100–500 MPa, room temperature, 10 min	Reduced antigenicity of sesame proteins at pH 7 and 10.	Achouri and Boye (2013)
Soy protein isolate	300 MPa, room temperature, 15 min	Soy protein allergenicity was reduced by 48.6%.	Li et al. (2012)
Ready-to-feed infant formula	600 MPa, 40.4 °C, 5 min	Reduced amounts of β-Lg made possible production of hypoallergenic infant formula.	Wazed and Farid (2019)

food and increase chances of food allergy. HPP has shown the potential to reduce the allergy risks of some foods without eliminating the allergenic proteins themselves, but rather through extraction or release of membrane-bound allergens into the environment, where they can be removed or attacked by hydrolytic enzymes (Kato et al., 2000). Some enzymes can be accelerated by HPP (Knorr et al., 2006). It has been successfully used to reduce allergenic potentials in dairy products (Zeece et al., 2008) and beef extracts (Han, 2006).

As shown in Table 4.1, HPP reduced the allergenic potential of a number of products, primarily nuts, fruits, vegetables, dairy products, and seafood. Various methods are used to establish changes in allergenic potential, which may explain the high degree of variability between study results.

HPP can be used to reduce the amount of allergenic beta-lactoglobulin in ready-to-feed infant formula. Reduction in the amount of β-Lg in infant formula with added α-Lac was reported with a synergistic effect of HPP and heat at 600 MPa for 5 min applied at 40.4 °C (Wazed & Farid, 2019).

4.2 HPP Preservation of Lipids

There is growing interest in HPP to enhance the range of safe, stable, and healthy food products. HPP also has applications to modify compounds and improve functionality. Table 4.2 lists studies of production of healthy food products using HPP.

Eicosapentaenoic acid (EPA) and decosahexaenoic acid (DHA) are the most important healthy polyunsaturated fatty acids (PUFAs) present in seafood and are recommended for inclusion in a healthy diet. Fresh fish and shellfish have a short

Table 4.2 Effect of HPP on lipid compositions in different foods

Lipids	Treatment	Observations	References
Salmon	200 MPa, 15 °C, 30 s	Free fatty acid formation increased	Ortea et al. (2010)
Turbot	200 MPa, 4 °C, 30 min	No significant change in free fatty acid production	Chevalier et al. (2001)
Milk	200 MPa, -4 °C, 30 min	Short chain fatty acid amounts increased	Kim et al. (2008)
Beef *pectoralis profundus*	400 MPa and 600 MPa, 35–45 °C, 20 min	n−6/n−3 fatty acid ratio was significantly increased	McArdle et al. (2011)
Pork *longissimus*	350 MPa and 500 MPa, 20 °C, 20 min	Significant increase in amounts of free fatty acids	He et al. (2012)
Pork *longissimus* ± EDTA	500 MPa, 20 °C, 20 min	Significant increase in amounts of free fatty acids	Haung et al. (2012)

shelf life (less than 7 days) due to degradation reactions. Fish are less nutritionally dense than other animals due to PUFAs produced by lipase enzymes, which are reactive and easily oxidized. As a result, new preservation methods have been developed and are gaining interest among consumers and industry.

Despite no changes in the fatty acid profile, there was an increase in lipid oxidation after 150 and 300 MPa pressure treatments at 20 °C for 15 min on Atlantic salmon dark muscle (Yagiz et al., 2009) and turbot muscle (100, 140, 180, and 200 MPa, 4 °C, 15 min, and 30 min) (Chevalier et al., 2001). As a result of heme proteins acting as catalysts, HPP induces lipid oxidation, which results in the destruction of lipid membranes (Bolumar et al., 2014). Compared to untreated oysters, HPP-treated oysters showed enhanced availability of n-3 PUFAs, which are beneficial to humans (Cruz-Romero et al., 2008). Salmon (135, 170, and 200 MPa, 15 °C, and 30 s) and carp (100, 140, 180, and 200 MPa, 4 °C, 15 min, and 20 min) treated with HPP formed more free fatty acids (FFAs) after treatment and storage (Ortea et al., 2010).

In milk, there are important nutraceuticals, like essential FFAs. However, due to lipolysis, nutritional degradation occurs in milk. Studies have investigated the effects of HPP on FFA in commercial milk. Raw milk was pasteurized at 200 MPa at −4 °C for 10 or 20 min. The short-chain FFA content did not change until the treatment time was increased to 30 min, when the FFA content slightly increased (Kim et al., 2008). In another study, a combined effect of milk and orange juice was investigated using HPP. As a result of processing at 100 and 200 MPa, monounsaturated (MUFA) and saturated (SFA) fat content increased, whereas it decreased after processing at 300 and 400 MPa. There was no change in PUFA content as a result of the pressure (Barba et al., 2012).

Myristic, palmitic, and trans-vaccenic fatty acids were significantly increased in beef treated with HPP (200 or 800 MPa/60 °C/20 min) (Tume et al., 2010). Beef treated with HPP showed an enhancement of the n−6/n−3 ratio during 30 days of storage (McArdle et al., 2011). According to He et al. (2012), HPP significantly increased FFA and phospholipid amounts when pork was treated at 200 MPa at

20 °C for 20 min after treatment with HPP. The FFA composition was significantly affected after 30 days at 4 °C. Polyunsaturated fatty acids such as linoleic acid (18:2), linolenic acid (18:3), eicosatrienic acid (20:3), and arachidonic acid (20:4) increased, whereas saturated fatty acids and monounsaturated fatty acids decreased. Huang et al. (2012) examined the effects of antioxidants on the fatty acid composition of pressurized pork and found that EDTA didn't affect the lipolysis of phospholipids. The fatty acid composition of FFA and phospholipids in meat treated with EDTA changed in a fashion similar to the change in HPP-treated meat without EDTA, indicating that EDTA has no effect on enzymatic hydrolysis (Huang et al., 2012).

4.3 Effect of HPP on Reduction of Salt Content

Due to the textural and sensory properties imparted to products, salts and additives are used in the manufacturing of processed food products. However, salts are an unhealthy additive (FSA, 2004; WHO, 2006). Several diseases are caused by high-salt diets, including hypertension, cardiovascular disease, and dementia (Faraco et al., 2018). Organoleptic and microbial safety properties are promoted by salt, so production of products with less sodium is difficult (Inguglia et al., 2017).

To reduce the salt content in processed meats, cheeses, and bread, several strategies are being considered. The development of meat products without or with reduced levels of preservatives, non-meat ingredients, salt, and phosphates while maintaining high product quality and safety involves the use of HPP at 150 or 300 MPa (Troy et al., 2001). Without changing food quality, HPP decreases the need for fat, salt, and phosphate in meat products. Processed meat and ready-to-eat meal manufacturers monitor developments in HPP treatment (Barba et al., 2015). Table 4.3 shows the effect of HPP on the production of healthy food products.

The high salt content of processed meat products plays a significant role in consumer perception. Consumers generally consider ready-to-eat meat products unhealthy because they are high in salt and fat. The effect of HPP treatments on the taste of prepared dried meat products has been investigated in a study in which there was no increase in salt content after pressurization nor could salt concentration be attributed to increased saltiness perception (Clariana et al., 2011). As a result of HPP's alteration of sodium-protein interactions, Na + ions were released, making them more accessible to taste buds (Clariana et al., 2011). In addition to reducing salt content, HPP enhances the perception of saltiness.

Strategies for substitution for sodium in dry-cured restructured hams have been investigated. The use of different combinations of potassium lactate, transglutaminase, drying levels, and HPP treatments (600 MPa/10 °C/6 min) resulted in hams that were 50% less salty than standard Serrano hams. Ferrini et al. (2012) and Fulladosa et al. (2012) found that HPP significantly altered the sensory texture parameters of hardness and adhesiveness. In addition, HPP treatment of cheddar cheese (405 MPa/9 °C/3 min) at various salt levels (normal 5.3% level to no salt 0.2%) with

Table 4.3 HPP and reduction of salt content in processed foods

Saltiness	Treatment	Observations	References
Dry cured minced pork	500 MPa and 600 MPa, 13 °C, 7 min	Production of dry-cured meat with reduced salt without affecting appearance.	Ferrini et al. (2012)
Dry cured ham	600 MPa, 10 °C, 6 min	K-lactate (salt) reduced.	Fulladosa et al. (2012)
Beef sausage	0–400 MPa, 10 °C, 2 min	Greater acceptability of HPP-treated sausages of lower salt content.	Sikes et al. (2009)
Pork sausage	800 MPa, 5–40 °C, 5 min	Carrot fiber or potato starch with reduced salt content without phosphates; improved texture and water binding of carrot fiber and potato starch.	Grossi et al. (2012)
Pork sausage	200 MPa, 10 min	A low salt sausage with good sensory and technological quality was produced.	Hayes and Allen (2011)
Cheddar cheese	450 MPa, 9 °C, 3 min	Cheeses had similar sensory flavor profiles during ripening.	Ozturk et al. (2013)
Beef gels	100–200 MPa, 20 °C, 10 min	Low salt was reported in beef.	Maksimenko et al. (2019)
Pork sausage emulsions	100–400 MPa	1% salt was reported.	Yang et al. (2015)
Frankfurters	100–400 MPa	2.5% salt was observed.	Yang et al. (2015)

no change in rheological or textural properties after 1 month was achieved (Ozturk et al., 2013). The acid, salt, and bitterness intensity values of HPP-treated and untreated cheeses were the same at the same salt concentration. Reducing the actual salt content had the effect of increasing the flavor attributes of acid and bitterness, in addition to markedly reducing saltiness.

It was assessed that salt level and HPP had an effect on cooking loss, emulsion stability, color, texture, and sensory properties of frankfurters by Crehan et al. (2000). A HPP treatment was applied to raw minced beef for 5 min at 20 °C before it was mixed with other ingredients to make frankfurters. For food preservation purposes, salt levels were reduced to 1.5% (normally 3%). The most effective treatment condition was HPP at 150 MPa. Hayes and Allen (2011) also examined the effect of HPP pretreatment of raw minced pork and fat (100–300 MPa, 10 min) following the preparation of reduced salt (1.4%) pork breakfast sausages. In sausages produced under 200 MPa, cook-loss, color, water-holding capacity, texture, and sensory attributes were similar to normal levels of salt (2.5%) in non-treated sausages.

The effect of HPP and salt reduction (NaCl concentrations of 0–2%) on beef sausages was analyzed (Sikes et al., 2009). Low-salt sausages treated with HPP (0–400 MPa, 10 °C, 2 min) reduced cooking loss and improved texture. Sensory panels found HPP-treated sausages to be more acceptable both in appearance and texture. As a result of HPP, the fibrous proteins myosin and actin were more readily soluble, which enhanced the binding of meat particles (Sikes et al., 2009).

As compared to sausages with the normal percentage of salt added to meat products for preservation purposes (1.5–3%), pressurized (400–800 MPa, 5 °C and 40 °C, 5 min) pork sausages (Grossi et al., 2012) have reduced salt content (1.2% and no phosphates). When starch or fiber is used, the textural properties are better than when salt is used. As a result of the pressure treatment, the product was also able to bind more water. Salt and phosphates affect the solubility of myofibrillar meat proteins (myosin and actin), thereby affecting their ability to form a protein matrix. A functional ingredient is needed to reduce the salt content of meat so as to improve its acceptability. In myofibrillar proteins, HPP increases their solubility and improves their functional properties. The main myofibrillar proteins lose their solubility as a result of protein denaturation and aggregation induced by HPP. A combination of HPP and natural starch or fiber at 400, 600, or 800 MPa clearly increased the protein binding and hardness of the product. Further, mild heating during pressurization improved meat emulsion characteristics in conjunction with pressure (Sikes et al., 2009).

Hong et al. (2008) examined the combination of salt level and gluconolactone and carrageenan on the binding properties of restructured pork after HPP treatment. The formation of gel structures was limited by examining cold-set meat binding at pressures below those required for protein solubility and denaturation. At a low pressure of 200 MPa, binding properties and meat restructuring were achieved by reducing NaCl content and adding glucono-δ-lactone and κ-carrageenan (Hong et al., 2008). Microbial transglutaminase, egg proteins, and HPP (500–900 MPa, 40 °C, 30 min) were used to produce chicken batter gels with a better texture than chicken batter cooked without enzymes (Trespalacios & Pla, 2007).

High pressure affects myofibrillar proteins in meat through solubilization and aggregation in the same way as salt. Using HPP at pressures of 300, 450, and 600 MPa for 5 min, *E. faecium* was reduced to 1 log, 4 log, and 6 log in meat marinated in high citric acid (2%) and high salt (2%) concentrations. Pressure, acid and salt concentrations, or storage time did not significantly affect redness or pH. Without affecting the quality attributes of meat and microbial safety, HPP can reduce the salt content in meat. The physicochemical properties of beef gels were examined using HPP treatments at 100–200 MPa for 10 min at 20 °C combined with sodium chloride and sodium phosphate. Water content, cooking loss, color, texture, and protein composition were examined using SDS-PAGE. A synergistic effect in increased water content and decreased cooking loss was observed, compared with unpressurized beef gels treated at a pressure of 150 MPa. After HPP treatment at 100–200 MPa, the L*, a*, and b* color values of beef gels were slightly reduced. The staining intensity of the α-actinin protein band was reduced in pressurized samples in SDS-PAGE analysis. After HPP treatment, the cohesiveness, adhesiveness, gel strength, and modulus of elasticity were increased. Manufacture of low-salt and/or low-phosphate meat products for a healthy diet is possible when a pressure treatment of 150–200 MPa was applied before heat treatment (Maksimenko et al., 2019). Decreased cooking loss values and increased emulsion stability in pork sausage emulsions (1% salt) and frankfurters (2.5% salt) were observed after treatment with pressures between 100 and 400 MPa (Yang et al., 2015).

4.4 HPP Application for Sea Foods

HPP has wide applications in the food industry, including seafood. In shucking and meat extraction, meat is separated from shells without using heat. Increased productivity, maximized labor usage, and enhanced operational efficiency are benefits of HPP. Post-package processing decreases the risk of recontamination in HPP products. Through HPP, 125% more yield is produced in the shucking of oysters, lobster, crab, mussels, clams, and scallops. Muscle proteins that are responsible for shell closing are denatured during HPP, and shells easily open to expose meat for easy extraction. Yield is increased significantly. Muscles contract and detach, allowing 100% harvesting of meat from crustaceans, including lobster and king crab. This procedure helps operators recover meat from small body parts. HPP-processed meat retains quality and natural flavors and has a longer shelf life than meat not treated with HPP. Shelf-life extension, freshness of products, sensory and functional qualities, and improved product safety are HPP-induced seafood qualities in final packaging (Hiperbaric.com) (Fig. 4.1).

Working conditions for HPP seafood meat extraction include 3000–4200 bar pressure levels (300–400 MPa) and holding times of 45–90 s. High pressure infuses salt into lobster meat when shucking with seawater (4–25 °C) to improve the flavor. Live lobsters or recently sacrificed lobsters are used for HPP shucking. Otherwise, lack of respiration hardens the muscle and complicates HPP shucking (Fig. 4.2).

HPP is also used in the processing and preservation of seafood. Kombu seaweed was placed in long-term storage after use of different preservation techniques and effects on volatile compounds and odor characteristics were examined. Salted and unsalted kombu samples were preserved using HPP, refrigeration at 5 °C, and freezing at −24 °C prior to storage for 180 days. HPP-treated samples showed the highest scores for odor acceptance. However, HPP reduced the formation of some groups of volatile compounds compared with refrigeration- and freezing-treated samples (López-Pérez et al., 2020). The effectiveness of HPP on the gelling capacity of heat-induced blue crab meat was also evaluated. Low-pressure levels improved the heat-induced gelling capacity of crab meat, thus improving the texture through protein structure modification (Martínez et al., 2017).

Fig. 4.1 HPP applications to seafood products for food safety

Fig. 4.2 HPP shucking of lobster

A study was conducted to determine the effects of HPP (200, 400, and 600 MPa) and storage temperature (4 °C and −20 °C) on red claw crayfish fatty acids and flavor compounds. HPP-treated crayfish had higher free amino acid, calcium, and chlorine contents compared to untreated crayfish ($p < 0.05$) (Liu et al., 2022).

References

Achouri, A., & Boye, J. I. (2013). Thermal processing, salt and high pressure treatment effects on molecular structure and antigenicity of sesame protein isolate. *Food Research International, 53*(1), 240–251.

Barba, F. J., Esteve, M. J., & Frigola, A. (2012). Impact of high-pressure processing on vitamin e (α-, δ, and γ-tocopherol), vitamin D (cholecalciferol and ergocalciferol), and fatty acid profiles in liquid foods. *Journal of Agricultural and Food Chemistry, 60*(14), 3763–3768.

Barba, F. J., Terefe, N. S., Buckow, R., Knorr, D., & Orlien, V. (2015). New opportunities and perspectives of high pressure treatment to improve health and safety attributes of foods. A review. *Food Research International, 77*, 725–742.

Beran, M., Klubal, R., Molik, P., Strohalm, J., Urban, M., Klaudyova, A. A., et al. (2009). Influence of high-hydrostatic pressure on tryptic and chymotryptic hydrolysis of milk proteins. *High Pressure Research, 29*(1), 23–27.

Besler, M., Steinhart, H., & Paschke, A. (2001). Stability of food allergens and allergenicity of processed foods. *Journal of Chromatography B: Biomedical Sciences and Applications, 756*(1–2), 207–228.

Bolumar, T., Georget, E., & Mathys, A. (2014). High pressure processing (HPP) of foods and its combination with electron beam processing. In S. Pillai & S. Shayanfar (Eds.), *Electron beam pasteurization and complementary food processing technologies* (pp. 127–155). Woodhead Publishing.

Chevalier, D., Le Bail, A., & Ghoul, M. (2001). Effects of high pressure treatment (100–200 MPa) at low temperature on turbot (*Scophthalmus maximus*) muscle. *Food Research International, 34*(5), 425–429.

Cianferoni, A., & Spergel, J. M. (2009). Food allergy: Review, classification and diagnosis. *Allergology International, 58*(4), 457–466.

Clariana, M., Guerrero, L., Sarraga, C., Diaz, I., Valero, A., & Garcia-Regueiro, J. A. (2011). Influence ofhigh pressure application on the nutritional, sensory andmicrobiological characteristics of sliced skin vacuumpacked dry-cured ham. Effects along the storage period. *Innovative Food Science & Emerging Technologies, 12*(4), 456–465.

Crehan, C. M., Troy, D. J., & Buckley, D. J. (2000). Effects of salt level and high hydrostatic pressure processing on frankfurters formulated with 1.5 and 2.5% salt. *Meat Science, 55*(1), 123–130.

Cruz-Romero, M. C., Kerry, J. P., & Kelly, A. L. (2008). Fatty acids, volatile compounds and colour changes in high-pressure-treated oysters (*Crassostrea gigas*). *Innovative Food Science & Emerging Technologies, 9*(1), 54–61.

Faraco, G., Brea, D., Garcia-Bonilla, L., Wang, G., Racchumi, G., & Chang, H. (2018). Dietary salt promotes neurovascular and cognitive dysfunction through a gut-initiated TH17 response. *Nature Neuroscience, 21*, 240–249.

Ferrini, G., Comaposada, J., Arnau, J., & Gou, P. (2012). Colour modification in a curedmeat model dried by Quick-Dry-Slice process® and high pressure processed as a function of NaCl, KCl, K-lactate and water contents. *Innovative Food Science & Emerging Technologies, 13*, 69–74.

FSA. (2004). *Nutrition statement*. Common statement of representatives of national food safety agencies and institutions involved in nutrition in the European countries and Norway on 13 January 2004. Retrieved from http://www.food.gov.uk/multimedia/webpage/europenutritionstatement

Fulladosa, E., Sala, X., Gou, P., Garriga, M., & Arnau, J. (2012). K-lactate and high pressure effects on the safety and quality of restructured hams. *Meat Science, 91*(1), 56–61.

Grossi, A., Soltoft-Jensen, J., Knudsen, J. C., Christensen, M., & Orlien, V. (2012). Reduction of salt in pork sausages by the addition of carrot fibre or potato starch and high pressure treatment. *Meat Science, 92*(4), 481–489.

Han, G. D. (2006). Heat and high-pressure treatments on in vitro digestibility and allergenicity of beef extract. *Food Science and Biotechnology, 15*, 523–528.

Hayes, J., & Allen, P. (2011). *Monitoring the effects of high pressure processing, salt levels and refrigeration on the sensory and technological properties of pork sausages*. In 57th international congress of meat science and technology.

He, Z., Huang, Y., Li, H., Qin, G., Wang, T., & Yang, J. (2012). Effect of high-pressure treatment on the fatty acid composition of intramuscular lipid in pork. *Meat Science, 90*(1), 170–175.

Hong, G. P., Ko, S. H., Choi, M. J., & Min, S. G. (2008). Effect of glucono-delta-lactone and k-carregeenan combined with high pressure treatment on the physicochemical properties of restructured pork. *Meat Science, 79*, 236–243.

Huang, Y., He, Z., Li, H., Li, F., & Wu, Z. (2012). Effect of antioxidant on the fatty acid composition and lipid oxidation of intramuscular lipid in pressurized pork. *Meat Science, 91*(2), 137–141.

Husband, F. A., Aldick, T., der Plancken, I., Grauwet, T., Hendrickx, M., Skypala, I., et al. (2011). High-pressure treatment reduces the immunoreactivity of the major allergens in apple and celeriac. *Molecular Nutrition & Food Research, 55*(7), 1087–1095.

Inguglia, S., Zhang, Z., Tiwari, B. K., Kerry, J. P., & Burgess, C. M. (2017). Salt reduction strategies in processed meat products – A review. *Trends in Food Science and Technolology, 59*, 70–78.

Johnson, P. E., Van Der Plancken, I., Balasa, A., Husband, F. A., Grauwet, T., Hendrickx, M., et al. (2010). High pressure, thermal and pulsed electric-field-induced structural changes in selected food allergens. *Molecular Nutrition & Food Research, 54*(12), 1701–1710.

Kato, T., Katayama, E., Matsubara, S., Omi, Y., & Matsuda, T. (2000). Release of allergenic proteins from rice grains induced by high hydrostatic pressure. *Journal of Agricultural and Food Chemistry, 48*(8), 3124–3129.

Kim, H. Y., Kim, S. H., Choi, M. J., Min, S. G., & Kwak, H. S. (2008). The effect of high pressure–low temperature treatment on physicochemical properties in milk. *Journal of Dairy Science, 91*(11), 4176–4182.

Knorr, D., Heinz, V., & Buckow, R. (2006). High pressure application for food biopolymers. *Proteins and Proteomics, 1764*(3), 619–631.

Li, H., Zhu, K., Zhou, H., & Peng, W. (2012). Effects of high hydrostatic pressure treatment on allergenicity and structural properties of soybean protein isolate for infant formula. *Food Chemistry, 132*(2), 808–814.

Liu, Y., Ai, X., Sun, R., Yang, Y., Zhou, S., Dong, J., & Yang, Q. (2022). Residue, biotransformation, risk assessment and withdrawal time of enrofloxacin in red swamp crayfish (*Procambarus clarkii*). *Chemosphere, 307*, 135–657.

López-Pérez, O., del Olmo, A., Picon, A., & Nuñez, M. (2020). Volatile compounds and odour characteristics during long-term storage of kombu seaweed (*Laminaria ochroleuca*) preserved by high pressure processing, freezing and salting. *Food Science and Technology, 118*, 108–710.

Maksimenko, A., Kikuchi, R., Tsutsuura, S., & Nishiumi, T. (2019). Effect of high hydrostatic pressure and reducing sodium chloride and phosphate on physicochemical properties of beef gels. *High Pressure Research, 39*, 385–397.

Maleki, S. J., Viquez, O., Jacks, T., Dodo, H., Champagne, E. T., & Chung, S. Y. (2003). The major peanut allergen, Ara h 2, functions as a trypsin inhibitor, and roasting enhances this function. *Journal of Allergy and Clinical Immunology, 112*(1), 190–195.

Martínez, M. A., Velazquez, G., Cando, D., Núñez-Flores, R., Borderías, A. J., & Moreno, H. M. (2017). Effects of high pressure processing on protein fractions of blue crab (Callinectes sapidus) meat. *Innovative Food Science and Emerging Technologies, 41*, 323–329.

McArdle, R. A., Marcos, B., Kerry, J. P., & Mullen, A. M. (2011). Influence ofHPP conditions on selected beef quality attributes and their stability during chilled storage. *Meat Science, 87*(3), 274–281.

Ortea, I., Rodriguez, A., Tabilo-Munizaga, G., Perez-Won, M., & Aubourg, S. P. (2010). Effect of hydrostatic high-pressure treatment on proteins, lipids and nucleotides in chilled farmed salmon (*Oncorhynchus kisutch*) muscle. *European Food Research and Technology, 230*(6), 925–934.

Ozturk, M., Govindasamy-Lucey, S., Jaeggi, J. J., Johnson, M. E., & Lucey, J. A. (2013). The influence of high hydrostatic pressure on regular, reduced, low and no salt added Cheddar cheese. *International Dairy Journal, 33*(2), 175–183.

Radauer, C., & Breiteneder, H. (2006). Pollen allergens are restricted to few protein families and show distinct patterns of species distribution. *Journal of Allergy and Clinical Immunology, 117*(1), 141–147.

Sikes, A. L., Tobin, A. B., & Tume, R. K. (2009). Use ofhigh pressure to reduce cook loss and improve texture of low-salt beef sausage batters. *Innovative Food Science & Emerging Technologies, 10*(4), 405–412.

Trespalacios, P., & Pla, R. (2007). Synergistic action of transglutaminase and high pressure on chicken meat and egg gels in absence of phosphates. *Food Chemistry, 104*(4), 1718–1727.

Troy, D., Crehan, C., Mullen, A. M., & Desmond, E. (2001). *High pressure technology in the manufacture of minimally-processed meat products*. National Food Centre.

Tume, R. K., Sikes, A. L., & Smith, S. B. (2010). Enriching M. sternomandibularis with α- tocopherol by dietary means does not protect against the lipid oxidation caused by high-pressure processing. *Meat Science, 84*(1), 66–70.

Wang, J., & Sampson, H. A. (2011). Food allergy. *The Journal of Clinical Investigation, 121*(3), 827–835.

Wazed, M. A., & Farid, M. (2019). Hypoallergenic and low-protein Ready-to-Feed (RTF) infant formula by high pressure pasteurization: A novel product. *Foods, 8*(9), 408.

WHO. (2006). *Reducing salt intake in population*. Report of a WHO forum and technical meeting, 5–7 October 2006.

Yagiz, Y., Kristinsson, H. G., Balaban, M. O., Welt, B. A., Ralat, M., & Marshall, M. R. (2009). Effect of high pressure processing and cooking treatment on the quality of Atlantic salmon. *Food Chemistry, 116*(4), 828–835.

Yang, H., Han, M., Bai, Y., Han, Y., Xu, X., & Zhou, G. (2015). High pressure processing alters water distribution enabling the production of reduced-fat and reduced-salt pork sausages. *Meat Science, 102*, 69–78.

Zeece, M., Huppertz, T., & Kelly, A. (2008). Effect of high-pressure treatment on in-vitro digestibility of beta-lactoglobulin. *Innovative Food Science & Emerging Technologies, 9*(1), 62–69.

Chapter 5
Applications of HPP for Extraction of Bioactive Compounds

Abstract This chapter reviews recent HPP applications for improvement of extraction and bioavailability of bioactive compounds from a diverse variety of foods. HPP has shown encouraging potential in the recovery of polyphenols and carotenoids. Bioavailability of micronutrients, phytonutrients, and minerals is also enhanced as HPP has proven to be a new tool for better extraction than conventional methods.

Keywords HPP · Bioactive compounds · Micronutrients · Phytonutrients

5.1 Effect of HPP on Recovery of Bioactive Compounds

5.1.1 Polyphenols

Polyphenols have antioxidant characteristics, and foods that have high quantities of these compounds are important due to their health benefits. Polyphenols are present in fruits, vegetables, cereals, legumes, and nuts (Barba et al., 2012; Craft et al., 2012). Natural antioxidants are safer than artificial substitutes. Recently, use of antioxidants has increased as a natural food item due to their health benefits and no side effects (Han et al., 2004). Further, the glucosinolates and their derived components, the isothiocyanates, are attractive for both the pharmaceutical and food industries due to their health benefits (Deng et al., 2014; Dinkova-Kostova & Kostov, 2012).

Generally, plant tissues and cells become porous and permeable for intracellular compound removal during heating-based extraction procedures. However, thermal mechanisms can cause deterioration of heat-sensitive bioactive compounds, colors, and flavors, lowering the value of food products. Disrupting plant cell structures using enzymes, chemicals, and physical methods can also facilitate the extraction of cellular compounds. Microwaves, ohmic heating, and both sub- and supercritical water allow limited use of heat. Whereas non-thermal methods include supercritical carbon dioxide, pulsed electric fields, shockwaves, ultrasound, and high-pressure

H. Muhammad Shahbaz et al., *Advances in Food Applications for High Pressure Processing Technology*, SpringerBriefs in Food, Health, and Nutrition,
https://doi.org/10.1007/978-3-031-33643-0_5

processing (Deng et al., 2014; Parniakov et al., 2014; Rosello-Soto et al., 2015). Classic grinding and heating techniques are being used in the industry. These treatments cause uncontrollable deterioration and disturb membranes and cell walls. Undesirable compounds are also present in extracts due to loss of selectivity in damaged tissue. Moreover, it is usually not possible to separate pectins and cell debris from extracts (Barba et al., 2015). Organic solvents used for extracting carbohydrates and polysaccharides, proteins, bioactive compounds, flavors, and aromas include dichloromethane, dichloroethane, acetone, and hexane. Water at room temperature is also used for extraction from plants (Kerton, 2009).

HPP treatment is an efficient method to extract polyphenol compounds from different plants (Table 5.1). HPP is an environmentally friendly technique that can be used to increase mass transfer mechanisms within plant and animal cells, resulting

Table 5.1 Effect of HPP on recovery of polyphenols from plant materials and food products

Plant food material	HPP treatment conditions	Increase in phenolic compound extraction	References
Grape by-products	200–600 MPa, 20–70 °C, 30–90 min	Total anthocyanin content (22–83%) Anthocyanin monoglucosides (58–130%) Cyanidin (8–15%) Delphinidin (up to 29%) Malvidin (58–107%) Peonidin (46–150%) Petunidin (477%) Acylated anthocyanin Glucosides (4–54%) Cyanidin (up to 15%) Delphinidin (up to 7%) Malvidin (5–26%) Peonidin (8–82%) Petunidin (12%)	Corrales et al. (2009)
Korean black raspberry	500 MPa, 60 °C, 5–15 min	Catechin (76%) Caffeic acid (22%) Ferulic acid (68%)	Seo et al. (2011)
Litchi fruit pericarp	200–500 MPa, 30–90 °C, 2.5–30 min	Total polyphenol content (1.6%)	Prasad et al. (2009a, b)
Propolis	500 MPa, 25 °C, 1 min	Flavonoids (4.5%)	Shouqin et al. (2005)
Rhodiola sachalinensis	400–600 MPa, 20 °C, 15 min	Flavonoids (10%)	Zhang et al. (2007)
Tea leaves	100–600 MPa, 25 °C, 15 min	Total polyphenol content (28%)	Jun et al. (2010)
Milk-based fruit beverages	400 MPa, 40 °C, 5 min	Total polyphenol content was increased with HPP	Rodriguez et al. (2015)
Fruit juice-based beverage	400 MPa, 40 °C, 5 min	Total isoflavones, daidzin, genistin, glycitin, daidzein, genistein, and glycitein were enhanced	Rodriguez et al. (2020)

in increased permeability of cytoplasmatic membranes (Toepfl et al., 2006). Application of HPP can increase mass transfer rates by increasing secondary metabolite diffusion and cell leakage.

Among the stages that Galanakis (2012) lists for recovering antioxidants are macroscopic pre-treatment, macro- and micro-molecular separation, extraction, isolation and purification, and product formation. As processing progresses from the macroscopic to the macromolecular levels, specific macromolecules are removed. In order to extract bioactive compounds from cells, HPP technology can be used as a macroscopic pre-treatment (Fig. 5.1).

In grapes, polyphenol by-products are present in large quantities, and HPP was useful for extraction of polyphenols from grape byproducts (Corrales et al., 2009). HPP treatment was better than conventional extraction techniques. Anthocyanin compound extraction was increased by HPP treatment (Corrales et al., 2009).

Compared with conventional thermal methods (24 h/100 °C using a reflux condenser), Seo et al. (2011) found that HPP-assisted extraction (500 MPa/60 °C/5–15 min) significantly increased phenolic compound yields from Korean black raspberries (*Rubus coreanus*). The effects of HPP and conventional methods on extraction of phenolic compounds from fruit pericarp were evaluated, and a large difference between the results of both treatments was reported (Prasad et al., 2009a, 2010). Amounts of corilagin and total phenolic contents were both increased by HPP at 200–500 MPa at 30–70 °C for 2.5–30 min. Further, a larger amount of product was recovered in a shorter time using HPP.

According to Prasad et al. (2009b), HPP treatment at 200–500 MPa at 30–90 °C for 2.5–30 min increased the amount of polyphenols recovered from litchi fruit pericarp. After HPP treatment (400 MPa/40 °C/1 min) of orange juice with pulp, a larger quantity of phenolic compounds was recovered than without the HPP treatment (Sanchez-Moreno et al., 2005). This treatment has also been used for

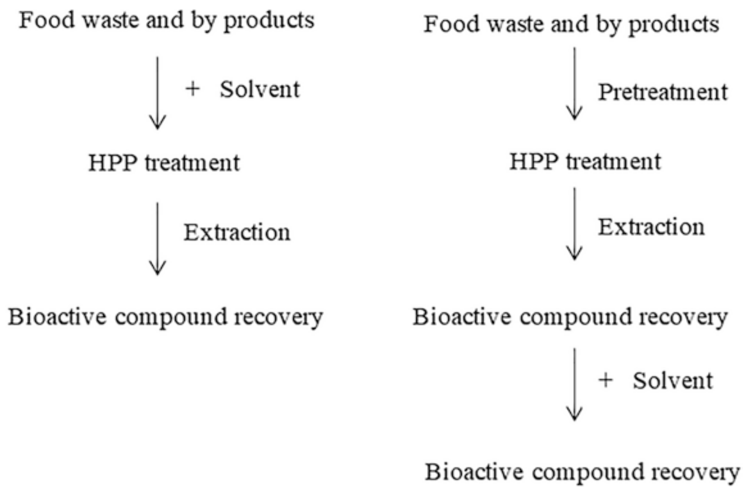


Fig. 5.1 Plant food HP extraction vs conventional solvent extraction. (Barba et al., 2015)

extraction of flavonoids from propolis (Shouqin et al., 2005) and *Rhodiola sachalinensis* (Zhang et al., 2007). Shouqin et al. (2005) observed that HPP treatment at 500 MPa at room temperature for 1 min produced better results for removal of flavonoids than both 7-day extraction at room temperature and heat reflux extraction for 4 h.

Antioxidants, particularly polyphenols, are present in large quantities in tea leaves. Recovery of polyphenols from green tea leaves has been achieved using ethanol, methanol, and water (Jun et al., 2010). However, extraction of essential components was greater and faster with HPP.

5.1.2 Carotenoids

Among the carotenoids used are β-carotene, α-carotene, and β-cryptoxanthin. Most carotenoids function as vitamin A (Melendez-Martinez et al., 2003). A significant increase in extraction of carotenoids from plant-based products was observed with use of HPP treatment in several studies, as summarized in Table 5.2. Increased extraction of carotenoids from orange juice, persimmon purée, and tomato

Table 5.2 Effect of HPP on recovery of carotenoids from plant materials

Plant material	HPP treatment condition	Carotenoids	References
Carrot purée	400–600 MPa, 20 °C, 15 min	Total carotenoid content was increased.	Patras et al. (2009)
Gazpacho soup (vegetable beverage)	400 MPa, 60 °C, 15 min	Extractable amounts of carotenoids (β-carotene, γ-carotene, lutein, lycopene, and lycopene-epoxide) were enhanced.	Plaza et al. (2006)
Orange juice with pulp	400 MPa, 40 °C, 1 min	β-crptoxanthin (43%), zeaxanthin (45%), lutein (75%), β-carotene (30%), and α-carotene (34%) contents were increased.	Sanchez-Moreno et al. (2005)
Papaya slices	400 MPa, 25 °C, 1 min	Amounts of the extractable carotenoids β-criptoxanthin, −criptoxanthin-5,8-epoxide, β-carotene, lutein, zeaxanthin, lycopene, and neolycopene were enhanced.	De Ancos et al. (2007)
Tomato puree	500 MPa, 25 °C, 12 min	Lycopene (21%) was increased.	Qiu et al. (2006)
Astringent persimmon	200 MPa, 6 min	Amounts of zeaxanthin, −β-cryptoxanthin, −β-carotene, and 9-cis-α-carotene were increased with HPP.	Cano et al. (2019)
Orange juice	200–400 MPa, 40 °C, 1 min	Carotenoid contents were increased.	De Ancos et al. (2020)

foodstuffs was reported after HPP treatment (Sanchez-Moreno et al., 2005). A study conducted by Patras et al. (2009) found that HPP treatment at 600 MPa at room temperature for 15 min increased the amount of total carotenoids by 3%. Citrus juice and pulp were found to have increased concentrations of cryptoxanthin, zeaxanthin, lutein, and β-carotene using HPP (Sanchez-Moreno et al., 2005). A large amount of carotenoids was recovered from papaya slices using HPP (De Ancos et al., 2007). HPP treatment at 400 MPa at 25 °C for 1 min also increased the carotenoid content of persimmon purée (De Ancos et al., 2007). HPP effects on tomato and carotenoid recovery have been examined. Krebbers et al. (2003) and Qiu et al. (2006) reported improvements in the lycopene yield from tomato purées of 60% and 21%, respectively, after HPP treatments at 500 MPa at 20–25 °C for 2–12 min.

5.1.3 Glucosinolates

Glucosinolates (thioglucosides) are biologically active sulfur-containing phytochemical esters with a β-D-thioglucopyranosyl at the aldoximecarbon in the Z-configuration of the ester group. They are manufactured by plants from eight amino acids (Hayes et al., 2008). The cruciferous vegetables (broccoli, Brussels sprouts, cabbage, cauliflower, and kale) all contain glucosinolates. The myrosinase enzyme creates sulforaphane, phenethylisothiocyanate, and benzyl isothiocyanate (all substitutes for isothiocyanates) from glucosinolates (Dinkova-Kostova & Kostov, 2012).

Conventional heat application procedures can cause inactivation of myrosinase, after which conversion to glucosinolates ceases. A comparison of conventional heat methods and HPP on broccoli juice isothiocyanates was carried out by Van Eylen et al. (2007) and Van Eylen et al. (2009). In addition to increasing cell interruption and membrane permeabilization, HPP increased myrosinase-catalyzed isothiocyanate synthesis from glucosinolates at 100–500 MPa for 15–35 min at 20–40 °C. Additionally, Van Eylen et al. (2009) assessed how HPP affected glucosinolates and degradation products, such as sulforaphane, glucoraphanin, and iberin. When HPP treatment (100–500 MPa/20–40 °C/15–35 min) is applied, isothiocyanate formation increases due to complex myrosinase-glucosinolate interactions. When HPP was used instead of thermal treatment (30–100 °C), degradation rates of isothiocyanate sulforaphane and phenylethyl isothiocyanate were lower. By using HPP, myrosinase activity can be controlled.

After HPP (200–600 MPa/20–40 °C/5 min), total isothiocyanates increased significantly compared with blanching (90–95 °C/3 min) (Alvarez-Jubete et al., 2014). Using HPP at 300 MPa at 40 °C for 10 min with subsequent refrigerated storage for 3 months, Penas et al. (2013) studied the breakdown of indole glucosinolate into ascorbigen, indole-3-carbinol, and indole-3-acetonitrile. The source material was naturally fermented cabbage and sauerkraut produced by fermentation with *Lactobacillus plantarum* and *Lactobacillus mesenteroides*. Ascorbigen content decreased significantly (33–67%).

5.2 Effect of HPP on Bioavailability and Bioaccessibility of Bioactive Compounds

The structure of foods is associated with the bioavailability and bioaccessibility of nutrients (Carbonell-Capella et al., 2014). When HPP can induce changes in food composition, increases in the bioavailability and bioaccessibility of intracellular elements can occur. HPP can improve the separation, bioaccessibility, and bioavailability of polyphenols, carotenoids, and glucosinolates (Cilla et al., 2012).

Nutrient bioaccessibility and bioavailability are complex effects of processing. The food matrix structure must also be considered. Several studies showed that the effect of HPP 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 used (Van Buggenhout et al., 2010).

5.2.1 Micronutrient and Phytonutrient Bioavailability

Numerous studies have examined the effect of HPP on nutrient bioavailability. According to McInerney et al. (2007), HPP (400–600 MPa/25 °C/2 min) affects carrot, broccoli, and green bean nutrients. HPP did not result in any damage to or reduce the availability of carotenoids. Knockaert et al. (2011) investigated the effects of HPP and sterilization processes on the bioavailability of β-carotene in carrots. HPP pasteurization treatment (500 MPa/25 °C/16 min) of carrots resulted in 1.2 times greater bioavailability of β-carotene than for thermal pasteurization (Knockaert et al., 2011).

The effects of thermal (93 °C/60 s), HPP (500–700 MPa/30 °C/0–10 min), and pressure-assisted thermal processing (PATP) (500–700 MPa/100 °C/10 min) on the bioavailability of lycopene in tomato juice have been studied by Gupta et al. (2011). HPP and PATP increased lycopene extraction by up to 12%, but bioavailability was not increased since less than 0.5% of lycopene was in micellar form.

A study conducted by Cilla et al. (2012) examined the nutrient-availability of carotenoids in 12 milk-based fruit beverages made from skim milk, milk, or whole milk after HPP (400 MPa/40 °C/5 min) and thermal pasteurization (90 °C/30 s). Nutrient bioavailability in HPP samples was significantly higher than for thermal pasteurization. The effects of HPP and thermal pasteurization on the bioavailability of vitamin E and vitamin C were also investigated. HPP can increase nutrient bioavailability by affecting enzyme activity. Vegetable sources of folate, for instance, usually contain polyglutamate forms that are less bioavailable. A key mechanism for converting polyglutamyl folates into more bioavailable short-chain or monglutamyl folates occurs upon cell decompartmentalization. As long-chain polyglutamyl folates are protected by blanching, freezing usually precedes blanching, so they have reduced bioavailability (Wang & Sampson, 2011).

5.2.2 *Bioavailability of Minerals After HPP*

Minerals are important parts of our regular diet. Minerals help make our diet healthy and balanced to maintain a good metabolism. However, our daily diet sometimes does not fulfill our mineral requirements, perhaps due to food processing and handling. Processing can result in the loss of calcium, iron, phosphorus, potassium, magnesium, and zinc (Cilla et al., 2011). HPP treatment does not affect food mineral content but can increase the availability of minerals present in foods. HPP effects on minerals are listed in Table 5.3.

After HPP treatment of apples for 2–10 min at 500 MPa, Ca, Fe, and Zn contents increased by 2–303%, 4–11%, and 8–28%, respectively (Briones-Labarca et al., 2011). Pressurization destroyed the plant cell wall, and bioavailability increased as nutrients were released into the extracellular space. An in vitro analysis of mineral bioaccessibility showed that mineral concentrations in the extracellular space had no effect on bioaccessibility. Dialysability of calcium was significantly decreased by HPP treatment, whereas iron and zinc dialysability was slightly improved. In seeds treated at 500 MPa for 10 min, algarrobo (*Prosopis chilensis*) seeds contained less calcium, iron, and zinc, but their bioaccessibility was improved (Briones-Labarca et al., 2011).

A more extensive investigation of HPP's effects on milk minerals has been conducted. In general, HPP treatment of milk affects the mineral balance, and calcium in particular, between the micellar and serum phases. In the serum phase, Regnault et al. (2006) found an increase in Ca and P after pressurizing raw skim milk to 300 MPa for 1–2 h, and the concentrations of ionic calcium increased by 12% after pressurization and incubation at 30 °C for 15 min (Zobrist et al., 2005). The concentration increase was reversed after 4 h of storage at 20 °C. Aside from this, HPP's effects were influenced by the length of the applied pressurization and the conditions of treatment. Results are affected by two types of conditions. Firstly, soluble calcium (serum) and insoluble calcium (micelles) can be converted back and forth depending on milk conditions. Second, proteins and inorganic compounds are able to bind with minerals released from micelles.

Table 5.3 Effect of HPP on bioavailability of minerals in foods

Food material	Treatment	Minerals	References
Apple	500 MPa, 20 °C, 2–10 min	Ca, Fe, and Zn content increased; minerals dialysability and solubility were reduced by HPP.	Briones-Labarca et al. (2011)
Beef	600 MPa, 31 °C, 10 min	No significant differences were found in Ca, K, Mg, Na, Cu, Fe, and Zn contents.	Garcia-Regueiro et al. (2002)
Bovine milk	100–300 MPa, 9 or 20 °C, 15 min	Ca and P released from micelles.	Sanchez-Moreno et al. (2005)
Milk-based fruit juices	400 MPa, 36 °C, 5 min	HPP improved Ca and P bioaccessibility but only improved P bioavailability.	Cilla et al. (2011)
Bovine whole milk	100–600 MPa, 20 °C, 5–30 min	Increased concentration of ionic Ca unrelated to pressure.	Zobrist et al. (2005)

According to a study conducted on soybeans, HPP significantly improved free amino acid release. After germination, starch digestibility increased by 2.42 times. Fe digestibility was significantly enhanced by 2.07 times following germination and by 2.06 times following 450 MPa/10 min treatment. As a result of germination and HPP, Zn digestibility was improved by 2.50 and 1.51, respectively. On average, HPP increased the digestibility of calcium by 1.91 times. A 52.4% decrease in phytic acid content was observed after germination and a 6.1% decrease after 300 MPa treatment. The tannin content was decreased by 450 MPa/10 min. After germination and HPP at 450 MPa/5 min, trypsin inhibitor content was reduced by 22.3% and 10.76%, respectively. This study enhances mineral digestibility, releases FAA, reduces anti-nutrition factors, and expands the use of soybeans in the food industry (Wu et al., 2023).

References

Alvarez-Jubete, L., Valverde, J., Patras, A., Mullen, A. M., & Marcos, B. (2014). Assessing the impact of high-pressure processing on selected physical and biochemical attributes of white cabbage (*Brassica oleracea* L. var. *Capitata alba*). *Food and Bioprocess Technology, 7*(3), 682–692.

Barba, F. J., Esteve, M. J., & Frígola, A. (2012). High pressure treatment effect on physicochemical and nutritional properties of fluid foods during storage: A review. *Comprehensive Reviews in Food Science and Food Safety, 11*, 307–322.

Barba, F. J., Terefe, N. S., Buckow, R., Knorr, D., & Orlien, V. (2015). New opportunities and perspectives of high pressure treatment to improve health and safety attributes of foods. A review. *Food Research International, 77*, 725–742.

Briones-Labarca, V., Munoz, C., & Maureira, H. (2011). Effect of high hydrostatic pressure on antioxidant capacity, mineral and starch bioaccessibility of a nonconventional food: Prosopis chilensis seed. *Food Research International, 44*(4), 875–883.

Briones-Labarca, V., Venegas-Cubillos, G., Ortiz-Portilla, S., Chacana-Ojeda, M., & Maureira, H. (2011). Effects of high hydrostatic pressure (HHP) on bioaccessibility, as well as antioxidant activity, mineral and starch contents in Granny Smith apple. *Food Chemistry, 128*(2), 520–529.

Cano, M. P., Gómez-Maqueo, A., Fernández-López, R., Welti-Chanes, J., & García-Cayuela, T. (2019). Impact of high hydrostatic pressure and thermal treatment on the stability and bioaccessibility of carotenoid and carotenoid esters in astringent persimmon (*Diospyros kaki Thunb*, var. *Rojo Brillante*). *Food Research International, 9*(123), 538–549.

Carbonell-Capella, J. M., Buniowska, M., Barba, F. J., Esteve, M. J., & Frígola, A. (2014). Analytical methods for determining bioavailability and bioaccessibility of bioactive compounds from fruits and vegetables: A review. *Comprehensive Reviews in Food Science and Food Safety, 13*(2), 155–171.

Cilla, A., Lagarda, M. J., Alegria, A., de Ancos, B., Cano, M. P., Sanchez-Moreno, C., et al. (2011). Effect of processing and food matrix on calcium and phosphorous bioavailability from milk-based fruit beverages in Caco-2 cells. *Food Research International, 44*(9), 3030–3038.

Cilla, A., Alegria, A., De Ancos, B., Sanchez-Moreno, C., Cano, M. P., & Plaza, L. (2012). Bioaccessibility of tocopherols, carotenoids, and ascorbic acid from milk- and soy-based fruit beverages: Influence of food matrix and processing. *Journal of Agricultural and Food Chemistry, 60*(29), 7282–7290.

Corrales, M., Garcia, A. F., Butz, P., & Tauscher, B. (2009). Extraction of anthocyanins from grape skins assisted by high hydrostatic pressure. *Journal of Food Engineering, 90*(4), 415–421.

Craft, B. D., Kerrihard, A. L., Amarowicz, R., & Pegg, R. B. (2012). Phenol-based antioxidants and the in vitro methods used for their assessment. *Comprehensive Reviews in Food Science and Food Safety, 11*(2), 148–173.

De Ancos, B., Rodrigo, M. J., Sánchez-Moreno, C., Pilar Cano, M., & Zacarías, L. (2020). Effect of high-pressure processing applied as pretreatment on carotenoids, flavonoids and vitamin C in juice of the sweet oranges "Navel" and the red-fleshed "Cara Cara". *Food Research International, 132*, 109–105.

DeAncos, B., Crespo, I., Sanchez-Moreno, C., Elez-Martinez, P., & Cano, M. P. (2007). *Effects of high pressure processing on vitamin C, carotenoids, and antioxidant activity of papaya fruit slices*. Poster presented in the session 189 ofnonthermal technologies, IFT annual meeting.

Deng, Q., Zinoviadou, K. G., Galanakis, C. M., Orlien, V., Grimi, N., & Vorobiev, E. (2014). The effects of conventional and non-conventional processing on glucosinolates and its derived forms, isothiocyanates: Extraction, degradation, and applications. *Food Engineering Reviews*, 1–25.

Dinkova-Kostova, A. T., & Kostov, R. V. (2012). Glucosinolates and isothiocyanates in health and disease. *Trends in Molecular Medicine, 18*(6), 337–347.

Galanakis, C. M. (2012). Recovery of high added-value components from food wastes: Conventional, emerging technologies and commercialized applications. *Trends in Food Science & Technology, 26*(2), 68–87.

Garcia-Regueiro, J. A., Sarraga, C., Hortos, M., Dias, I., Valero, A., & Rius, M. A. (2002). *Bioequivalence of meat products treated by high hydrostatic pressure*. Profit final project report.

Gupta, R., Kopec, R. E., Schwartz, S. J., & Balasubramaniam, V. M. (2011). Combined pressure–temperature effects on carotenoid retention and bioaccessibility in tomato juice. *Journal of Agricultural and Food Chemistry, 59*(14), 7808–7817.

Han, S. S., Lo, S. C., Choi, Y. W., Kim, J. H., & Baek, S. H. (2004). Antioxidant activity ofcrude extract and pure compounds of Acer ginnala Max. *Bulletin of the Korean Chemical Society, 25*(3), 389–391.

Hayes, J. D., Kelleher, M. O., & Eggleston, I. M. (2008). The cancer chemopreventive actions of phytochemicals derived from glucosinolates. *European Journal of Nutrition, 47*(2), 73–88.

Jun, X., Shuo, Z., Bingbing, L., Rui, Z., Ye, L., & Deji, S. (2010). Separation of major catechins from green tea by ultrahigh pressure extraction. *International Journal of Pharmaceutics, 386*(1–2), 229–231.

Kerton, F. M. (Ed.). (2009). *Alternative solvents for green chemistry*. RSC Publishing.

Knockaert, G., De Roeck, A., Lemmens, L., Van Buggenhout, S., Hendrickx, M., & Van Loey, A. (2011). Effect of thermal and high pressure processes on structural and health- related properties of carrots (*Daucus carota*). *Food Chemistry, 125*(3), 903–912.

Krebbers, B., Matser, A. M., Hoogerwerf, S. W., Moezelaar, R., Tomassen, M. M. M., & van den Berg, R. W. (2003). Combined high-pressure and thermal treatments for processing of tomato puree: Evaluation of microbial inactivation and quality parameters. *Innovative Food Science & Emerging Technologies, 4*(4), 377–385.

McInerney, J. K., Seccafien, C. A., Stewart, C. M., & Bird, A. (2007). Effects of high pressure processing on antioxidant activity, and total carotenoid content and availability, in vegetables. *Innovative Food Science & Emerging Technologies, 8*(4), 543–548.

Melendez-Martinez, A. J., Vicario, I. M., & Heredia, F. J. (2003). A routine high-performance liquid chromatography method for carotenoid determination in ultrafrozen orange juices. *Journal of Agricultural and Food Chemistry, 51*(15), 4219–4224.

Parniakov, O., Barba, F. J., Grimi, G., Lebovka, N., & Vorobiev, E. (2014). Impact of pulsed electric fields and high voltage electrical discharges on extraction of high-added value compounds from papaya peels. *Food Research International, 65*, 337–343.

Patras, A., Brunton, N., Da Pieve, S., Butler, F., & Downey, G. (2009). Effect of thermal and high pressure processing on antioxidant activity and instrumental colour of tomato and carrot purées. *Innovative Food Science and Emerging Technologies, 10*(1), 16–22.

Penas, E., Limon, R. I., Vidal-Valverde, C., & Frias, J. (2013). Effect ofstorage on the content of indole-glucosinolate breakdown products and vitamin C of sauerkrauts treated by high hydrostatic pressure. *LWT Food Science and Technology, 53*(1), 285–289.

Plaza, L., Sanchez-Moreno, C., De Ancos, B., & Cano, M. P. (2006). Carotenoid content and antioxidant capacity of Mediterranean vegetable soup (gazpacho) treated by high-pressure/temperature during refrigerated storage. *European Food Research and Technology, 223*(2), 210–215.

Prasad, K. N., Hao, J., Shi, J., Liu, T., Li, J., & Wei, X. (2009a). Antioxidant and anticancer activities of high pressure-assisted extract of longan (*Dimocarpus longan Lour*.) fruit pericarp. *Innovative Food Science & Emerging Technologies, 10*(4), 413–419.

Prasad, N. K., Yang, B., Zhao, M., Wang, B. S., Chen, F., & Jiang, Y. (2009b). Effects of high-pressure treatment on the extraction yield, phenolic content and antioxidant activity of litchi (*Litchi chinensis Sonn*.) fruit pericarp. *International Journal of Food Science and Technology, 44*(5), 960–966.

Prasad, K. N., Yang, B., Shi, J., Yu, C., Zhao, M., & Xue, S. (2010). Enhanced antioxidant and anti-tyrosinase activities of longan fruit pericarp by ultra-high-pressure-assisted extraction. *Journal of Pharmaceutical and Biomedical Analysis, 51*(2), 471–477.

Qiu, W., Jiang, H., Wang, H., & Gao, Y. (2006). Effect of high hydrostatic pressure on lycopene stability. *Food Chemistry, 97*(3), 516–523.

Regnault, S., Dumay, E., & Cheftel, J. C. (2006). Pressurisation of raw skim milk and of a dispersion of phosphocaseinate at 9 °C or 20 °C: Effects on the distribution of minerals and proteins between colloidal and soluble phases. *Journal of Dairy Research, 73*(1), 91–100.

Rodríguez-Roque, M. J., deAncos, B., Sánchez-Moreno, C., Cano, M. P., Elez, P., Martínez, O., & Martín-Belloso. (2015). Impact of food matrix and processing on the in vitro bioaccessibility of vitamin C, phenolic compounds, and hydrophilic antioxidant activity from fruit juice-based beverages. *Journal of Functional Foods, 14*, 33–43.

Rodríguez-Roque, M. J., De Ancos, B., Sánchez-Vega, R., Sánchez-Moreno, C., Elez-Martínez, P., & Martín-Belloso, O. (2020). In vitro bioaccessibility of isoflavones from a soymilk-based beverage as affected by thermal and non-thermal processing. *Innovative Food Science & Emerging Technology, 66*, 102–504.

Rosello-Soto, E., Galanakis, C. M., Brncic, M., Orlien, V., Trujillo, F. J., & Mawson, R. (2015). Clean recovery of antioxidant compounds from plant foods, by-products and algae assisted by ultrasounds processing. Modeling approaches to optimize processing conditions. *Trends in Food Science & Technology, 42*(2), 134–149.

Sanchez-Moreno, C., Plaza, L., Elez-Martinez, P., De Ancos, B., Martin-Belloso, O., & Cano, M. P. (2005). Impact of high pressure and pulsed electric fields on bioactive compounds and antioxidant activity of orange juice in comparison with traditional thermal processing. *Journal of Agricultural and Food Chemistry, 53*(11), 4403–4409.

Seo, Y. C., Choi, W. Y., Kim, J. S., Yoon, C. S., Lim, H. W., & Cho, J. S. (2011). Effect of ultra high pressure processing on immuno-modulatory activities of the fruits of Rubus coreanus Miquel. *Innovative Food Science & Emerging Technologies, 12*(3), 207–215.

Shouqin, Z., Jun, X., & Changzheng, W. (2005). High hydrostatic pressure extraction of flavonoids from propolis. *Journal of Chemical Technology and Biotechnology, 80*(1), 50–54.

Toepfl, S., Mathys, A., Heinz, V., & Knorr, D. (2006). Review: Potential of high hydrostatic pressure and pulsed electric fields for energy efficient and environmentally friendly food processing. *Food Reviews International, 22*(*4*), 405–423.

Van Buggenhout, S., Alminger, M., Lemmens, L., Colle, I., Knockaert, G., & Moelants, K. (2010). In vitro approaches to estimate the effect of food processing on carotenoid bioavailability need thorough understanding of process induced microstructural changes. *Trends in Food Science and Technology, 21*(12), 607–618.

Van Eylen, D., Oey, I., Hendrickx, M., & Van Loey, A. (2007). Kinetics of the stability of broccoli (*Brassica oleracea* Cv. *Italica*) myrosinase and isothiocyanates in broccoli juice during pressure/temperature treatments. *Journal of Agricultural and Food Chemistry, 55*(6), 2163–2170.

Van Eylen, D., Bellostas, N., Strobel, B. W., Oey, I., Hendrickx, M., & Van Loey, A. (2009). Influence ofpressure/temperature treatments on glucosinolate conversion in broccoli (*Brassica oleraceae* L. cv *Italica*) heads. *Food Chemistry, 112*(3), 646–653.

Wang, J., & Sampson, H. A. (2011). Food allergy. *The Journal of Clinical Investigation, 121*(3), 827–835.

Wu, X., Tan, M., Zhu, Y., Duan, H., Ramaswamy, H. S., Bai, W., & Wang, C. (2023). The influence of high pressure processing and germination on anti-nutrients contents, in vitro amino acid release and mineral digestibility of soybeans. *Journal of Food Composition and Analysis, 115*, 104–953.

Zhang, S. Q., Bi, H. M., & Liu, C. J. (2007). Extraction of bio-active components from Rhodiola sachalinensis under ultrahigh hydrostatic pressure. *Separation and Purification Technology, 57*(2), 277–282.

Zobrist, M. R., Huppertz, T., Uniacke, T., Fox, P. F., & Kelly, A. L. (2005). High-pressure- induced changes in the rennet coagulation properties of bovine milk. *International Dairy Journal, 15*(9), 655–662.

Chapter 6
Current Challenges and Future Applications of HPP

Abstract HPP equipment requires a large capital investment. The HPP Toll Processing initiative started by Avure Technologies and Hiperbaric reduces start-up costs for food processors. Successful commercialization of HPP food products, innovations in HPP equipment, wider availability of toll processing facilities for HPP processing, and advancements in engineering technology have made HPP technology more commercially feasible for more processors.

Keywords HPP Toll Processing · Clean label · Spore · High pressure thermal sterilization

A large capital investment for purchase of high-pressure equipment remains the biggest obstacle to commercial expansion of HPP technology. The cost of industrial equipment ranges from 500,000 to over 3 million US dollars, depending upon the capacity and extent of equipment automation (Sampedro et al., 2014; Jermann et al., 2015; Spielman, 2019). Variable expenses, including labor, facilities, energy, utilities, and maintenance, also increase costs. Approximately 80% of the investment goes to the cost and installation of HPP equipment (van den Berg et al., 2001). Therefore, to overcome the issue of equipment cost, Avure Technologies and Hiperbaric have set up a worldwide network of HPP Toll Processing centers to provide the benefits of a lower startup cost and reduced capital investment for food processors. Toll processing business models allow any food or beverage manufacturer to access industrial HPP equipment without the need for direct capital investment (Koutchma, 2014). Hiperbaric is conducting HPP toll processing in Spain, Italy, the Netherlands, Germany, Switzerland, the United Kingdom, Mexico, the United States, Canada, Korea, Japan, Australia, and New Zealand (www.hiperbaric.com). Toll processing units can be used by meat and juice processors, dairies, seafood providers, and pharmaceutical companies. Toll processing centers are a growing business, and three centers have been installed in Asia in the year 2020. Recently, Hiperbaric installed a dedicated toll service in Singapore through Warehouse Logistics Net Asia.

H. Muhammad Shahbaz et al., *Advances in Food Applications for High Pressure Processing Technology*, SpringerBriefs in Food, Health, and Nutrition,
https://doi.org/10.1007/978-3-031-33643-0_6

Increased demand for minimally processed, clean-label foods with a fresh flavor and taste has led to increased demand for use of HPP non-thermal food processing technology. In recent years, successful commercialization of HPP food products, innovations in HPP equipment, and wider availability of toll processing facilities for HPP processing have made this technology commercially feasible. It is anticipated that the cost of HPP equipment, as well as processing costs, will be reduced in the future with advancements in engineering technology. The latest advancements in HPP equipment have led to a shift towards continuous processing. HPP toll processing has become a growing part of the HPP market, where Hiperbaric has installed more than 270 equipment centers in 40 different countries in a concerted effort to overcome the economic issues of HPP technology. HPP processing will become simpler with fewer stages and higher productivity. More recently, HPP technology has been used in combination with bacteriocins, natural preservatives, and other processing treatments to make the HPP process more efficient and economical.

Another application of interest is high-pressure thermal sterilization (HPTS), which is a combination of high pressure and high temperature. The HPTS process can be used for production of ambient-stable packed food products that require a lower thermal impact than those provided by traditional sterilization processes. Lower-impact thermal processing results in better color, texture, taste, and nutrient content than heat sterilization. However, industrial applications are complex due to technical limitations and an inability to monitor temperature, an uneven distribution of temperature, and a lack of reliable industrial machines. In addition, increased food processing costs will be reflected in the final product price and might not be acceptable to consumers. A strategy that addresses some of these limitations includes use of isolated processing containers. Pre-heated pressurizing fluid and products are added to these containers, and conventional HPP units can be used for pressurization of pre-heated batches.

References

Jermann, C., Koutchma, T., Margas, E., Leadley, C., & Ros-Polski, V. (2015). Mapping trends in novel and emerging food processing technologies around the world. *Innovative Food Science and Emerging Technologies, 31*, 14–27.

Koutchma, T. (2014). *Adapting high hydrostatic pressure (HPP) for food processing operations*. Academic.

Sampedro, F., Mcaloon, A., Yee, W., Fan, X., & Geveke, D. J. (2014). Cost analysis and environmental impact of pulsed electric fields and high pressure processing in comparison with thermal pasteurization. *Food and Bioprocess Technology, 7*, 1928–1937.

Spielman, S. (2019). HPP: Equipment, trends and the science behind the technology. *Food Safety Magazine*.

van den Berg, R. W., Hoogland, H., Lelieveld, H. L. M., & Van Schepdael, L. (2001). High pressure equipment designs for food processing applications. In *Ultra high pressure treatments of foods* (pp. 297–313). Kluwer Academic/Plenum Publishers.

Index

H. Muhammad Shahbaz et al., *Advances in Food Applications for High Pressure Processing Technology*, SpringerBriefs in Food, Health, and Nutrition,
https://doi.org/10.1007/978-3-031-33643-0