Journal of
Food Chemistry & Nanotechnology

https://doi.org/10.17756/jfcn.2024-s1-013

Review Article

Open Access

High Pressure Processing as an Advancement in Food Processing

Rafeeya Shams[1*], Qurat ul eain Hyder Rizvi[2], Aayeena Altaf[3*], Kshirod Kumar Dash[4], Aamir Hussain Dar[5] and Hanu Sharma[3]

[1]*Department of Food Technology and Nutrition, Lovely Professional University, Phagwara, Punjab, India*
[2]*Department of Food Technology, Dr. Khim Singh Gill Akal College of Agriculture Eternal University, Barusahib, Himachal Pradesh, India*
[3]*Amity Institute of Biotechnology, Amity University, Jaipur, Rajasthan, India*
[4]*Ghani Khan Choudhary Institute of Engineering & Technology, Malda, West Bengal, India*
[5]*Department of Food Technology, Islamic University of Science and Technology, Kashmir, India*

***Correspondence to:**
Rafeeya Shams
Department of Food Technology and Nutrition,
Lovely Professional University,
Phagwara, Punjab, India.
E-mail: rafiya.shams@gmail.com

Aayeena Altaf
Amity Institute of Biotechnology,
Amity University,
Jaipur, Rajasthan, India.
E-mail: aaltaf@jpr.amity.edu

Received: November 24, 2023
Accepted: March 08, 2024
Published: March 12, 2024

Citation: Shams R, Rizvi QH, Altaf A, Dash KK, Dar AH, et al. 2024. High Pressure Processing as an Advancement in Food Processing. *J Food Chem Nanotechnol* 10(S1): S101-S110.

Published by United Scientific Group

Abstract

The increasing interest amongst consumers in healthy, convenient, and minimally processed foods has led food processors to develop novel and non-thermal techniques like high pressure processing (HPP). This technique involves processing moisture-rich solid and liquid foods under high pressure conditions (400 - 1000 MPa). HPP is a promising alternative to the conventional modes of thermal and chemical preservation of food. Numerous studies have claimed the potential of HPP in extending the product shelf-life without compromising its nutritional and organoleptic aspects. This non-thermal approach eliminates harmful and spoilage microorganisms while preserving covalent bonds in food molecules, thereby limiting the effect on nutritional and sensory properties of the product. As compared to heat treatments, HPP has far less of an impact on low molecular weight components like vitamins, pigments, and flavorings. As a result, the quality of high pressure processed foods is quite like that of fresh foods. This paper provides an overview on preservation of foods by HPP including basic principle, process equipment, mechanistic effect on food components, microbial destruction, and applications.

Keywords

High pressure processing, Sterilization, Nutritional, Sensory, Shelf life

Introduction

HPP refers to the process of ultra-high-pressure treatment to the product uniformly for few min. High pressure technology (HPT) is gaining popularity among food processors due to its food preservation capability as well as its potential to achieve various functional effects [1]. The growing research on HPP has produced many opportunities to enhance the quality and safety of food products. HPT, also called ultra-high-pressure processing or high hydrostatic pressure, is the technique in which the food is subjected to ultra-high hydrostatic pressure, usually in the range of 100 - 1000 MPa. The processing temperature during treatment is adjusted from below 0 °C to above 100 °C with exposure times ranging from a few seconds to about 20 min. Processing time can be varied from milli-second pulse (formed by oscillating pump) to a treatment time of over 1200 sec (20 min). The processing conditions used in this technology inactivate vegetative microbes, ensure safety, and enhance shelf-life of chilled or high-acid (e.g., guacamole, fruit juices) food products [2]. Covalent bonds of food molecules which attribute to them a characteristic structure and property are minimally affected by pressures used in HPP [3]. Hence, food products treated with HPT at or near room temperature do not undergo notable chemical transformations which results in improved sensory and nutritional characteristics of food. This technology has also been used for the pasteurization of various food stuffs including cooked meat, dairy, seafood, and vegetable products [4]. Spores of bacteria are resistant to high pressure levels due to which shelf stability of low-acidic foods cannot be attained by higher pressure alone [5]. High hydrostatic pressure causes protein denaturation, leading to the inactivation of some inherent enzymes as well as the biogenic activity of certain microbes. However, high pressure can also increase lipid oxidation within muscle tissues. Current intensive research on the impact of high hydrostatic pressure on fish tissues has shown the advantages as well as drawbacks of this novel technology. It was found that HPP can kill microbes present in milk and may increase the time of realistic usability [6]. It was observed that a pressure over 463 MPa for 1 h slows down the souring of milk for not less than 24 h. This innovative technique is used for the preparation of food and crude ingredients for obtaining desirable sensory and functional properties [7]. As an alternative to conventional thermal processing, HPP has the potential to produce food with 'fresh-like' qualities and improved functional properties [8]. HPP is an effective innovative technique to increase food protection and spread their time span of usage [9]. One of the most important applications of HPT is microbial inactivation that results in enhancing the shelf-stability and microbial stability of foods. HPP can be used to eliminate *Listeria monocytogenes* in processed meat-based products and cheese [10]. Further, hydrostatic pressure treatment is advantageous for inactivation of certain hazardous microorganisms like *Escherichia coli, Salmonella*, and *Vibrio*, many bacteria, molds, yeasts that may cause deterioration in foods [11]. This technology can also be used to modify the sensory and functional characteristics of certain food constituents, mainly proteins. The protein molecular structure maintained by hydrophobic and ionic interactions are modified by high pressure usually above 200 MPa [12]. The hydrophobic and electrostatic bonding get severely affected but hydrogen bonds remain unaffected resulting in stabilization of α-helical and ß-pleated sheets [13]. Egg, fish, dairy and meat proteins are denatured due to HPP in absence of high temperatures. Viscosity is increased and opacity is achieved with minimum changes in flavor. On the other hand, HPP possesses minimum effect on low molecular weight components like flavoring compounds, pigments, and vitamins, as compared to thermal processing. The quality is mainly influenced by storage temperatures, distribution, and barrier properties of the packaging material than by the HPP operations [14]. Over the past 20 years, advancement in HPP technology as semi-continuous system has been used to increase the pilot units to commercially viable processes [15]. Presently industrial HPP treatment of food is done by a batch or semi-continuous process; solid food is mostly processed in a batch mode while liquid foods are processed by continuous as well as semi-continuous process [16]. In 1992, the main revolution in HPP came in Japan by releasing first high pressure processed product in the market. The pressure-treated jam launched in the food markets by a company at the beginning, subsequently made remarkable success. HPP started fetching notable presence in the market when six other companies brought in similar products in the next three years [17]. Over the past 30 years, HPP has been successfully used in the food industry. Further, this technology is also used in the material and process engineering industry for sheet-metal forming and isostatic pressing of certain materials including ceramics and turbine components. Engineering aspects of HPP were enormously investigated in the early 20th century (1909 - 1959) [18]. Depending on the processing conditions of pressure, temperature, and the operating scale, the cost of processing is about $0.10 higher than thermally processed products. The history events in the use of HPP for food products is elucidated in table 1 [19]:

Table 1: Historical developments in the use of HPP for processing food (1899-2001).

Product/ Commodity	Intended purpose	Year
Fruit juices and pieces	Launch of the first high pressure treated fruit juices in United Kingdom (UK). HPP fruit pieces were given approval for sale in UK	2001
Cooked meat, fruit juices	Marketing of high pressure self-shucking oysters, fruit juices, poultry product, and other products were done in United States of America (USA). Mainland (Europe) started to produce fresh fruit juices (mostly citrus) and delicatessen-style cooked meat	2000
Guacamole from avocados	Avomex (USA) started to produce high pressure processed product with prolonged shelf life and fresh taste	1990
Fruit jam	Japan started producing high pressure processed products	1980
Food products	Hite (USA) used high pressure treatments for preservation of foods	1899

Lately, HPP has received significant interest amongst scientists, academicians, and industrialists. It is a promising technique for the future of food processing with immense potential to mitigate the current problems associated with conventional methods of thermal processing. The scope of this comprehensive review is to synthesize an amalgamated body of literature on key aspects of this novel technology, comprising the unravelling of the underlying principles and design of a basic HPP unit, its effect on primary food compounds, and applications in the processing and shelf-life extension of diverse food products.

HPP Technology

HPP doesn't cause distortion or damage to the food unless the treated product has an empty space inside. During the processing time, decline in the number of microbes and protein denaturation occurs without affecting molecular bonds. Further, chemical reactions that result in the destruction of vitamins or off-flavors development can be reduced under high-pressure treatments [20]. Further, the implication of HPP ravages a mild effect on the covalent bond providing a least effect on the chemical transformations when applied at ambient temperature or near ambient/room temperature [21]. The rate of microbial and enzyme linked damage can be appreciably reduced by the unification of HPP and heat. It may be noted that any chemical change in the food will be the function of time and temperature combination selected during the process in aggregation with pressure treatment [22].

HPP principles

HPP can inactivate food borne pathogens, spoilage bacteria, yeasts, and molds with minimum degradation of color, flavor, texture, and nutritive quality of foods, as compared to traditional methods of food preservation [23]. The general principles that explain the behavior of foods due to the impact of high pressure include:

Le-Chatelier's principle

Le-Chatelier's principle states that the pressure applied shifts the system equilibrium towards the state occupying the lesser volume and, thus, any process including phase transition, chemical reaction, changes in molecular configuration, etc., along with a decline in volume would be increased by raising the pressure and vice versa [24].

Microscopic ordering principle

As per the principle of microscopic ordering, with a pressure increment, under constant temperature, mutually rises the degree of order of molecules of the given substance. As a result, pressure and temperature exert antagonistic effects on chemical reactions and molecular structure [25].

Isostatic principle

As per this principle, food is compressed uniformly by applying pressure and then returned to their original shape when the pressure is released. The products are compressed independent of the geometry and product size as the transmission of pressure to the core is not mass/time dependent, thus the process is minimalized if a food contains sufficient moisture, pressure will not damage the product at the macroscopic level if the uniform pressure is applied in all directions [26].

Equipment

The two ways of processing food in high pressure vessels include in-container processing and bulk processing. Although foil pouches and conventional plastics are most suitable, various studies are constantly being done on seal integrity, the ideal package design, and other suitable packaging materials which can be utilized. Automatic equipment is used for obtaining material handling for in-container processing which is like that used to load or unload batch retorts. Bulk handling is less complex; it requires pumps, pipes, and valves. Processing of fluid foods like juices can be done in both semi-continuous and batch mode [27]. HPP leads to a reduction in the volume of foods while processing them (like the volume of water, which is reduced by nearly 15% at a pressure of 600 MPa). In HPP there is a substantial impact and deformation to the seal and the package when in-container processing is being used. One of the companies in Japan has used semi continuous processing of fruit juices at 4000 - 6000 for 1 h with pressures of about 400 - 500 MPa for period of 1 - 5 min under optimum temperature, whereas other companies use similar processes operating at 120 - 400 MPa followed by small heat treatments before juice packaging. These liquid foods can be used as pressurizing fluid by pumping with high pressure pumps directly. If liquids are promptly decompressed through a small opening, the turbulent flow and high velocity will raise the shearing forces on microorganisms and will increase their destruction rate [28]. The main high pressure system components are pressure vessel and its closure, pressure generation system, temperature control device, and materials handling system. The main HPP system components are shown in figure 1.

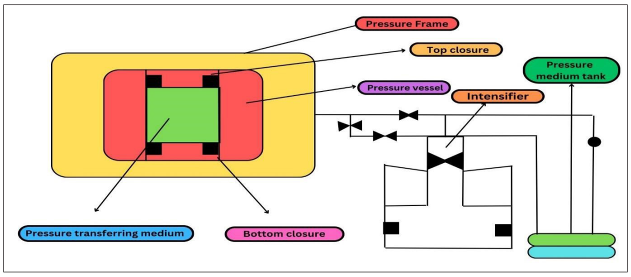

Figure 1: Schematic assembly of a HPP equipment.

Pressure vessel

Typically, pressure vessels used in the food industry are cylindrical in structure. Pressure vessels are constructed in three different ways. Vessels made with steel alloys having high tensile strength are known as 'monoblocs' (single-forged) chambers. Monolithic chambers are simple to build and less expensive, but they cannot withstand pressure levels above 400 - 600 MPa. Multiwall chambers made from a shrink-fitting series of concentric cylinders can withstand higher pressures and are safer than single-wall vessels. For higher pressure, wire-wound or pre-stressed multi-layer vessels are used, which can be utilized for pressure vessels with a larger diameter. Depending on the target process conditions, pressure vessels possess an external jacket to control the temperature [23].

Top and bottom closures to contain the pressure

Two end closures hold the food product and pressure-transmitting fluid within the pressure vessel during operation. For food processing operations, rapid opening and closing of the closure is required. The pressure vessel along with the associated closure and yoke are mostly installed in either horizontal or vertical orientation.

Yoke

At elevated pressures, often a secondary structure is required to contain end closures. This secondary external frame is referred to as yoke. It consists of a wire-wound frame or a high-tensile strength steel.

Pressure intensifier and pump for pressure generation

Pressure vessels at industrial scale use an external pumping intensifier system to produce target pressure with a minimum pressure come-up time of about 1 - 2 min. They use a motor to run the lower-pressure pump that compresses the hydraulic fluid to be used in a larger intensifier. The most widely used pressure-transmitting medium in larger, industrial-scale pressure vessels is water. The larger intensifier compresses the water and sends it to the pressure vessel.

A material handling system for sample loading and unloading

During batch processing, pre-packaged samples are carried into a cylindrical shaped canister. The canister containing the sample is pre-heated or chilled before loading into the pressure vessel.

Control system for monitoring and recording process variables

The control system helps to monitor and provide relevant process data like temperature, pressure, etc. The sensors need to be periodically calibrated using the standard protocols [29].

Pressure and temperature effect

To predict and understand the HPP effect on food products it is essential to take into consideration the combination impact of temperature-pressure on the foods being treated as shown in figure 2. Food products during the compression cycle (T_1 - T_2) of pressure treatment undergo a decline in volume as a function of the pressure. The food products are kept under pressure for a definite period (T_2 - T_3) before decompression (T_3 - T_4). The product will return to its initial volume upon decompression [30].

During this process, compression and decompression occurs due to change in transition temperature in the product. The food temperature (T_1 - T_2) rises due to physical compression (P_1 - P_2). Temperature of product (T_2 - T_3) at pressure (P_2 - P_3) is not dependent of compression rate until the heat exchange between surroundings and the product is negligible. The product will return to its initial temperature upon decompression (P_3 - P_4) in a perfectly insulated system. During the compression phase, the product will return to a temperature (T_4) slightly lesser than its initial temperature (T_1) due to heat loss. The water temperature rises about 3 °C for every 100 MPa increase in pressure at ambient temperature. The heat compression value for oils and fats is of the order 8 - 9 °C/100 MPa, whereas carbohydrates and proteins have an intermediate range [31].

In the given figure 2, T_1 is the initial temperature of the product at pressure P_1, T_2 - T_3 is the temperature range of the product at pressure levels P_1 and P_2, and T_4 is the final temperature of the product while the pressure is P_4.

Effect of HPP

Effect of HPP on chemical composition of food

HPP increases temperature naturally due to adiabatic heating, depending on the target pressure and chemical composition of the food. The water temperature rises to about 3 °C per 100 MPa of pressure, and it can be higher for more compressible foods like fats. Thus, the temperature increase is higher during HPP for foods with a higher fat content.

Effect on microorganisms

HPP causes the inactivation of microbes by various techniques; the cellular membrane changes, like changes in permeability and the cell structure, are mainly responsible for microbial destruction. Further, the reduction in volume due to HPP causes the synthesis of certain enzymes, protein inhibition, cell morphology alteration, and changes in the survival and reproductive mechanisms of certain microbes. Resistance to HPP in eukaryotic microbes (such as protozoa and fungi) is less than that in prokaryotes (such as bacteria). Among bacteria, Gram-negative bacteria are less pressure-resistant than Gram-positive bacteria because of their greater cell wall rigidity. Further, rods are usually less resistant than cocci because of their spatial configuration [32]. The pressure capability to destroy each microorganism is difficult to define because it is also influenced by the contamination level in food and the growth phase (process efficiency reduces at higher concentrations of microorganisms because of auto-protective mechanisms among the cells), food characteristics (such as pH, water activity, acidity, presence of antimicrobials, etc.), and other process variables (including pre-process characteristics, temperature, time, etc.). Spore germination under high pressures is temperature-dependent; near 0 °C, spores are resistant to germination even at pressures of 1000 MPa, while at moderate temperatures, pressure-produced germination can be attained at a pressure of 100 MPa only. Germinated spores can be eliminated at a temperature of 50 - 70 °C and a pressure of 600 MPa. However, these effects are not constant, and a combination of moderate heating and high pressure has both synergistic and antagonistic effects on the growth of microorganisms (depending on the type of microorganism), enzymatic activity, and chemical reactivity. HPP can either make microbes more sensitive to heat or prevent their destruction at high temperatures, depending on the type of microorganism being used [15]. The behavior of microbes towards high pressure is the same as that observed during thermal processing operations in acidic conditions. The susceptibility of microorganisms is greater; they are less resistant in the presence of fats or proteins, high sugar concentrations, the presence of antimicrobials, and at the log growth phase [33]. It is necessary to take bacterial spores and molds into consideration in addition to vegetative spores that are found in foods. For fruit juices with a lower pH, the fungi ascospores from the genera *Byssochlamys* and *Neosartory* needs to be destroyed [34]. For low acid foods, the bacterial spores of considerable importance are from genera *Bacillus* and *Clostridium,* including pathogens such as *Bacillus cereus* and *Clostridium botulinum*. The process (up to 1200 MPa) is not able to promote a sufficient decline in the number of spores because the effect of processing on the structure of spores is minimal or negligible. Based on various research, the Food and Drug Administration (FDA) (2010) recommended a varying time (at least 3 min) and pressure of

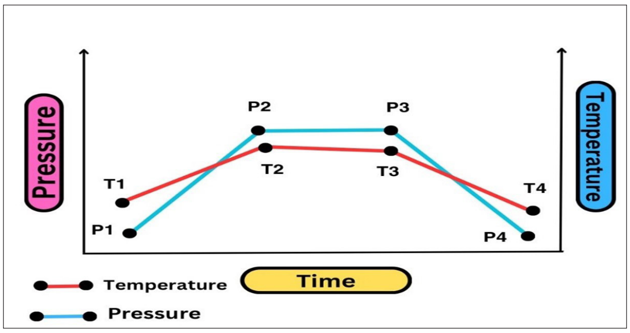

Figure 2: Pressure-temperature relationship during HPP.

580 MPa for stabilizing acidic and low-acidic food products when the method is carried out under refrigerated conditions. Low pH is the main attribute characterizing fruit juices; for such foods, only HPP is responsible for food safety [34]. To prevent spoilage, juices processed at high pressure are usually kept under refrigeration to increase shelf stability. Pressure-assisted thermal sterilization is a method that uses pressure and temperature combinations to achieve commercial sterility for the product. This method has advantages over traditional thermal treatments. The use of pressures provides sensibilization of microbial spores, lowering the time and temperature of the process required for its destruction, and due to the adiabatic heating (3 ˚C/100 MPa), the process increases the temperature of the product to around 24 - 30 ˚C instantaneously. Pressure-assisted thermal sterilization has been used for the sterilization of food by the FDA since 2009, but due to a lack of research, the use of this technology is limited in the food industry [35].

Effect on enzymes

Fruit processing being the major application of HPP treatment, various studies of enzyme deactivation are concerned that it deteriorates the quality of fruit products and affects their shelf stability. Enzymes produce their effect on food structure (such as cellulases and hemicellulases, pectinases as pectin methylesterase, or cause changes in nutritional value, flavor, or color due to oxidation (ascorbate oxidase, peroxidase, and polyphenol oxidase. The enzyme's structure, stability, and activity are maintained by non-covalent bonds like electrostatic, hydrophobic, hydrogen linkage, van der Waals interaction, and disulfide linkage. Therefore, for various enzymes, HPP at pressures of around 100 MPa or more induces certain changes in enzyme structure. HPP doesn't break covalent linkage, and hence, hydrostatic pressure causes changes in enzymes mostly by changing tertiary and quaternary structures. For example, polyphenol oxidase shows resistance to pressures of up to 1200 MPa for 10 min before deactivation, although it is sensitive at high pH values [36]. Differences in polyphenol oxidase baro-sensitivity from various sources, such as mushrooms (800 - 900 MPa), apricots (100 MPa), strawberries (400 MPa), and grapes (600 MPa) have also been reported [12]. Pectin esterase causes loss of consistency in tomato products, gelation of fruit concentrates, and cloud destabilization in juices. It is more resistant than polyphenol oxidase; its activity is decreased above 300 MPa, and it can be deactivated at pressures above 700 MPa at 45 ˚C for 10 min. Orange pectin esterase is partially, i.e., around 90%, inactivated at a pressure of 600 MPa at ambient temperature and does not get activated by storage conditions [37]. The effects on enzymatic and microbial activity with a combination of high pressures and lower water activity, compressed or supercritical carbon dioxide pre-treatments with enzymes (e.g., lysozyme, glucose oxidase) or biopolymers (e.g., chitosan), sodium sulfite ethanol, ultrasonic waves, and high electric field pulses have also been reported. Having difficulty achieving the inactivation of enzymes under process conditions applied to induce microbiological stability as pasteurization (600 MPa/few min at ambient temperature), most fruit products treated with HPP use certain forms to minimize enzymatic activity (such as anti-browning agents).

Effect of HPP on various food components

Effects of high pressure on water

During HPP operations, water is used as a pressure-transmitting fluid during various processes. Under pressure, water compressibility and the volume decrease at 20 ˚C are 4%, 7%, and 15% at 100 MPa, 200 MPa, and 600 MPa, respectively. At the same time, a moderate temperature rise assists this adiabatic compression as the pressure increases. At 25 ˚C, the order of this increase is 3 ˚C per 100 MPa, but it can be hindered by thermal exchanges between the vessel and the water [38]. Under pressure, the ionic product of the water rises, resulting in a decrease in pH that is reversible upon depressurization. This process has various important effects on the product being treated (gelation, texture, emulsification, etc.). High pressures applied to 210 MPa cause depression in the melting point of the water, resulting in negative temperatures with no crystal formation [39].

Effects of high pressure on lipids

Two lipid properties are mostly affected by HPP treatments: the oxidation level and the melting temperature. With the pressure applied at a rate of 20 ˚C per 100, the temperature of melting increases reversibly, leading to the crystallization of lipids under pressure and thus altering bio-middles, resulting in potential enhancements in microbial inactivation, cell content leakage, and cell permeability [13]. Various studies have concluded that oxidation is accelerated due to high pressures, depending on the matrix studied [40].

Effects of high pressure on proteins

Proteins are large molecules existing in aqueous environments in equilibrium with varying conformations, including monomers, denatured monomers, partially denatured monomers, and oligomers, whose partial volume reduces in the order of increasing hydration [41]. Thus, when pressure is applied, Le Chatelier's principle shifts the equilibrium to a system with less volume, thereby causing oligomer dissociation, monomer denaturation, etc., depending on the protein and pressure application level [42]. As proteins are present in higher amounts in food, pressure-induced reactions are responsible for the gelation of protein molecules and irreversible aggregation [43]. Further, HPP treatments form disulfide bonds. Examples include milk treated at 200 MPa, which causes β-lactoglobulin to form disulfide-bonded dimmers [44]. Moreover, pressure treatments can alter the protein structure, thereby causing changes in its function, like masking or better access to epitopes or modification of the active site of enzymes [45, 46]. In proteins, the pressure is responsible for molecular structure unfolding and then aggregation with either different proteins present in a food or in a different form, causing an alteration of the texture of the food. Gel formation is seen in certain proteins, like fish, soy, egg albumin, and meat. Pressure-treated gels retain their natural color and flavor, are referred to as glossy, smooth, and soft, and possess higher elasticity as compared to heat-induced gels. Research is also being done to unfold the structure of low-quality proteins using HPP to modify their functional properties, like emulsification and gel-forming capacity.

Effects of high pressure on carbohydrates

Simple sugars are affected by HPP produced with covalent bonds of high energy. However, high pressure can alter carbohydrates composed of sugar chains linked by low-energy bonds. Therefore, starch swelling and starch gelatinization are caused by HPP. Alginate and pectin also produce different gelling and thickening characteristics after pressurization [47].

Applications of HPP in Food Preservation

does not reduce the sensory and nutritional properties of the food and helps in maintaining the shelf stability of food products (Figure 3).

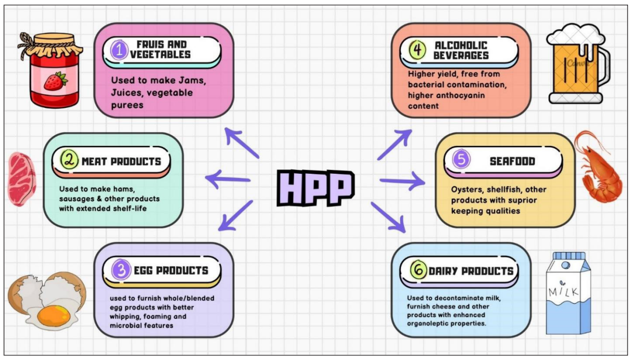

Figure 3: Applications of HPP in various food products.

Fruit jams

Fruit jams like apple, strawberry, and kiwi jams are examples of the first pressure-pasteurized products [48]. They are mostly processed at pressures of 400 MPa for up to 5 min at ambient temperature. The product is kept under refrigerated conditions after processing to prevent browning and flavor changes that may occur due to enzymatic activities. The refrigerated shelf life of jams treated with high pressure is about 30 days. They have better sensory quality as compared to those produced by conventional methods [49].

Fruit juices

Acidic fruit juices treated with high pressure, like orange juice, are available commercially in the USA, Mexico, Canada, Japan, and Europe. They are treated at ≥ 400 MPa for a short duration (usually not more than 10 min) at ≤ 20 ˚C, which not only reduces the number of yeasts and molds significantly but also decreases the number of certain pathogens, like *E. coli* O157:H7. The shelf-life of pressurized fruit juices can be increased by about 30 days.

Vegetable products

Non-thermal processing of freshly prepared vegetable products to improve food safety is of major concern because of the high pH and chances of growth and survival of spore-forming pathogenic microbes. Guacamole (acidified avocado puree) is an example of a high-pressure processed vegetable product in the USA. Guacamole is mostly treated at pressures of around 500 - 600 MPa for 2 min or longer, which results in a 5-log reduction in the number of pathogens [48]. The shelf-life of the product can be increased from 7 to 30 days under refrigerated conditions.

Meat products

HPP of meat and poultry products like ready-to-eat ham, chicken, and turkey products is mostly used as the last step of preservation after packaging to lower the risk of post-processing contamination from various pathogenic microorganisms like *L. monocytogenes* and *E. coli*. High-pressure-treated sliced cooked hams are available in the USA and Spain and are processed in flexible pouches at a pressure of 500 MPa for a short duration of time. This maintains the sensory characteristics and extends the shelf life to 60 days under chilled storage conditions [2]. High-pressure treatments, along with heat, can reduce the bacterial spore population significantly in meat products. The high pressure eliminates *Citrobacter freundii, Pseudomonas fluoresecens*, and *Listeria innocua* at pressures greater than 200, 280, and 400 MPa, respectively, at 20 ˚C. Total inhibition of microorganisms occurs at pressures of 400 - 500 MPa. However, *Pseudomonas* spp. is observed after 3 - 9 days at 30 ˚C, which means that they are not eliminated but are stressed by HPP treatments. Hence, HPP needs to be coupled with certain other treatments, like a moderate temperature of 50 ˚C, to reduce the viable *Pseudomonas* spp. The HPP effect on color and myoglobin content of minced beef showed a meat that was pink when treated with pressure of 200 - 350 MPa, resulting in an increase in color values and lightness (L), which turns grey, brown at 400 - 500 MPa (showing a reduction in L values). Meat discoloration is due to a whitening effect of 200 - 300 MPa, due to globin denaturation and the oxidation of ferrous myoglobin to ferric myoglobin at a pressure of 400 MPa.

Egg products

Blended liquid eggs or whole liquid egg products are used in several foods due to their nutritive value and hence are responsible for various physicochemical properties of the food like coagulation, foaming, and emulsification properties. The advantages of HPP in egg compounds include an improvement in egg white foaming capacity due to the presence of SH groups, which enhance the stability of foams [50, 51]. In various studies on the inactivation of microbes in liquid whole eggs using high-pressure treatment, the application of HPP treatments with low intensity (300 MPa/3 min) followed by heating at 52 ˚C/3.5 min or 55 ˚C/2 min provided an equal level of microbial stability in the presence of 2% triethyl citrate as compared to that of liquid whole eggs processed at 71 ˚C/1.5 min, but had the same quality properties as those of fresh liquid whole eggs [52]. Further, high-pressure treatments are used to enhance the functional properties and emulsifying qualities of egg protein. Research has shown that high-pressure treatment effect at a pressure of 100 - 500 MPa on certain functional and physicochemical characteristics of egg yolks and found that HPP produces egg yolk solubility loss and reduces the surface hydrophobicity, free sulfhydryl content, emulsifying activity index, and viscosity of egg yolks Additionally, conformational and physiochemical variations under high-pressure treatment are critical as they affect the bioactivities of egg proteins and their functional properties. Ovo-transferrin, as a good bioactive peptide source, accounts for 12% - 13% of egg albumin proteins. High-pressure treatments change the conformational structure from helices, turns, sheets, and aggregated strands to intermolecular β-sheets or aggregated strands at pH level 8 and a pressure of 200 MPa, and it can return to its native form at higher pressure treatments. These changes result in a rise in protein surface hydrophobicity without changing the total SH groups, due to which aggregation is inhibited [53].

Alcoholic beverages

Various traditional techniques used for the stabilization of wines, like pasteurization and flash pasteurization at 60 - 70 ˚C and filtration, affect their sensory characteristics and decrease their pigment, polyphenolic compounds, and volatile compound content. Whereas HPP can control *Brettanomyces* species efficiently and reduce degrading effects [54]. In the case of grape wines, bacterial spoilage is the most crucial problem, and hence, SO_2 is used as a chemical preservative that acts as an antioxidant and an antimicrobial agent in wines, but it has a detrimental impact on human health [55]. Treatment of wine from the variety of grape, namely Dornfelder, using HPP and observed the predominant anthocyanin stability, namely malvidin-3-O-glucoside (Mv3gl). A reduction in the level of Mv3gl at pressure (600 MPa for 1 h at 70 ˚C) samples was observed, while as heat processed (0.1 MPa for 1 h at 70 ˚C), samples did not show any loss of Mv3gl as compared to the untreated ones (0.1 MPa for 1 h at 20 ˚C). When the processing of wine was done at a pressure of 600 MPa at 70 ˚C for 10 min, antioxidant activity or anthocyanin composition remained unaffected. The study on the effect of HPP on the shelf-life stability of lager beer has also been reported. The processing of filtered bright lager beer samples was done with the pasteurization technique (60 ˚C for 15 min) or high-pressure treatments (350 MPa for 3 and 5 min at 20 ˚C). A storage period of 56 days reported similar results in color and with both HPP and heat pasteurization. However, the samples treated at high pressure reported lower protein sensitivity, lower bitterness, and increased chill haze values than the samples treated with heat-pasteurization. Similarly, studies on the effect of HPP on the quality characteristics of lager beer are also conducted. Unpasteurized lager beer samples were treated with high pressure (200, 250, 300, and 350 MPa at 20 ˚C for 3 and 5 min) or pasteurization technique (60 ˚C for 15 min). The major characteristics of the beer, including fermentation degree, density, ethanol content, extract, and pH, remained the same in both cases. However, HPP and heat pasteurization affected the protein sensitivity, chill haze, color, and bitterness. The protein sensitivity, chill haze, and color values enhanced with the higher pressures, whereas the bitterness change was greater in conventional heat pasteurization as compared to HPP. It was observed that high-pressure treatment inhibits spoilage-causing microbes and enhances the organoleptic of beer. The high-pressure processed product has a fresh-like taste that is mostly accepted by consumers. HPP technology is also used in the wine industry to enhance product quality and provide a unique, environmentally friendly technique [56].

Oysters and other seafood

High-pressure treatment is used in seafood, including shellfish and oysters. *Vibrio* species associated with seafood products are relatively sensitive to HPP. Oysters are treated for 1 - 3 min at 250 - 350 MPa at optimum temperature to eliminate *Vibrio* species. from the product with minimum or no effect on sensory properties [57]. A 7-log reduction of *V. parahaemolyticus* has been reported by processing oysters at 345 MPa and 22 ˚C for 1.5 min [58]. A 5-log reduction in the *V. parahaemolyticus* O3:K6 (the most resistant strain among the 10 strains studied) at 10 ˚C for 3 min by a 300 MPa treatment has also been reported [59]. Furthermore, HPP can enhance the limited refrigerated shelf stability of oysters while maintaining the overall quality of the product. The mechanical shucking effect is an important benefit of HPP for oysters by releasing and denaturing the adductor muscle from the shell [60].

Dairy products

Milk is highly susceptible to microbial growth, which affects its safety as well as its quality. Low-temperature long-time (63 ˚C, 30 min) and high-temperature short-time (72 ˚C, 15 sec) pasteurizations and ultra-high-temperature (~140 ˚C for a few seconds) treatment are the most used methods to eliminate pathogenic microbes in combination with hygienic milk harvesting [61]. HPP application for milk preservation dates back over a century, when a 5 - 6 log decrease was observed in the total microbial growth of milk treated at 680 MPa for 10 min at room temperature [62]. The combined pressure and temperature effect (67 - 71 ˚C) further enhances the shelf-life of milk. The high-pressure treatment improves the microbial stability of milk without altering lacto-peroxidase activity (a native milk enzyme). Bovine serum albumin and s-lactalbumin are resistant to pressure of about 400 MPa for 60 min. The rise in cheese yield is observed (at 300 and 400 MPa) in combination with additional s-lactoglobulin and moisture retention. HPP results in improving the moisture retention properties of fresh cheese and enhancing the coagulation properties of milk. The exact mechanism of microbial deactivation by high-pressure treatment is not completely understood yet but is thought to act in different ways. The viability of vegetative microbes can be influenced by changing cell membrane structure or by inactivating the enzymatic systems responsible for ribosome disintegration and metabolic reaction control [24]. Microorganisms' viability depends upon temperature, pressure, holding time, food constituents, and the condition and growth phase of microbes present in milk [63]. Temperature and high-pressure treatment can cause sufficient inactivation of microbes when applied separately, but various studies have shown that the combination of these two treatments dramatically improves the level of inactivation, mostly in the case of bacterial spores [15]. The type of substrate present and food composition has a considerable impact on the microbial response during pressure treatment. Various food components, like proteins, carbohydrates, lipids, and vitamins, have a protective effect on microbial destruction [64]. The water activity (aw) of the food is also an essential parameter that determines the effectiveness of high-pressure treatment [65]. Microorganisms in the lag phase are more sensitive to high pressures as compared to those in the stationary phase. This may be because the microorganism is in the cellular division process and the membrane is more environmentally sensitive during the lag phase. Yeasts and molds are mostly inactivated at a pressure of 200 - 400 MPa, but when they are in the state of spore or ascospore or in a food with a higher sugar concentration, the pressure is required to inactivate them, and it could be as close as the pressure of 600 MPa [66]. The resistance of spores is more towards pressure than that of vegetative cells, which can survive at 1000 MPa pressure [67, 68]. However, various studies have shown the recovery of injured bacteria at high pressure present in milk during further storage [69, 70]. The recovery process during storage is the most crucial issue when food safety is to be considered. High-pressure injured cells in milk can be restored within 1 - 15 days using high pressure, which indicates the capability for the recovery of bacteria from these foods. Mild-heat treatment effects at 30 - 50 ˚C following high pressure treatment at 550 MPa on the inhibition of L. monocytogenes present in milk have also been studied [69-71].

Combination Treatments Involving Pressure

HPP treatments can effectively be used when combined with other processing methods to decrease the severity of other treatments and increase their preservative effect. It is possible that this combined technique approach can be used in many commercial applications of the HPP technique. Beneficial combination treatments may include the use of pressure (mostly < 15 MPa) with carbon dioxide to enhance the microbial stability of orange juice, egg yolk, chicken, shrimp, and certain fermented vegetables. Irradiation combined with pressure techniques has been shown to enhance the microbial stability of poultry meat and lamb meat. Combination of pressure with ultrasound and heat treatment has successfully inactivated *B. subtilis* spores [72]. Certain antimicrobial compounds are also used in combination with high pressure to inactivate microorganisms. Nisin with high pressure reduces the growth of *Bacillus coagulans* spores successfully. Other antimicrobials, like pediocin, and the monoterpenes, in combination with pressure treatment, caused microbial inactivation successfully. The most important advantage of HPP is that it can be considered a 'natural' and minimal processing technique [73].

Conclusion

HPP is a promising technology for the future of food processing. It can furnish food products with high sensory and nutritional characteristics while extending their shelf stability. Preservation of foods by HPP without using high-heat treatment or chemical preservatives ensures the safety of the food, leaving no chances of toxicity associated with the conventional utilization of chemicals. Since this process can be done with the final packaging system, the possibility of recontamination and cross-contamination can be significantly prevented. Lower operational temperatures in HPP ensure the retention of heat-labile nutrients like vitamins post-processing, making them nutritionally superior to thermally processed products. This advantage also makes it highly suitable to process heat-sensitive foods like colostrum, eggs, and certain other proteins. Apart from being highly efficient, this process is environmentally friendly as electricity and water are the only requirements, making it a sustainable technology with a lower carbon footprint. Presently, spore inactivation is the only hurdle that is to be duly considered. Synergistic techniques involving acidity, additives, heat, etc., can be exploited to attain the desired microbiological quality of the product.

Acknowledgements

None.

Conflict of Interest

None.

References

1. Bhoite AA. 2017. Ultra high pressure technology: principle, its application and microbiological aspects of food. *Int J Innov Sci Eng Technol* 4(5): 211-219.
2. Patterson MF. 2005. Microbiology of pressure-treated foods. *J Appl Microbiol* 98(6): 1400-1409. https://doi.org/10.1111/j.1365-2672.2005.02564.x
3. Aghamohammadi B, Morshedi A, Akbarian M, Akbarian A, Hadidi M, et al. 2014. Effect of high pressure processing of food characteristics: a review of quality aspect. *Int J Biosci* 4(10): 193-205.
4. Wilson DR, Dabrowski L, Stringer S, Moezelaar R, Brocklehurst TF. 2008. High pressure in combination with elevated temperature as a method for the sterilisation of food. *Trends Food Sci Technol* 19(6): 289-299. https://doi.org/10.1016/j.tifs.2008.01.005
5. Black EP, Setlow P, Hocking AD, Stewart CM, Kelly AL, et al. 2007. Response of spores to high-pressure processing. *Compr Rev Food Sci Food Saf* 6(4): 103-119. https://doi.org/10.1111/j.1541-4337.2007.00021.x
6. Ginsau MA. 2015. High pressure processing: a novel food preservation technique. *J Environ Sci Toxicol Food Technol* 9(5): 109-113.
7. Bárcenas ME, Altamirano-Fortoul R, Rosell CM. 2010. Effect of high pressure processing on wheat dough and bread characteristics. *LWT Food Sci Technol* 43(1): 12-19. https://doi.org/10.1016/j.lwt.2009.06.019
8. Akhmazillah MF, Farid MM, Silva FV. 2013. High pressure processing (HPP) of honey for the improvement of nutritional value. *Innov Food Sci Emerg Technol* 20: 59-63. https://doi.org/10.1016/j.ifset.2013.06.012
9. Tao Y, Sun DW, Górecki A, Błaszczak W, Lamparski G, et al. 2012. Effects of high hydrostatic pressure processing on the physicochemical and sensorial properties of a red wine. *Innov Food Sci Emerg Technol* 16: 409-416. https://doi.org/10.1016/j.ifset.2012.09.005
10. Fonberg-Broczek M, Windyga B, Szczawiński J, Szczawińska M, Pietrzak D, et al. 2005. High pressure processing for food safety. *Acta Biochim Pol* 52(3): 721-724.
11. Hayman MM, Baxter I, O'riordan PJ, Stewart CM. 2004. Effects of high-pressure processing on the safety, quality, and shelf life of ready-to-eat meats. *J Food Prot* 67(8): 1709-1718. https://doi.org/10.4315/0362-028X-67.8.1709
12. Hendrickx MEG, Knorr D, Ludikhuyze L, Van Loey A, Heinz V. 2005. Ultra High Pressure Treatment of Foods. Springer, New York.
13. Heremans K. 2001. The Effects of High Pressure on Biomaterials. In Hendrickx MEG, Knorr D, Ludikhuyze L, Van Loey A, Heinz V (eds) Ultra High Pressure Treatments of Foods. Springer, Boston.
14. Utz PB, Serfert Y, Garcia AF, Dieterich S, Lindauer R, et al. 2004. Influence of high-pressure treatment at 25 ˚C and 80 ˚C on folates in orange juice and model media. *J Food Sci* 69(3): SNQ117-21. https://doi.org/10.1111/j.1365-2621.2004.tb13380.x
15. Considine KM, Kelly AL, Fitzgerald GF, Hill C, Sleator RD. 2008. High-pressure processing–effects on microbial food safety and food

quality. *FEMS Microbiol Lett* 281(1): 1-9. https://doi.org/10.1111/j.1574-6968.2008.01084.x

16. Tao Y, Sun DW, Hogan E, Kelly AL. 2014. High-Pressure Processing of Foods: An Overview. In Sun D-W (ed) Emerging Technologies for Food Processing. Academic Press.
17. Elamin WM, Endan JB, Yosuf YA, Shamsudin R, Ahmedov A. 2015. High pressure processing technology and equipment evolution: a review. *J Eng Sci Technol Rev* 8(5): 75-83.
18. Balasubramaniam VM. 2003. High Pressure Food Preservation. In Heldman DR (ed) Encyclopedia of Agricultural, Food, and Biological Engineering. CRC Press, pp 490-496.
19. Brennan JG, Grandison AS. 2011. Food Processing Handbook. Wiley.
20. Rastogi NK. 2013. Introduction. In Rastogi NK (ed) Recent Developments in High Pressure Processing of Foods. Springer, New York, pp 1-7.
21. Chakraborty S, Kaushik N, Rao PS, Mishra HN. 2014. High-pressure inactivation of enzymes: a review on its recent applications on fruit purees and juices. *Compr Rev Food Sci Food Saf* 13(4): 578-596. https://doi.org/10.1111/1541-4337.12071
22. Koutchma T. 2014. Adapting High Hydrostatic Pressure (HPP) for Food Processing Operations. Academic Press.
23. Yordanov DG, Angelova GV. 2010. High pressure processing for foods preserving. *Biotechnol Biotechnol Equip* 24(3): 1940-1945. https://doi.org/10.2478/V10133-010-0057-8
24. Farkas DF, Hoover DG. 2001. High pressure processing. *J Food Sci* 65(8): 47-64. https://doi.org/10.1111/j.1750-3841.2000.tb00618.x
25. Benet UG. 2006. High-pressure low-temperature processing of foods: impact of metastable phases on process and quality parameters. Department of Food Biotechnology and Food Process Engineering, Berlin University of Technology. (Doctoral Dissertation)
26. Torres JA, Velazquez G. 2005. Commercial opportunities and research challenges in the high pressure processing of foods. *J Food Eng* 67(1-2): 95-112. https://doi.org/10.1016/j.jfoodeng.2004.05.066
27. Balasubramaniam VM, Farkas D. 2008. High-pressure food processing. *Food Sci Technol Int* 14(5): 413-418. https://doi.org/10.1177/1082013208098812
28. Martínez-Monteagudo SI, Yan B, Balasubramaniam VM. 2017. Engineering process characterization of high-pressure homogenization—from laboratory to industrial scale. *Food Eng Rev* 9: 143-169. https://doi.org/10.1007/s12393-016-9151-5
29. Balasubramaniam VM, Ting EY, Stewart CM, Robbins JA. 2004. Recommended laboratory practices for conducting high-pressure microbial inactivation experiments. *Innov Food Sci Emerg Technol* 5(3): 299-306. https://doi.org/10.1016/j.ifset.2004.04.001
30. Balasubramaniam VM, Farkas D, Turek EJ. 2008. Preserving foods through high-pressure processing. *Food Technol* 62(11): 32-38.
31. Rasanayagam V, Balasubramaniam VM, Ting E, Sizer CE, Bush C, et al. 2003. Compression heating of selected fatty food materials during high-pressure processing. *J Food Sci* 68(1): 254-259. https://doi.org/10.1111/j.1365-2621.2003.tb14148.x
32. Huang HW, Lung HM, Yang BB, Wang CY. 2014. Responses of microorganisms to high hydrostatic pressure processing. *Food Control* 40: 250-259. https://doi.org/10.1016/j.foodcont.2013.12.007
33. Georget E, Sevenich R, Reineke K, Mathys A, Heinz V, et al. 2015. Inactivation of microorganisms by high isostatic pressure processing in complex matrices: a review. *Innov Food Sci Emerg Technol* 27: 1-4. https://doi.org/10.1016/j.ifset.2014.10.015
34. Tribst AAL, Sant'Ana AD, de Massaguer PR. 2009. Microbiological quality and safety of fruit juices—past, present and future perspectives. *Crit Rev Microbiol* 35(4): 310-319. https://doi.org/10.3109/10408410903241428
35. Pressure-Assisted Sterilization Accepted by FDA. [https://www.foodprocessing.com/on-the-plant-floor/plant-operations-and-engineering/article/11366570/production-operations-pressure-assisted-sterilization-accepted-by-fda] [Accessed on March 12, 2024]
36. Júnior BRCL, Tribst AAL, Cristianini M. 2017. Effect of High-Pressure Technologies on Enzymes Applied in Food Processing. In Senturk M (ed) Enzyme Inhibitors Activators. IntechOpen, pp 49-72.
37. Fellows PJ. 2009. Food Processing Technology. Woodhead Publishing.
38. Balasubramaniam VM, Martinez-Monteagudo SI, Gupta R. 2015. Principles and application of high pressure–based technologies in the food industry. *Annu Rev Food Sci Technol* 6: 435-462. https://doi.org/10.1146/annurev-food-022814-015539
39. Kalichevsky MT, Knorr D, Lillford PJ. 1995. Potential food applications of high-pressure effects on ice-water transitions. *Trends Food Sci Technol* 6(8): 253-259. https://doi.org/10.1016/S0924-2244(00)89109-8
40. Guyon C, Meynier A, de Lamballerie M. 2016. Protein, and lipid oxidation in meat: a review with emphasis on high-pressure treatments. *Trends Food Sci Technol* 50: 131-143. https://doi.org/10.1016/j.tifs.2016.01.026
41. Akasaka K. 2003. Highly fluctuating protein structures revealed by variable-pressure nuclear magnetic resonance. *Biochem* 42(37): 10875-10885. https://doi.org/10.1021/bi034722p
42. Akasaka K. 2006. Probing conformational fluctuation of proteins by pressure perturbation. *Chem Rev* 106(5): 1814-1835. https://doi.org/10.1021/cr040440z
43. Akasaka K. 2010. High pressure NMR study of proteins–seeking roots for function, evolution, disease and food applications. *High Press Res* 30(4): 453-457. https://doi.org/10.1080/08957959.2010.530266
44. Patel HA, Singh H, Anema SG, Creamer LK. 2006. Effects of heat and high hydrostatic pressure treatments on disulfide bonding interchanges among the proteins in skim milk. *J Agric Food Chem* 54(9): 3409-3420. https://doi.org/10.1021/jf052834c
45. Rahaman T, Vasiljevic T, Ramchandran L. 2016. Effect of processing on conformational changes of food proteins related to allergenicity. *Trends Food Sci Technol* 49: 24-34. https://doi.org/10.1016/j.tifs.2016.01.001
46. Barba FJ, Terefe NS, 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 Res Int* 77: 725-742. https://doi.org/10.1016/j.foodres.2015.05.015
47. Simonin H, Guyon C, Orlowska M, De Lamballerie M, Le-Bail A. 2011. Gelatinization of waxy starches under high pressure as influenced by pH and osmolarity: gelatinization kinetics, final structure and pasting properties. *LWT Food Sci Technol* 44(3): 779-786. https://doi.org/10.1016/j.lwt.2010.07.002
48. Tonello C. 2011. Case Studies on High-Pressure Processing of Foods. In Zhang HQ, Barbosa-Cánovas GV, Balasubramaniam VM, Dunne CP, Farkas DF, et al. (eds) Nonthermal Processing Technologies for Food. Blackwell Publishing, pp 36-50.
49. Ludikhuyze L, Hendrickx ME. 2001. Effects of High Pressure on Chemical Reactions Related to Food Quality. In Hendrickx MEG, Knorr D, Ludikhuyze L, Van Loey A, Heinz V (eds) Ultra High Pressure Treatments of Foods. Springer, Boston, MA, pp 167-188.
50. Van der Plancken I, Van Loey A, Hendrickx ME. 2007. Foaming properties of egg white proteins affected by heat or high pressure treatment. *J Food Eng* 78(4): 1410-1426. https://doi.org/10.1016/j.jfoodeng.2006.01.013
51. Yang RX, Li WZ, Zhu CQ, Zhang Q. 2009. Effects of ultra-high hydrostatic pressure on foaming and physical-chemistry properties of egg white. *J Biomed Sci Eng* 2(08): 617-620.
52. Monfort S, Ramos S, Meneses N, Knorr D, Raso J, et al. 2012. Design and evaluation of a high hydrostatic pressure combined process for pasteurization of liquid whole egg. *Innov Food Sci Emerg Technol* 14: 1. https://doi.org/10.1016/j.ifset.2012.01.004
53. Yan W, Qiao L, Gu X, Li J, Xu R, et al. 2010. Effect of high pressure treatment on the physicochemical and functional properties of egg yolk. *Eur Food Res Technol* 231: 371-377. https://doi.org/10.1007/s00217-010-1286-7

54. Morata A, Benito S, González MC, Palomero F, Tesfaye W, et al. 2012. Cold pasteurisation of red wines with high hydrostatic pressure to control Dekkera/Brettanomyces: effect on both aromatic and chromatic quality of wine. *Eur Food Res Technol* 235: 147-154. https://doi.org/10.1007/s00217-012-1742-7
55. Corrales M, Butz P, Tauscher B. 2008. Anthocyanin condensation reactions under high hydrostatic pressure. *Food Chem* 110(3): 627-635. https://doi.org/10.1016/j.foodchem.2008.02.055
56. Buzrul S, Alpas H, Bozoglu F. 2005. Effects of high hydrostatic pressure on shelf life of lager beer. *Eur Food Res Technol* 220: 615-618. https://doi.org/10.1007/s00217-004-1086-z
57. Chauvin MA, Swanson BG. 2011. Biochemical Aspects of High Pressure Food Processing. In Zhang HQ, Barbosa-Cánovas GV, Balasubramaniam VM, Dunne CP, Farkas DF, et al. (eds) Nonthermal Processing Technologies for Food. Blackwell Publishing, pp 72-88.
58. Calik H, Morrissey MT, Reno PW, An H. 2002. Effect of high-pressure processing on *Vibrio parahaemolyticus* strains in pure culture and Pacific oysters. *J Food Sci* 67(4): 1506-1510. https://doi.org/10.1111/j.1365-2621.2002.tb10313.x
59. Cook DW. 2003. Sensitivity of *Vibrio* species in phosphate-buffered saline and in oysters to high-pressure processing. *J Food Prot* 66(12): 2276-2282. https://doi.org/10.4315/0362-028X-66.12.2276
60. Cruz-Romero M, Smiddy M, Hill C, Kerry JP, Kelly AL. 2004. Effects of high pressure treatment on physicochemical characteristics of fresh oysters (*Crassostrea gigas*). *Innov Food Sci Emerg Technol* 5(2): 161-169. https://doi.org/10.1016/j.ifset.2004.01.002
61. Sun D-W. 2005. Thermal Food Processing: New Technologies and Quality Issues. CRC Press, Boca Raton.
62. The effect of pressure in the preservation of milk: a preliminary report.
63. Goyal A, Sharma V, Upadhyay N, Sihag M, Kaushik R. 2013. High pressure processing and its impact on milk proteins: a review. *J Dairy Sci Technol* 2(1): 2319-3409.
64. Erkmen O. 2011. Effects of high hydrostatic pressure on *Salmonella typhimurium* and aerobic bacteria in milk and fruit juices. *Rom Biotechnol Lett* 16(5): 6540-6547.
65. Bulut S. 2012. Survival of microorganisms in high pressure treated minced meat during chilled storage and at pH and temperature mimicking gastrointestinal tract. *Afr J Microbiol Res* 6(36): 6558-6564.
66. Torres Bello EF, González Martínez G, Klotz Ceberio BF, Rodrigo D, Martínez López A. 2014. High pressure treatment in foods. *Foods* 3(3): 476-490. https://doi.org/10.3390/foods3030476
67. Reineke K, Mathys A, Knorr D. 2011. The impact of high pressure and temperature on bacterial spores: inactivation mechanisms of *Bacillus subtilis* above 500 MPa. *J Food Sci* 76(3): M189-M197. https://doi.org/10.1111/j.1750-3841.2011.02066.x
68. Zhang H, Mittal GS. 2008. Effects of high-pressure processing (HPP) on bacterial spores: an overview. *Food Rev Int* 24(3): 330-351. https://doi.org/10.1080/87559120802089290
69. Muñoz-Cuevas M, Guevara L, Aznar A, Martínez A, Periago PM, et al. 2013. Characterisation of the resistance and the growth variability of *Listeria monocytogenes* after high hydrostatic pressure treatments. *Food Control* 29(2): 409-415. https://doi.org/10.1016/j.foodcont.2012.05.047
70. Bozoglu F, Alpas H, Kaletunç G. 2004. Injury recovery of foodborne pathogens in high hydrostatic pressure treated milk during storage. *FEMS Immunol Med Microbiol* 40(3): 243-247. https://doi.org/10.1016/S0928-8244(04)00002-1
71. Koseki S, Mizuno Y, Yamamoto K. 2008. Use of mild-heat treatment following high-pressure processing to prevent recovery of pressure-injured *Listeria monocytogenes* in milk. *Food Microbiol* 25(2): 288-293. https://doi.org/10.1016/j.fm.2007.10.009
72. Terefe NS, Buckow R, Versteeg C. 2014. Quality-related enzymes in fruit and vegetable products: effects of novel food processing technologies, part 1: high-pressure processing. *Crit Rev Food Sci Nutr* 54(1): 24-63. https://doi.org/10.1080/10408398.2011.566946
73. Roberts CM, Hoover DG. 1996. Sensitivity of *Bacillus coagulans* spores to combinations of high hydrostatic pressure, heat, acidity and nisin. *J Appl Bacteriol* 81(4): 363-368. https://doi.org/10.1111/j.1365-2672.1996.tb03520.x