**CHAPTER**

**High Pressure Processing – A Novel Technique for Food Preservation**

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**Abstract**

The increasing consumer’s interest in high quality food products with fresh sensory characteristics, free from chemical preservatives and minimal processing attracts the focus on the non-thermal processing of foods. This chapter describes the high-pressure processing (HPP), which is one of the promising non-thermal techniques for food preservation. This novel processing method has many advantages over traditional thermal processing. HPP eliminates food pathogens and spoilage microbes at ambient temperature and extends the shelf life of foods circulated through the cold chain. Food products processed with HP treatment preserves the organoleptic properties and nutritional content of foods. Many countries including USA and EU approved HPP as a non-thermal pasteurization technology that can replace conventional pasteurization in food industries. Clearly defined rules and regulations are needed in the field of HPP to improve product quality and built the consumer’s trust. HPP can be widely utilized in the production of fruits and vegetables products, meat products, marine products and dairy products. In spite of many advantages, HPP has also some limitations. The global market of HPP is gradually increasing every year. HPP technology can also be combined with existing food trends (such as organic food, health food, clean label food, functional food etc) to boost the development in the food sector.

**Introduction**

Food is a vital part of daily life for humans and essential for their survival. When the world's population was significantly lower and resources were abundant, the goal towards food processing was not quite as critical. But, as population increases, it is important to feed safe and nutritious food to whole population for their survival and metabolic activities. This is a great challenge for all of us. To overcome this challenge, food processing plays a crucial role (Islam et al., 2022). Food processing refers to the transformation of raw animal or plant products or ingredients into a variety of food products suitable for consumption (consumer ready products). The goal of food processing is to stabilise food items by avoiding or decreasing detrimental changes in quality. Food preservation refers to the various methods and techniques used to prevent or delay food spoilage, maintain the nutritional value, and extend the shelf life of food products. There are many preservation techniques that are widely employed in the food industry. These include physical methods (such as heating, drying, dehydration, canning, smoking, chilling, freezing, packaging etc.) and chemical methods (such as pickling, fermentation, reduction of pH, use of preservatives, etc.). These traditional preservation methods work on the principle of eliminating or reducing the microbial population to prevent unfavourable chemical changes in food. In food industry, thermal processing (such as blanching, pasteurization, sterilization etc.) is the most commonly used preservation techniques. Heat treatment of food products kills or reduces the level of microorganisms and extends its shelf life. At the same time, it may destroy the nutritional quality of food products and alters its natural taste and flavour. Now a days, the perception of consumers regarding processed food products also changed. Now, the consumers are focusing more attention to the nutritional content of food products along with its sensory attributes (such as taste, texture, flavour, aroma, shape, colour etc). They are demanding more minimally processed food products without any food additives. Hence, Food producers seek to establish or maintain the ideal sensory and nutritional attributes, minimise undesirable processing-related changes in food, and increase the shelf life of food items (Tao et al., 2014).

In order to produce safe, nutritious foods with a fresh taste without the use of heat or chemical preservatives, alternative or new food-processing methods are being investigated and deployed. Novel food preservation methods are innovative and attracted the attention of many researchers as well as food manufacturers. These novel and non-thermal food preservation techniques are High pressure processing (HPP), Pulse electric field (PEF), Cold plasma, Ionization radiation (Ozone based preservation), Gamma irradiation, Ultra-sonication, Nano-technology etc. This chapter focuses on the different aspects of high-pressure processing (HPP) of food products in brief. It includes history, operation of HP equipment, its parameters, basic principles, packaging specification, effects of HP on microorganisms and food quality, applications of HPP, its advantages and disadvantages, regulation related to HPP and its future scope.

**High Pressure Processing (HPP)**

High pressure processing is a novel and innovative non-thermal decontamination technique for preserving and preparing food products with improved functional and microbiological properties (Parekh et al.,2017). HPP uses pressure to create a pasteurisation effect and destroy dangerous pathogens and vegetative spoilage bacteria. Many foods are preserved using HPP, which applies strong pressure (upto 87000 psi or 6000 bar or 600 MPa) at low to moderate process temperatures (<45°C) (Muntean et al., 2016) for 1-15 min (Penchalaraju & Shireesha, 2013), with little or no effect on taste, flavour, texture, appearance, or nutritional content. Both, solid and liquid foods with high moisture content can be processed using HPP. HPP does not rupture covalent bonds and has a little impact on chemical composition of food. High pressure processing (HPP) is also known as high hydrostatic pressure processing (HHP) or ultra-high-pressure processing (UHP) or pascalization or cold pasteurization in literature (Muntean et al., 2016). It has been considered as a viable alternative to thermal treatments, in terms of assuring safety and minimising the impacts of processing on qualitative attributes. During HPP, if proper pressure is applied on food products, it maintains the quality of food without over-treated portions, as applied pressure is instantly and uniformly distributed throughout the sample (Tao et al., 2014).

Bacterial spores are highly resistant to commercially feasible pressure levels of HPP. Therefore, Low-acid shelf-stable food products cannot be processed by HP treatment alone. It requires an additional processing treatment to meet commercial sterility. High pressure processing of fish and fish products results in protein denaturation, inhibition of some inherent enzymatic activities and biogenic activity of microorganisms. It also accelerates the lipid oxidation in muscle tissues (Penchalaraju & Shireesha, 2013).

**History of HPP**

The first person to relate the effects of high pressure on organisms was Certes in 1883 (Elamin et al., 2015). After a long research, Bert Hite from the Agriculture Research Station in Morgantown, West Virginia, designed and developed a high-pressure (HP) machine to pasteurise milk and other food products in 1899 (Tao et al., 2014). In 1914, Hite began using high hydrostatic pressure (up to 600 MPa) to preserve milk, and later, fruits and vegetables (Elamin et al., 2015). However, high processing techniques was not used commercially by food industry for a long time due to its high cost of making, technical difficulties and inappropriate packaging. HPP is used to inactivate the pathogens and spoilage microorganisms at ambient temperature and reduce the enzymatic activity of foods, while maintaining the original food quality. It is also used to modify the food ingredients to develop new one with improved functionalities (Tao et al., 2014). The advancement of HP techniques throughout the 1970s and 1980s in the ceramics and metallurgical sectors has made it feasible to treat food using this technology on an industrial scale (Parekh et al.,2017). For the first time in 1993, the HPP was commercially used by Japanese food companies to stabilize the food product and introduced into the market. Now, high-capacity pressure systems are able to be manufactured to enable reliable HP treatment of food items at even greater pressure because of advancements in computational stress analysis and new materials. Till date, many HP-processed foods (such as Juices, beverages, vegetable products, dairy foods, jams, sauces, meat products, seafood, fish etc.) have been commercialized (Tao et al., 2014).

**HPP Equipment and its Operation**

A HP equipment is required for HPP of food products. The components of well-designed HP equipment should include a pressure vessel or chamber, closures to seal the chamber, a holding mechanism to hold the closures while processing, HP intensifier pumps, systems to monitor and control the pressure and temperature, a temperature control device, and a product-handling system to move product into and out of the pressure chamber (Fig. 1). Additionally, the pressure chamber and HP intensifier pumps are the primary components of the HP system. The working pressure is an essential parameter of any HP system. In it, Pressures ranging from 50 to 1000 MPa are often employed (Tao et al., 2014).



Figure 1 A standard high-pressure processing (batch process) system (Nabi et al., 2021)

There are two types of HPP devices namely, horizontal and vertical type. Most devices utilised in commercial applications are of the horizontal type to make it easier to load and unload containers on the manufacturing line (Huang et al., 2017).



Figure 2 A horizontal HPP manufacturing system (Huang et al., 2017)

After being packed and sealed in flexible pouches or in vacuum packs, the food sample is kept in a pressure chamber utilising water as a pressure-transfer medium (Nabi et al., 2021). Other food grade fluids (such as castor oil, silicon oil, ethanol, glycol and sodium benzoate) can also be used as pressure transmitting medium. Before loaded into the pressure vessel, food products must be packed in a flexible container in such a way that they can withstand a 10–20% decline in volume during pressurisation and a return to the original volume when the pressure is released, taking into account the reduction of volume during pressurisation and the corresponding expansion upon decompression (Tao et al., 2014). Pressure may be created by injecting more fluid into the pressure chamber. Pressure is instantly and uniformly distributed throughout the sample during HP treatment. The size of the pressure vessel used in HPP depends on its capacity to hold packed food product and pressurization fluid. The pressure vessel is designed to withstand a particular pressure and temperature. A pressure vessel may also be used to create a pressure intensifier.

The pressurisation systems used in HPP of food products are mainly classified into three categories, namely batch process, semi-continuous process and continuous process (Fig. 2). Most solid food items are processed using batch systems. whereas, liquids and other pumpable products are processed using continuous systems (Nabi et al., 2021). Batch type HPP systems are mostly used in food processing industries for solid and liquid foods. Semi-continuous systems may be suggested, if the product is pumpable (e.g., fruit juice) (Tao et al., 2014). The components of semi-continuous process systems include two or more pressure vessels, holding and sterile tanks, high-pressure transmission pumps, small pressure pumps to fill the vessels, and controlling valves. A free-moving separating piston is present in pressure vessels to separate the product from the pressurising fluid. Controlling valves guard against cross-contamination between the treated product and the incoming untreated product. Starting the process, a low-pressure pump fills the pressure vessel with the liquid product. Once the food compartment is full, the inlet valve is closed and pressurising fluid pushes the free piston to compress the liquid. After a proper holding period, the vessel is depressurized, which will decompress the food and bring back the piston to its initial position. The last step is aseptic packaging of the processed liquid product in sterile containers. Vessels are linked in such a way that when one vessel is filled with food sample, a second vessel is pressurised and the third vessel discharges its contents. As a result, continuous output of final product has been maintained. Generally, three pressure vessels HPP system is used at commercial scale to provide a continuous production of food products (Nabi et al., 2021). "Cycle time" refers to the total duration of time that is needed for pressurisation, holding, and depressurization. The performance of HPP system is determined by cycle time and loading factor (Tao et al., 2014). Cycle time is the sum of the times required for loading, vessel closure, compression, holding, decompression, and unloading. A pasteurisation process only takes 3 to 8 minutes to complete one production cycle (Elamin et al., 2015).

Figure 3 Different pressurization system used in HPP

**Parameters affecting HPP**

There are mainly three parameters, that affect the HP treatment process. These parameters are pressure (P), temperature (T) and exposure time (t). These parameters are inter-related to each other for successful HPP of food products (Fig. 3). During HPP, the pressure is raised to a certain point until it achieves the required pressure. The target pressure is held for a specific period of time before being released. The process pressure is the pressure at which the food sample is maintained in the pressure vessel. Whereas, the process temperature refers to the temperature at which the product acquires its process pressure. The process temperature is influenced by the starting temperature, the pressure-transmitting medium, and the heat compression parameters. The amount of time needed to raise the pressure from atmospheric pressure (approx. 0.1 MPa) to the required process pressure is known as pressure come-up time. However, the pressure come-up time is affected by the pump's horsepower and the intended process pressure. The period of time during which the product must be kept under process pressure is known as the pressure holding time. It is the time frame between the end of compression and the beginning of decompression.



Figure 4 Relation of pressure, temperature and time during HPP (Nabi et al., 2021)

For a commercial HP treatment that are also economically viable, generally a pressure holding time of 3 to 10 minutes is employed. The product's temperature rises after pressurisation as a result of molecular arrangements. As a result, a decompression period is required to bring the food sample back to air pressure (0.1 MPa). Additionally, the product temperature is decreased during depressurization (Nabi et al., 2021). After decompression, the final product temperature is slightly lower than its initial temperature due to the heat loss during compression (Tao et al., 2014). Most of the HP processes operate at 400-600 MPa pressure and low temperature. The water temperature of the product in the pressure vessel may rise by 3-6 °C for every 100 MPa increase in pressure, depending on the product's composition (Nabi et al., 2021). Using water as an example, at a starting temperature of 25 °C and a pressurisation rate of 100 MPa/s, its temperature rises by around 3 °C for every 100 MPa increase in pressure. Foods rich in water content and low in fat, such orange juice and skim milk, probably have similar compression heating values. Food products with considerable amounts of fat, such butter and cream, might experience higher temperature rise. HP treatment in conjunction with adiabatic heating may be applied in practical applications to quickly sterilize low-acid foods at high temperatures (Tao et al., 2014).

**HPP Principles**

Pressure is a fundamental thermodynamic variable, similar to heat. The effects of temperature and pressure together during HPP cannot be distinguished. This is because there is a corresponding pressure for every temperature. During HP treatment, volume and energy changes might result from thermal impacts. But the volume of the processed product is primarily influenced by pressure. The combined net effect during HPP may be synergistic, antagonistic, or additive. Using Gibb’s theory of free energy, it is mathematically possible to quantitatively connect the effects of pressure (P) and temperature (T). The equation of Gibb’s free energy (G) can be expressed as

G = H – TS,

Since, the enthalpy (H) can be mathematically written as

H = U + PV,

Where, S = entropy and U = internal energy.

By combining above two equation, Gibb’s free energy equation can be modified to

G = U + PV – TS,

It can be deduced in the form of

d (∆G) = dP. ∆V – dT. ∆S.

As a result, it is impossible to handle independently temperature and pressure dependent processes such as phase transitions or molecular reorientation (Balasubramaniam et al., 2015). There are three general scientific principles, that are directly related to high pressure processing. These theories, which include the Le Chatelier’s principle, Isostatic pressing rule, and Microscopic-ordering principle, describe how foods react to extreme pressure (Elamin et al., 2015).

Le Chatelier's principle states that when a system in equilibrium is disturbed, the system responds in a way that seeks to minimise the disturbance. It is applicable to all physical processes. In high pressure processing, HP dampens responses that involve a rise in volume while stimulating reactions that involve a reduction in volume. Pressure will accelerate any process (such as a phase transition, change in molecular configuration, or chemical reaction) that is accompanied by a reduction in volume (Tao et al., 2014). Due to pressure variations between the compressibility of air and water, the food cannot be restored its earlier size and shape after HPP unless it is completely elastic (Muntean et al., 2016).

Whereas, the isostatic rule states that if a sample is in direct contact with the pressure medium or hermetically sealed in a flexible packaging that transfers pressure, pressure is instantly and evenly distributed throughout the sample. Therefore, unlike thermal processing, the time required for pressure processing is independent of sample size and geometry (Tao et al., 2014). So, HP treatment-based processes can be successfully commercialized. Pressure treatment does not macroscopically damage non-porous foods with high moisture contents. Whereas, pressure treatment may alter the structure and shape of foods with air pockets (such as marshmallows), unless the food is completely elastic and composed of closed-cell foam that prevents air from escaping (Balasubramaniam et al., 2015). Also, food is not pulverised during HP treatment because of isostatic pressure (Muntean et al., 2016).

According to the "microscopic ordering principle," increasing pressure while maintaining a constant temperature causes the molecules of a material to become more systematically arranged (high degree of ordering). Therefore, pressure and temperature exert antagonistic forces on molecular structure (Elamin et al., 2015).

**Packaging Specifications for HPP**

Prior to HP processing in a batch system, food items must be packaged in a flexible container in order to account for potential volume decreases in the food inside the package as well as the collapse of the head space. The selection of packaging material for HPP depends on many factors such as material’s safety, potential development of compounds that affect the flavour and odour of food, strength and barrier properties of material etc (Tao et al., 2014). The volume, geometry and composition (polymer type, film thickness, sealing and barrier properties) of the packaging material are also vital to take into account for selecting packaging materials for HPP. Since, dissolved oxygen becomes more reactive at high pressure, the presence of headspace air, particularly oxygen, can have a negative impact on product quality at higher pressure-temperature conditions. Therefore, it would be preferable to vacuum-package the product or at least reduce the amount of headspace air in the containers (Balasubramaniam et al., 2015). Glass, metal and paper packaging can not be used in HPP because they can not tolerate high pressure and change in volume. The packing materials for HP treatment are often made of polymeric materials such as polyethylene terephthalate, polyethylene, polypropylene, ethylene vinyl alcohol copolymer, and their mixtures (Tao et al., 2014). The packaging materials are occasionally metalized by the deposition of a thin layer of aluminium (about 0.01 µm thick) or coated with extremely thin layers (a few nano-meters thick) of inorganic compounds such as aluminium oxide and silicon oxide to increase the barrier characteristics of the polymeric films. In general, the majority of synthetic materials used for food packaging can resist HP treatment without experiencing structural and functional modifications greater than 10% to 15% of their initial value (Mensitieri et al., 2013).

**Effect of HPP on microorganisms**

HP can be used as a cold pasteurisation method or in conjunction with thermal energy for pasteurisation to inactivate microorganisms. Generally, a moderate pressure (10–50 MPa) slows down the microbial growth and reproduction, whereas a greater pressure causes microbial inactivation. After pressurisation, a number of structural and morphological alterations may be seen within the cell, including the compression of gas vacuoles, the condensation of nucleoids, the separation of the cell membrane from the cell wall, and the aggregation of cellular proteins (Bajovic et al., 2012).

HP treatment denatures the bacterial protein, which directly affect the survival of microorganisms. If proper amount of pressure is applied, it lethally damages the bacterial cells, which cannot be recovered back. In this way, HPP eliminates the microbial population. But, commercial dose of HP is not effective against all type of microorganisms. Clostridium botulinum spores pose a special danger because they may develop and create the extremely strong paralytic neurological toxin in low acid foods. Since, bacterial spores are extremely resistant to HPP, So, other antimicrobial treatments are combined with high pressure processing to achieve a significant reduction in its population (Muntean et al., 2016). Bacterial spores in foods can be effectively removed by HP treatment (>800 MPa) at elevated temperatures (up to 90 °C) (Black et al., 2007).

The inactivation process for yeasts under pressure is similar to that for bacteria, in that both cell membrane permeability and cellular structure are altered (Black et al., 2007). Additionally, HP can have an impact on the mitochondria of yeast cells. The release of cytochrome C from mitochondria may result in cell death (Rivalain et al., 2010). In general, HP can have to be more destructive impacts on organisms with more structural complexity. As a result, Yeasts and Molds are relatively more susceptible to HPP than bacteria and can be inactivated using relatively low pressure (Black et al., 2007). Majority of yeast cells are eliminated within few minutes by HP treatment (300-400 MPa) at room temperature (Daryaei et al., 2008). Most of the Molds are inactivated using pressure treatment of 300-600 MPa (Tao et al., 2014). However, treatment at higher pressure could be necessary for inactivation of yeast and mould ascospores (Muntean et al., 2016). Practically speaking, it has been discovered that ascospores of heat-resistant Molds can be inactivated by a combination of pressure more than 600 MPa and temperature greater than 60 °C (Chapman et al., 2007).

Viruses exhibit a broad range of sensitivity, when exposed to high pressure (Muntean et al., 2016). It is yet unclear how HP inactivates viruses. It has been hypothesised that HP can denature viral capsid proteins, inhibit viruses from attaching to their host cell's receptors, and subsequently stop virus infection (Tao et al., 2014). The temperature and salinity of the food environment can have an impact on the removal of viruses by HP. A greater than 1% NaCl concentration can have a baro-protective effect for hepatitis A virus (HAV), whereas low temperatures can encourage the inactivation of viruses by HP (Kovač et al., 2010).

The chemical composition of the food products and the type of microorganisms are two factors affecting how effectively the HPP treatment works against the microbes (Muntean et al., 2016). Generally, gram positive bacteria are more pressure resistant than gram negative bacteria, due to structural differences in the cell envelope (Pilavtepe‐Çelik et al., 2008). Critical processing parameters for HPP of food products include initial temperature of product, pH of product, water activity of product, initial temperature of pressurization fluid, target pressure, come up time, pressure holding time and decompression time (Muntean et al., 2016).

**Effect of HPP on food quality**

High pressure processing is a novel technology that minimally alters the organoleptic characteristics of food products; hence, the product maintains its original quality and remains nutritious, fresh and safe. Fruits and vegetables-based products contain natural pigments such as anthocyanins, carotenoids, and chlorophyll etc. Moderate HP treatment has no impact on the colour characteristics of fruit and vegetable-based products. However, HP can have an impact on pigment stability at high temperatures and/or high pressure (Tao et al., 2014). The chlorophyll in broccoli juice was degraded when the temperature was increased to 50 °C while under pressure. Additionally, a rise in pressure could accelerate the deterioration of chlorophyll present in broccoli (Oey et al., 2008).

The colour qualities of meat and meat products, particularly fresh red meat, are more significantly impacted by HP. The optical characteristics of the meat surface and the myoglobin concentration in the muscle determine the colour of meat, although the presence of nitrosyl-myoglobin, which results from the interaction of myoglobin and nitric oxide, is principally responsible for the colour of cured meat (Bajovic et al., 2012). In fresh meat, HP can cause significant chromatic changes, such as an increase in lightness (L\*) and a reduction in redness (a\*) in minced beef and Caiman tail meat, which results in a loss of red colour (Bajovic et al., 2012; Canto et al., 2012). Consumer acceptability is impacted when a usual red colour of meat is lost. But if meats are further processed into other meat products, the adverse effect of HP on the colour of fresh meat can be neglected (Bajovic et al., 2012).

HP treatment also affects the rheological or textural properties of food products. The physical structure of the majority of high-moisture food products is unaffected by exposure to HP, due to the absence of shear forces caused by pressure. Gas-containing materials treated with HP may see changes in colour and texture due to gas displacement and liquid penetration. Shape distortion may be connected to anisotropic behaviour, and physical shrinkage may result from the mechanical collapse of air pockets. Typically, HP causes little to no lasting alteration in the textural properties of foods without air spaces.

Sensory analysis is the simplest method for assessing the quality and consumer acceptance of food products. HP can still have a small impact on the sensory quality of food. Foods treated with HP may have different sensory qualities, and this is due to the physical and chemical changes caused by HP treatment (Tao et al., 2014). HP-treated tomato juice and strawberry jam were discovered to have unfavourable sensory qualities, such as the presence of rancid flavour (Oey et al., 2008). After being pressed at 800 MPa, the fresh tomato flavour of cherry tomato puree was observed to diminish (Viljanen et al., 2011). HP can trigger lipid oxidation in meat and meat products and leads to the development of off-flavour and rancidity (Ma & Ledward., 2013).

Additionally, HP treatment was shown to favour the production of hydrogen sulphide, which might harm the aromatic qualities of milk (Vazquez-Landavrde et al., 2006). By using the right processing conditions, the detrimental impact of HP on food sensory attributes may be reduced. A red wine's in-mouth flavours, such as sour, bitter, and astringent ones, were improved by HP processing at 600 MPa, but no statistically significant difference in overall quality was discovered between wines that had been HP processed and those that hadn't (Tao et al., 2012).

**Application of HPP**

HP treatment has been extensively used in the processing of meat, marine, dairy, fruit, vegetable and varying beverage products. Among all HPP products, ready to eat HPP meat products such as burger patties, ham, bacon represent the largest application followed by HPP juices including coconut water. HP treatment eliminates bacteria from packaged food and can be utilised in this role as one of the antibacterial components of hurdle technology, along with other processing technologies, keeping the original procedure intact (Huang et al., 2017).

The USDA Food Safety and Inspection Service approved HPP technology as an authorised method for eliminating Listeria monocytogenes in processed meat (Simonin et al., 2012). Additionally, HPP enhances the enzyme activity (such as protease), speeds up the ageing process and tenderization of meat products, and gives meat products specific flavours and softness, making them easier to digest for consumers. The bactericidal properties of high pressure for cured meat products minimise the saltiness of the product and the inclusion of antibacterial agents, resulting in more healthy meat products that comply with Clean Label regulations (Verma & Banerjee, 2012).

HPP eliminates the pathogens and spoilage microorganisms and increases the shelf life of product. It also minimally affects the nutrients present in food products and hence, the products remain fresh and natural in their organoleptic properties and nutritional value. HP processed fruits and vegetables products such as juices, fresh-cut pieces, fruit jam, purees etc are natural, fresh and safe and widely accepted by consumers. HP treatment extends its shelf life by more than 3-fold (Huang et al., 2017). HPP inhibits the growth of microorganisms while reducing the polyphenol oxidase activity to prevent enzymatic browning. Under commercially viable conditions, enzymes such as polyphenol oxidase (PPO), peroxidase (POD), and pectin methylesterase (PME) are extremely resistant to HPP and only partially inactivated, while their sensitivity to pressure varies depending on their environment and place of origin. On the other hand, lipoxygenase (LOX) and polygalacturonase (PG) are somewhat more pressure sensitive enzyme and can be significantly inactivated by HPP under commercially feasible conditions (Terefe et al., 2014). The pre-treatment stage of food processing may be carried out using HPP technology. High pressure physically damages the plant cells, making possible the easy extraction of interior nutritious components. Physical injury increases the mass transfer rate and facilitates the release of extracts by making cells more permeable to solvents. Additionally, high pressure processing is used at room temperature, which minimises the destruction of thermally sensitive components and boosts the effectiveness of extraction (Huang et al., 2017).

**Regulations for HPP**

The USFDA has authorised HPP as a non-thermal pasteurisation technique that can take the place of conventional pasteurisation in the food business. Escherichia coli O157:H7 strains have been shown to have the highest level of pressure resistance when compared to other vegetative food-borne pathogens. According to USDA specifications, E. coli O157:H7 is the indicator strain for reprocessing. HPP process that achieves a 5-log E. coli O157:H7 reduction should be adequate for processed food products to assure microbiological safety (USDA, 2012). In 2009, the Food and Drug Administration (FDA) approved HPP for the manufacturing of low-acid foods and several food processing industries in the USA. This method is already being used in Japan and parts of Europe to prepare various foods. HPP is recognised as a novel technology in Europe and is governed by the Novel Food Regulation. High pressure processing is a relatively emerging industry in India (Parekh et al.,2017).

Generally speaking, it is important to prepare HP-pasteurized food items in accordance with good manufacturing practise (GMP) guidelines and other industry-specific laws, such as those governing juice and seafood and hazard analysis and critical control points (HACCP). Furthermore, the Pressure Equipment Directive (PED) rule, which came into force in 2002, must be complied with by all new pressure vessels used in the European Union (EU). This law expands upon the CE safety standard, which is already in use in the EU and is now accepted globally. Pressure vessels of all kinds use energy that might be harmful, therefore the PED regulation aims to identify appropriate design, GMPs, and thorough safety evaluations for the safe operation and maintenance of the pressure vessels and its auxiliary parts (Tao et al., 2014).

**Advantages and Limitations of HPP**

Some of the advantages of HPP are listed below (Parekh et al.,2017; Muntean et al., 2016; Penchalaraju & Shireesha, 2013; Naveena & Nagaraju, 2020; Nabi et al., 2021):

* Inactivation of pathogenic and spoilage microorganisms at high pressure
* Shorten the processing time
* Preserve the natural taste, texture, flavour, aroma, colour and nutritional composition of food
* Potential for reducing or eliminating the use of thermal treatment and chemical preservative
* HP treatment does not depend on the size, shape and geometry of the product
* Uniform distribution of HP treatment throughout the sample
* No evidence of toxicity
* Positive feedback of consumer regarding HP processed food product
* Extend shelf-life
* Potential for design of new food products with improved properties
* Increases extraction yield
* Decreases food waste
* Clean, novel and non-thermal technology
* Enhance food safety, minimal processing and novel market opportunities
* Improved supply chain operation
* possibilities of in-package processing
* HPP is environment friendly
* Utilized in different food categories (e.g., fruits, vegetables, dairy, meat, seafoods, jams, fruits jellies, sauces, purees, juices, salads, infant foods etc) for different purposes

Some of the limitations of using HPP are pointed below (Parekh et al.,2017; Muntean et al., 2016; Penchalaraju & Shireesha, 2013; Naveena & Nagaraju, 2020; Huang et al., 2017):

* Bacterial spores are extremely resistant to commercially attainable pressure levels
* Costly equipment
* For HPP, foods should have high moisture content (40% free water) for anti-microbial effect
* Batch processing
* Restricted options for packaging of HP treated foods
* Minimal effect on some food enzyme activity due to its high-pressure resistant nature
* Foods with fragile structures need extra care
* Most of the HP treated foods require low temperature for storage and distribution to retain their sensory and nutritional qualities
* HP treatment may change the structure and shape of porous foods, which are not elastic in nature
* Majority of HPP products must be stored and transported in refrigerated conditions because pressure treatment at ambient or chilled temperatures has been effective for more than 5-logs reduction of vegetative pathogens.
* Low-acid HPP products might have potential microbial risks associated with survival of Clostridium spores.
* HPP is not suitable for many food products such as flour or powdery food items having low moisture content and foods containing large number of air bubbles because HPP uses water as a pressure transfer medium and items with air bubbles could deform while under pressure.
* Only plastic packaging materials are acceptable for HPP since the packaging material used in HPP needs to have a compressibility of at least 15%.
* Some regulatory issues

**Future scope of HPP**

The global market for high-pressure processed (HPP) foods is forecasted to grow at a CAGR of 8.60% from 2023 to 2028. The market is projected to be driven by customers' rising demand for ready-to-eat, wholesome, minimally processed foods that taste and smell like fresh food and have a longer shelf life. The other major drivers of the market include the urbanisation, changing lifestyles, growing disposable income, and increase in online food ordering. After a standard high-pressure processing (HPP) operation, most vegetative bacteria counts are often decreased by up to 4 log units or more, and many enzymes are inactivated with just a little alteration in the food's organoleptic qualities. However, bacterial and other microorganism resistance to high-pressure processing (HPP) varies greatly. For instance, some gramme positive bacteria, like Listeria monocytogenes, may exhibit greater resistance than gramme negative bacteria, like Salmonella. Foods, containing high water content, are thought to be suitable for HPP. The HPP industry is primarily based in North America, Latin America, the Middle East and Africa, Europe, and Asia Pacific (*Global High-pressure Processing (HPP) Foods Market Report and Forecast 2023-2028*, n.d.).

Clean label foods are slowly becoming more and more popular. If a food product is made from simple ingredients with minimal processing and free from any chemical additives, it is regarded as a clean label food. Recently, an increasing number of global food manufacturers have taken an interest in clean label food products. High pressure processing, which uses no chemicals while preserving the necessary food quality and microbiological safety, is a key technique for the production of Clean Label products. High pressure processing, which is a new hurdle technology, reduces the potential risk of microorganisms contaminating food and lowers the need of extra additives. Furthermore, it prolongs the shelf life and maintain the natural colour, flavour and taste of food.

The advancement of the food business can be aided by combining HPP technology with current developments in the industry. Future developments in the field of HPP include high-quality organic food raw materials, fresh local foods with low food miles, and functional health foods. HPP Process conditions that are precisely defined will guarantee microbiological safety, product quality, and compliance to legal and regulatory requirements for food hygienic safety. A healthy HP processed food market will be facilitated by well-defined rules, regulations and standards, which will increase product quality, production efficiency, and consumer trust. In the future, HPP will play a significant pre-treatment role in the research and development of healthcare-related components in order to enhance the manufacturing efficiency of functional components in the food and pharmaceutical sectors (Huang et al., 2017).

**Conclusion**

Food processing sector is closely related to the health of consumers. Since, consumers’s perception changes regarding consumption of food products, they are demanding healthier food with minimal processing and natural taste, texture, flavour, aroma and nutritional value. To meet their demand, high pressure processing (HPP) emerges as a novel technology that can replace the conventional thermal processing to some extent. HPP provides food manufacturers with the chance to create new foods that have a longer shelf life while still maintaining their organoleptic qualities and nutritional characteristics. This non-thermal technology meets the consumer demand for safe and wholesome, free from food additives. HPP has several advantages over conventional heat treatment in terms of ensuring food safety and quality. However, there are still some limitations of using HP treatment that has to be reduced in the future by doing research and development in this field.

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