HIGH PRESSURE PROCESSING – A NOVEL TECHNIQUE FOR FOOD PRESERVATION

Abstract

Non-thermal techniques of food processing have gained attention due to the growing customer demand for high-quality food items with fresh sensory qualities, free of chemical preservatives, and minimal processing. We explore high-pressure processing (HPP), a promising non-thermal method for food preservation, in this chapter. HPP is superior to conventional thermal processing in a number of ways. By successfully eradicating Foodborne viruses and rotting bacteria at room temperature are prolonged, hence increasing the shelf life of cold chain foods. Foods that have been HPP-treated maintain both their nutritional content and sensory qualities. A number of international regulatory bodies, such as those in the USA and the EU, have certified HPP as a non-thermal pasteurization technology that can take the place of traditional techniques in the food business. Well-defined rules and regulations are necessary in the field of HPP to guarantee product quality and client confidence. Products such as fruits, vegetables, meat, fish, and dairy products can all be affected by HPP. Even though HPP has several drawbacks, the market for HPP is growing annually on a global scale. To propel innovations in the food industry, this technology can work in concert with popular food trends including organic, health-conscious, clean label, and functional foods.

Keywords: A Novel Technique, consumer preferences evolve

Authors

Nirbhay Kumar
Research Scholar
Department of Food Engineering and Technology
Sant Longowal Institute of Engineering and Technology (SLIET)
Longowal, Punjab, India.
nirbhaynir000@gmail.com

Smita Dimri
Guest Faculty
Department of Food Engineering and Technology
Sant Longowal Institute of Engineering and Technology (SLIET)
Longowal, Punjab, India.
gairolasmita@gmail.com

Sukhcharn Singh
Professor
Department of Food Engineering and Technology
Sant Longowal Institute of Engineering and Technology (SLIET)
Longowal, Punjab, India.
sukhcharn@sliet.ac.in

I. INTRODUCTION

Food constitutes a fundamental aspect of human life, being indispensable for our survival and metabolic functions. In earlier times, when the global population was smaller, and resources were abundant, the significance of food processing was less pronounced. However, with the steady rise in population, the imperative to provide safe and nutritious sustenance to everyone has grown considerably. This presents a substantial challenge that we must collectively address. Food processing emerges as a pivotal player in surmounting this challenge (Islam et al., 2022).

Food processing involves the conversion of raw materials, be they of plant or animal origin, into a diverse array of food products ready for consumption by consumers. Its primary objective is to stabilize food items by mitigating or preventing detrimental alterations in their quality. Contrarily, food preservation refers to a variety of methods and approaches used to prevent or postpone food spoilage, preserve nutritional value, and increase the shelf life of food items. The food industry employs numerous preservation approaches, including both physical methods (such as heating, drying, dehydration, canning, smoking, chilling, freezing, packaging, etc.) and chemical methods (such as pickling, fermentation, pH reduction, preservative usage, etc.). These traditional preservation methods operate on the principle of eradicating or diminishing the microbial population to forestall unfavourable chemical changes in food.

Thermal processing, which includes techniques like blanching, pasteurization, and sterilization, remains the predominant preservation method utilized in the food industry. This approach entails subjecting food products to heat treatment, which effectively reduces or eliminates microorganisms and extends the product's shelf life. However, it has the potential to impact the nutritional quality of the food and modify its inherent taste and flavour. Modern consumers are undergoing a perceptual shift concerning processed food items. They are becoming increasingly concerned with the nutritional content of food products, along with their sensory characteristics, which encompass taste, texture, flavour, aroma, shape, colour, and more. As a result, there is a growing demand for minimally processed food products without additives. As a result, food producers work to reduce unintended processing-related changes, maintain or create the ideal sensory and nutritional qualities, and extend the shelf life of their goods (Tao et al., 2014).

In order to produce fresh, healthy foods without the use of heat or chemical preservatives, food manufacturers and researchers are investigating and implementing novel or alternative approaches to food processing. The food industry and scientific community have shown a great deal of interest in these innovative non-thermal food preservation methods, which include High Pressure Processing (HPP), Pulse Electric Field (PEF), Cold Plasma, Ionization Radiation (Ozone-based preservation), Gamma Irradiation, Ultrasound, and Nanotechnology.

This chapter specifically delves into the various aspects of High-Pressure Processing (HPP) for food products. It covers a range of topics, including the historical context, the operation of HPP equipment, key parameters, fundamental principles, packaging specifications, the impact of HPP on microorganisms and food quality, applications of HPP, its advantages and disadvantages, regulatory considerations related to HPP, and the potential future developments in this field

II. HIGH PRESSURE PROCESSING (HPP)

High-Pressure Processing (HPP) represents an innovative and groundbreaking non-thermal technique used for preserving and preparing food products, resulting in improved functional and microbiological qualities (Parekh et al., 2017). HPP employs pressure to create a pasteurization effect, effectively eradicating harmful pathogens and vegetative spoilage bacteria. This method is applicable to the preservation of a wide range of foods, subjecting them to significant pressure levels, reaching up to 87,000 psi or 6,000 bar or 600 MPa, while maintaining relatively low to moderate process temperatures, typically below 45°C (Muntean et al., 2016). The processing duration typically falls within the range of 1 to 15 minutes (Penchalaraju & Shireesha, 2013). Remarkably, HPP leaves the taste, flavour, texture, appearance, and nutritional content of food products largely unchanged. It is effective for both solid and liquid foods with high moisture content. Importantly, HPP avoids breaking covalent bonds and exerts minimal influence on the chemical composition of food.

High-Pressure Processing (HPP) is also known as Cold Pasteurization, Pascalization, High Hydrostatic Pressure Processing (HHP), and Ultra-High-Pressure Processing (UHP) in the literature (Muntean et al., 2016). It is acknowledged as a strong substitute for heat treatments, guaranteeing food safety while reducing the negative effects of processing on the nutritional qualities of food. During the HPP procedure, as appropriate pressure is applied to food products, it preserves food quality by ensuring that no sections are excessively treated, thanks to the uniform and instantaneous distribution of applied pressure across the entire sample (Tao et al., 2014).

Bacterial spores display remarkable resistance to the pressure levels attainable through commercially viable High-Pressure Processing (HPP). Consequently, low-acid shelf-stable food products require additional processing to achieve commercial sterility, as HPP alone is inadequate. When it comes to the high-pressure processing of fish and fish products, multiple effects come into play. These effects encompass protein denaturation, the inhibition of specific intrinsic enzymatic activities, and the suppression of microorganism biogenic activity. Additionally, it accelerates the oxidation of lipids within muscle tissues (Penchalaraju & Shireesha, 2013).

III. HISTORY OF HPP

Beginning with Certes in 1883, researchers have been examining how high pressure affects living things (Elamin et al., 2015). Bert Hite, however, at the Agriculture Research Station in Morgantown, West Virginia, did not envision and create a high-pressure (HP) device for pasteurizing milk and other food items until after a thorough examination in 1899 (Tao et al., 2014). In 1914, Hite broadened the application of high hydrostatic pressure—600 MPa—to encompass the preservation of fruits and vegetables. Hite had first introduced this technique for milk. (Elamin et al., 2015). Still, because of their high production costs, intricate technical requirements, and inappropriate packaging, these high-pressure methods were not extensively used by the food sector for a considerable amount of time.

HPP serves the dual purpose of inactivating pathogens and spoilage microorganisms at room temperature while also reducing the enzymatic activity of foods, thereby preserving the original food quality and transforming food components to create new ones with improved functionalities (Tao et al., 2014). It was during the 1970s and 1980s, with advancements in the ceramics and metallurgical industries, that high-pressure (HP) techniques became feasible for large-scale food treatment (Parekh et al., 2017). Japanese food companies were pioneers in the commercial use of HPP in 1993 to stabilize food products and introduce them to the market. These days, advances in computational stress analysis and novel materials enable the production of high-capacity pressure systems that enable the reliable HP treatment of food items at even greater pressures. There are currently many different types of HP-processed foods available on the market, including as drinks, juices, vegetable goods, dairy products, jams, sauces, meat products, shellfish, and fish (Tao et al., 2014).

IV. HPP EQUIPMENT AND ITS OPERATION

High-pressure (HP) equipment plays a crucial role in the high-pressure processing (HPP) of food products. A properly designed HP apparatus should consist of various essential components. These parts consist of a temperature control unit, an HP intensifier pump, a pressure vessel or chamber, strong sealing mechanisms to safely enclose the chamber, a mechanism to hold the closures in place while processing, and a product-handling system to efficiently transfer products into and out of the pressure chamber (as shown in Figure 1).

The HP system relies heavily on the HP intensifier pumps and pressure chamber among other components. The working pressure is a crucial component of any HP system, and typical pressure ranges are between 50 and 1000 MPa (Tao et al., 2014).

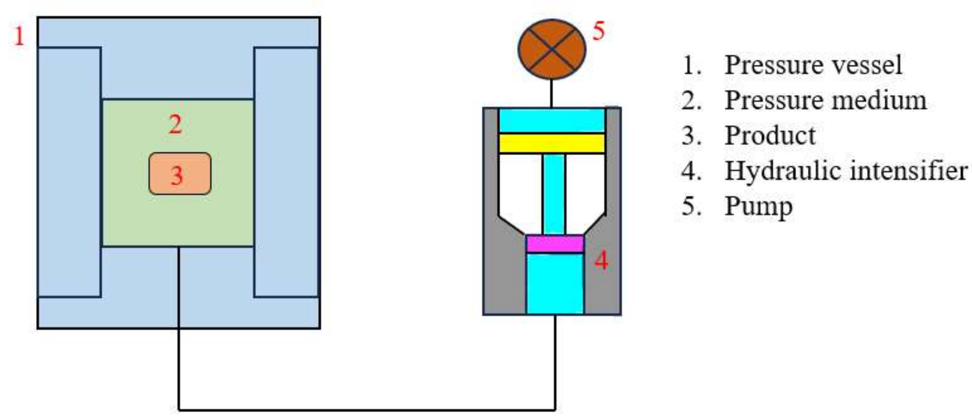

Figure 1: A standard High-Pressure Processing (Batch Process) System (Nabi et al., 2021)

HPP devices come in two varieties: horizontal and vertical. To facilitate the loading and unloading of containers on the manufacturing line, the majority of devices used in commercial applications are horizontal in design (Huang et al., 2017).

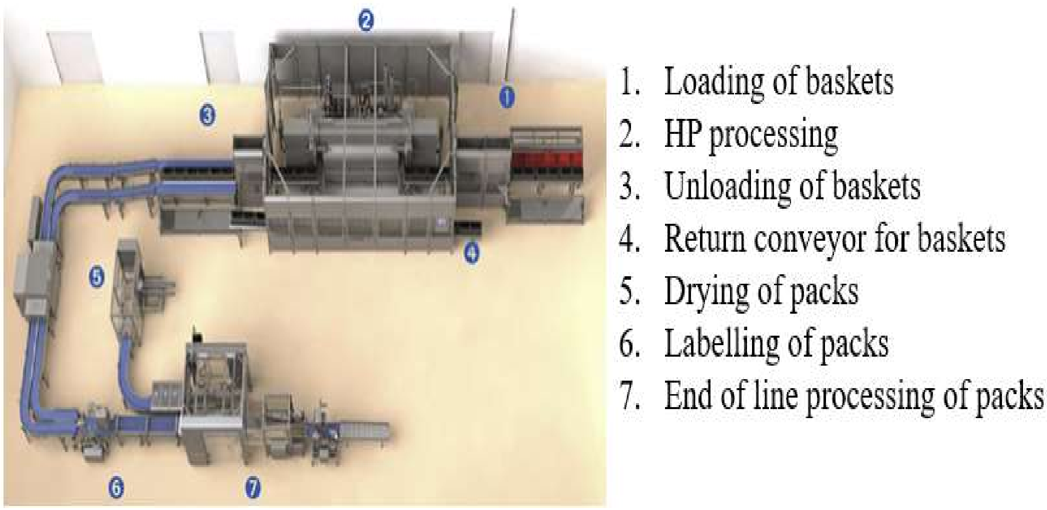

Figure 2: A horizontal HPP Manufacturing System (Huang et al., 2017)

After the food sample is packaged and sealed, typically in flexible pouches or vacuum packs, it is placed inside a pressure chamber where water is commonly used as the primary pressure-transfer medium, as emphasized by Nabi et al. (2021). It is noteworthy to add that other food-grade liquids that can serve as pressure-transmitting media include silicone oil, castor oil, ethanol, glycol, and sodium benzoate.

Prior to being placed into the pressure vessel, it is essential to pack food products meticulously within a flexible container that can withstand a 10–20% reduction in volume during pressurization. This volume reduction accounts for the subsequent expansion upon decompression, guaranteeing a return to the initial volume (Tao et al., 2014). The pressure inside the chamber can be generated by introducing additional fluid.

During high-pressure processing (HPP), pressure is rapidly and uniformly distributed throughout the sample. The selection of the pressure vessel's size hinges on its capacity to accommodate the packed food product and the pressurization fluid. Additionally, pressure vessels are meticulously designed to withstand specific pressure and temperature conditions. It's important to note that a pressure vessel can also be employed 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. 3). Most solid food items are processed using batch systems. whereas, liquids and other pumpable products are processed using continuous systems (Nabi et al., 2021). In the food processing industry, batch-type high-pressure processing (HPP) systems are predominantly employed for both solid and liquid food items. However, if the product is pumpable, as is the case with fruit juice, semi-continuous systems can be a viable alternative (Tao et al., 2014).

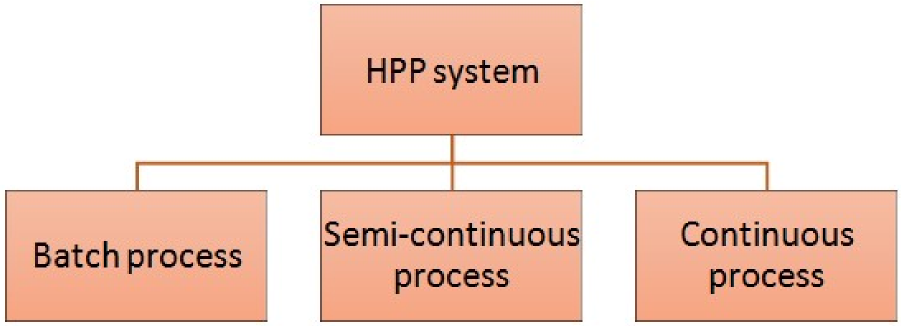

Figure 3: Different Pressurization System Used in HPP

Semi-continuous process systems consist of several key components, including two or more pressure vessels, holding and sterile tanks, high-pressure transmission pumps, small pressure pumps used to fill the vessels, and control valves. A freely moving separating piston in these pressure containers efficiently separates the product from the pressurizing fluid. In order to avoid any cross-contamination between the treated product and the incoming untreated product, control valves are essential. The process begins with a low-pressure pump filling the pressure vessel with the liquid product. Once the food compartment reaches capacity, the inlet valve is sealed, and pressurizing fluid is introduced to compress the liquid. Following an appropriate holding period, the vessel is depressurized, which leads to the decompression of the food, allowing the piston to return to its initial position. The final step involves aseptically packaging the processed liquid product in sterile containers.

These vessels are interconnected in such a way that as one vessel is filled with a food sample, another vessel is pressurized, and a third vessel discharges its contents. This setup ensures the continuous production of the final product.

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).

V. PARAMETERS AFFECTING HPP

Three primary parameters impact the High-Pressure Processing (HPP) treatment process: pressure (P), temperature (T), and exposure time (t). To guarantee the successful HPP of food goods, these criteria are interrelated (see Fig. 4). Pressure is progressively raised during HPP until the necessary pressure level is reached. Next, the pressure is kept at the desired level for a predetermined amount of time before being released. The pressure at which the food sample is maintained inside the pressure vessel is known as the process pressure. On the other hand, the temperature at which the product reaches its process pressure is referred to as the process temperature. The heat compression parameters, the pressure-transmitting medium, and the starting temperature all have an impact on the process temperature.

The pressure come-up time is the amount of time needed to raise the pressure from ambient pressure (about 0.1 MPa) to the specified process pressure. However, the horsepower of the pump and the desired process pressure can affect the pressure come-up time. The pressure holding time is the amount of time that the product must be kept under process pressure. This is the amount of time that passes between the end of compression and the beginning of decompression.

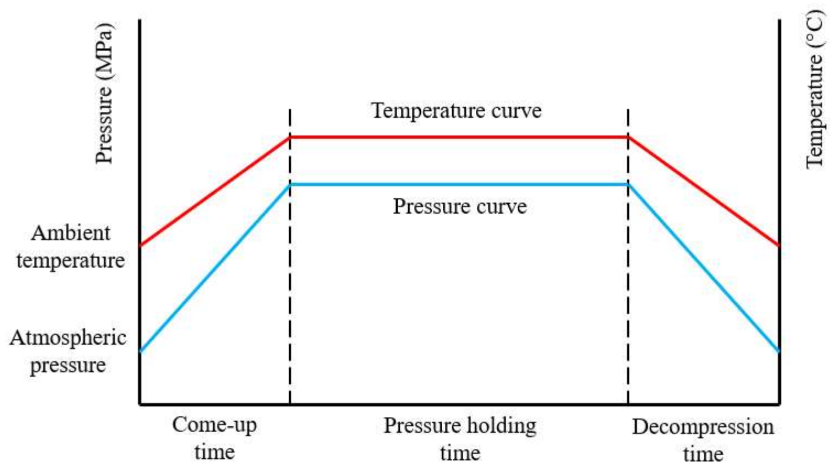

Figure 4: Relation of Pressure, Temperature and Time during HPP (Nabi et al., 2021)

For economically viable commercial high-pressure (HP) treatments, a pressure holding period ranging from 3 to 10 minutes is commonly employed. After pressurization, the temperature of the product rises due to molecular changes. As a result, a decompression phase is essential to restore the food sample to normal atmospheric pressure (0.1 MPa). Additionally, during the depressurization process, there is a decrease in the product's temperature (Nabi et al., 2021).

Following decompression, the final product's temperature is slightly lower than its initial temperature due to heat loss experienced during compression (Tao et al., 2014). The majority of HP processes are conducted within the pressure range of 400-600 MPa and at low temperatures. The product's composition determines how much the water temperature in the pressure vessel rises, usually by 3 to 6 °C for every 100 MPa increase in pressure (Nabi et al., 2021). As an example, water that is initially 25 °C in temperature will grow in temperature by about 3 °C for every 100 MPa of pressure that is added. This pressure is applied at a rate of 100 MPa/s. Orange juice and skim milk are two examples of low-fat, high-water food products that might undergo comparable compression heating. However, food items rich in fat, like butter and cream, may undergo more significant temperature increases. In practical applications, HP treatment, in combination with adiabatic heating, can be employed to swiftly sterilize low-acid foods at elevated temperatures (Tao et al., 2014).

VI. HPP PRINCIPLES

Pressure is a fundamental thermodynamic parameter, much like heat. When it comes to High-Pressure Processing (HPP), the effects of temperature and pressure are intertwined and cannot be separated. This is due to the fact that for every temperature, there exists a corresponding pressure. During HP treatment, changes in volume and energy may arise as a result of thermal influences. However, it is the pressure that primarily influences the volume of the processed product. The overall impact during HPP treatment can be either synergistic, antagonistic, or additive in nature. The effects of pressure (P) and temperature (T) can be quantitatively shown theoretically by utilizing Gibbs' theory of free energy. The Gibbs' free energy (G) equation looks like this:

(Gibbs' equation formula here)

This allows for a comprehensive understanding of the interplay between pressure and temperature during HPP.

$$G = H - TS,$$

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

$$H = U + PV,$$

Where, S = entropy and U = internal energy.

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

$$G = U + PV - TS,$$

It can be deduced in the form of

$$d\,(\Delta G) = dP.\ \Delta V - dT.\ \Delta S.$$

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, a fundamental concept, asserts that when an equilibrium system is disturbed, it responds in a manner to minimize the disturbance. This principle applies universally to all physical processes. In the context of high-pressure processing (HPP), pressure mitigates responses that result in an increase in volume while enhancing reactions that lead to a decrease in volume. Pressure can expedite various processes, such as phase transitions, alterations in molecular configurations, or chemical reactions, provided they are associated with a reduction in volume (Tao et al., 2014).

Due to differences in compressibility between air and water, food products subjected to HPP cannot regain their original size and shape unless they possess full elasticity (Muntean et al., 2016).

On the other hand, the isostatic principle dictates that when a sample is either in direct contact with the pressure medium or is securely sealed within a flexible package capable of transmitting pressure, the pressure is uniformly and instantly distributed throughout the entire sample. Consequently, unlike thermal processing, the time required for pressure processing remains unchanged regardless of the size and shape of the sample (Tao et al., 2014). This characteristic is instrumental in facilitating the successful commercialization of processes based on high-pressure treatment. Foods that are non-porous and possess high moisture content do not undergo significant macroscopic changes due to pressure treatment. However, food items containing air pockets, such as marshmallows, may experience structural alterations unless they exhibit complete elasticity and are made of closed-cell foam, preventing the escape of air (Balasubramaniam et al., 2015). Importantly, high-pressure treatment does not pulverize food items due to the application of isostatic pressure (Muntean et al., 2016).

In accordance with the "microscopic ordering principle," elevating pressure while keeping temperature constant leads to a more organized arrangement of a material's molecules, resulting in a high degree of molecular ordering. Consequently, pressure and temperature exert opposing influences on molecular structure (Elamin et al., 2015).

VII. PACKAGING SPECIFICATIONS FOR HPP

Before subjecting food items to high-pressure (HP) processing in a batch system, they must be securely packaged and the collapse of headspace. The choice of packaging material for HP processing involves various considerations, including the material's safety, the potential for compounds that could affect the flavour and odour of the food, as well as the material's strength and barrier properties (Tao et al., 2014).

Furthermore, the volume, form, and composition of the packing material must be carefully considered when selecting materials for High-Pressure (HP) processing. Numerous factors are important, including the type of polymer, barrier qualities, sealing integrity, and film thickness. It is important to remember that under high pressure, dissolved oxygen becomes more reactive, especially when headspace air, especially oxygen, is present. This reactivity can have adverse effects on product quality under conditions of increased pressure and temperature. Therefore, it is advisable to either vacuum-package the product or, at the very least, minimize the presence of headspace air within the containers (Balasubramaniam et al., 2015).

Because they cannot tolerate the extreme pressure and volume fluctuations necessary in high-pressure (HP) processing, materials including glass, metal, and paper packaging are not appropriate. Rather, polymeric materials such polyethylene terephthalate, polyethylene, polypropylene, ethylene vinyl alcohol copolymer, and their mixtures make up the majority of packaging materials frequently used for HP treatment (Tao et al., 2014). These packaging materials may occasionally be metallized with a thin layer of aluminium, usually approximately 0.01 µm thick, or they may be coated with incredibly thin layers of inorganic substances, such as silicon oxide and aluminium oxide, usually a few nano-meters thick. The purpose of these treatments is to improve the polymeric films' barrier qualities. According to Mensitieri et al. (2013), most synthetic materials used in food packaging can withstand HP treatment without experiencing structural and functional alterations that alter them more than 10% to 15% from their original state.

VIII. EFFECT OF HPP ON MICROORGANISMS

By efficiently killing bacteria, High-Pressure (HP) technology can be used as a cold pasteurization technique or in combination with heat energy to accomplish pasteurization objectives. The application of moderate pressure, typically between 10 and 50 MPa, inhibits the development and reproduction of germs, whereas greater pressure levels cause the inactivation of microorganisms. Following the pressurization process, the cell exhibits a number of structural and morphological changes. According to Bajovic et al. (2012), these modifications include the agglomeration of cellular proteins, the compression of gas vacuoles, the condensation of nucleoids, and the separation of the cell membrane from the cell wall.

High-Pressure (HP) treatment induces denaturation of bacterial proteins, which directly impacts the survival of microorganisms. When an adequate amount of pressure is applied, it causes irreversible damage to bacterial cells, rendering them incapable of recovery. Consequently, HPP effectively eliminates the microbial population. However, it's essential to note that the commercial dose of HP may not be equally effective against all types of microorganisms. Notably, Clostridium botulinum spores present a unique concern as they can develop and produce highly potent paralytic neurological toxins in low-acid foods. Since bacterial spores exhibit extreme resistance to HPP, additional antimicrobial treatments are often combined with high-pressure processing to achieve a significant reduction in their population (Muntean et al., 2016). Bacterial spores in foods can be successfully eradicated through HP treatment (>800 MPa) conducted at elevated temperatures, reaching up to 90 °C (Black et al., 2007).

Similar to how bacteria deactivate under pressure, yeasts also undergo changes to their cellular structure and permeability of their cell membranes (Black et al., 2007). Additionally, high pressure (HP) can impact the mitochondria of yeast cells, potentially causing the release of cytochrome C and subsequent cell death (Rivalain et al., 2010). Generally, HP tends to exert more pronounced effects on organisms with greater structural complexity. Consequently, yeasts and molds are relatively more susceptible to HPP than bacteria and can be efficiently deactivated using relatively low pressures (Black et al., 2007). In most cases, the majority of yeast cells can be eliminated within a few minutes through HP treatment at approximately 300-400 MPa and at room temperature (Daryaei et al., 2008). For most molds, pressure treatments ranging from 300-600 MPa are adequate (Tao et al., 2014). However, higher pressure levels may be necessary to deactivate yeast and mold ascospores (Muntean et al., 2016). In practical terms, it has been observed that ascospores from heat-resistant molds can be inactivated by applying pressures exceeding 600 MPa and temperatures surpassing 60 °C (Chapman et al., 2007).

When exposed to high-pressure conditions, viruses exhibit a broad range of sensitivity (Muntean et al., 2016). The specific mechanism through which HP inactivates viruses remains unclear. One hypothesis suggests that HP may induce the denaturation of viral capsid proteins, thereby preventing viruses from binding to the receptors on their host cells and interrupting viral infection (Tao et al., 2014). It's crucial to remember that the temperature and salinity of the food environment can affect how well HP inactivates viruses. For instance, a salinity concentration exceeding 1% NaCl might offer protection against hepatitis A virus (HAV), while lower temperatures can enhance virus inactivation through HP (Kovač et al., 2010).

According to Muntean et al. (2016), there are two aspects that affect how effective HPP therapy is against microbes: the type of bacteria and the chemical content of the food products. Because of differences in the structure of the cell membrane, gram-positive bacteria are often more resistant to pressure than gram-negative bacteria (Pilavtepe-Çelik et al., 2008). Important processing factors for HPP of food products include the goal pressure, pressure come-up time, pressure holding time, decompression time, initial product temperature, product pH, and product water activity (Muntean et al., 2016).

IX. EFFECT OF HPP ON FOOD QUALITY

By minimizing changes to food product’s sensory qualities, high-pressure processing (HPP) is a cutting-edge technology that preserves food product’s original quality, nutritional value, freshness, and safety. Naturally occurring pigments include anthocyanins, carotenoids, and chlorophyll found in fruits and vegetable-based goods. When subjected to moderate HPP, there is no noticeable impact on the colour attributes of these products. However, it's essential to note that high temperatures and/or high-pressure conditions can affect pigment stability. For example, in the case of broccoli juice, an increase in temperature to 50°C under pressure resulted in the degradation of chlorophyll. Additionally, higher pressure levels could expedite the deterioration of chlorophyll in broccoli (Tao et al., 2014; Oey et al., 2008).

Particularly with fresh red meat, high-pressure processing (HP) has a more notable effect on the colour characteristics of meat and meat products. Meat colour is mostly determined by the optical characteristics of the meat's surface and the amount of myoglobin present in the muscle. It's important to highlight that the existence of nitrosyl-myoglobin, which forms when myoglobin interacts with nitric oxide, is a key factor influencing the colour of cured meat (Bajovic et al., 2012).

As seen in minced beef and caiman tail meat, HP treatment can cause notable colour changes in fresh meat, including a rise in lightness (L*) and a decrease in redness (a*). The characteristic red hue of fresh meat is altered as a result of these modifications (Bajovic et al., 2012; Canto et al., 2012). This shift in colour may impact consumer satisfaction when the expected redness of meat is compromised. However, it's important to highlight that when meats undergo further processing to create various meat products, the adverse effect of HP on the colour of fresh meat is often less noticeable (Bajovic et al., 2012).

HP treatment also influences the rheological or textural characteristics of food products. Most high-moisture food products remain structurally unaffected when exposed to HP, primarily because pressure does not induce shear forces in these products. However, due to gas displacement and liquid infiltration, materials containing gas may undergo colour and texture changes. Shape distortion is associated with anisotropic behaviour, but mechanical collapse of air pockets may result in physical shrinkage. In general, HP causes little to no long-lasting alterations to the texture of foods that don't have air holes.

The simplest method for assessing the acceptability and quality of food products by consumers is sensory analysis. However, it's important to note that HP treatment can have a subtle impact on the sensory attributes of food due to the physical and chemical alterations it induces (Tao et al., 2014). Food items subjected to HP may exhibit distinct sensory characteristics. For instance, HP-treated tomato juice and strawberry jam were found to possess unfavourable sensory traits, including the presence of a rancid flavour (Oey et al., 2008). Additionally, the application of 800 MPa pressure to cherry tomato puree was observed to reduce its fresh tomato flavour (Viljanen et al., 2011). In the context of meat and meat products, HP can initiate lipid oxidation, leading to the formation of off-flavour and rancidity (Ma & Ledward, 2013).

Furthermore, it has been demonstrated that HP treatment can promote the generation of hydrogen sulphide, potentially affecting the aromatic characteristics of milk (Vazquez-Landavrde et al., 2006). However, with the appropriate processing parameters, the adverse influence of HP on the sensory attributes of food can be mitigated. For instance, in the case of red wine, certain in-mouth flavours like sourness, bitterness, and astringency were enhanced by HP treatment at 600 MPa. Nevertheless, there was no statistically significant difference in overall quality observed between wines subjected to HP processing and those that were not (Tao et al., 2012).

X. APPLICATION OF HPP

High-pressure processing (HPP) has found widespread application in the processing of meat, seafood, dairy, fruits, vegetables, and various beverages. Among the range of HPP-treated products, the most prominent application is in ready-to-eat HPP meat products, including items like burger patties, ham, and bacon. Following closely behind are HPP-treated juices, which include popular options like coconut water. In the food industry, HP treatment serves as an effective means to eliminate bacteria from packaged foods. It plays a vital role as one of the antibacterial components within the hurdle technology framework, working in conjunction with other processing techniques to ensure the preservation of the original product characteristics (Huang et al., 2017).

According to Simonin et al. (2012), HPP technology has been formally authorized by the USDA Food Safety and Inspection Service as a means of eliminating Listeria monocytogenes from processed beef. Moreover, HPP increases the activity of certain enzymes, especially proteases, which speeds up the tenderization and aging process of meat products. This procedure gives beef products unique tastes and suppleness, which improves customer digestion. Beyond these advantages, cured meat products made with high pressure have bactericidal qualities that lower their total salinity and eliminate the need for extra antibacterial agents. As a result, healthier meat products that comply with Clean Label requirements are produced (Verma & Banerjee, 2012).

HPP effectively eradicates pathogens and spoilage microorganisms, significantly prolonging the shelf life of food products. Moreover, it has a minimal impact on the nutritional content of these products, preserving their natural organoleptic properties and nutritional value intact. Fruits and vegetables subjected to HP processing, such as juices, fresh-cut pieces, fruit jams, and purees, maintain their natural freshness and safety, earning wide consumer acceptance. HPP extends their shelf life by over threefold (Huang et al., 2017).

One of the notable outcomes of HPP is its ability to hinder microbial growth while concurrently reducing the activity of polyphenol oxidase, thereby preventing enzymatic browning. Enzymes such as polyphenol oxidase (PPO), peroxidase (POD), and pectin methyl-esterase (PME) tend to exhibit considerable resistance to HPP, experiencing only partial inactivation. However, the extent of their sensitivity to pressure varies depending on several factors, including their specific environment and source. In contrast, enzymes like lipoxygenase (LOX) and poly-galacturonase (PG) are comparatively more pressure-sensitive and can be substantially deactivated by HPP under commercially viable conditions (Terefe et al., 2014).

HPP technology is also utilized in the initial stages of food processing. The application of high pressure causes structural damage to plant cells, making it easier to extract valuable components. This physical disruption increases the rate of mass transfer and simplifies the extraction process by making cells more permeable to solvents. An important advantage of high-pressure processing is that it is carried out at room temperature, reducing the degradation of thermally sensitive components and thus improving the extraction efficiency (Huang et al., 2017).

XI. REGULATIONS FOR HPP

HPP has received approval from the USFDA as a non-thermal pasteurization method that can replace traditional pasteurization in the food industry. Among various food-borne pathogens, Escherichia coli O157:H7 strains have shown the greatest resistance to pressure. According to USDA guidelines, E. coli O157:H7 is used as the indicator strain for reprocessing. A successful HPP procedure, resulting in a 5-log reduction in E. coli O157:H7, should be adequate to guarantee the microbiological safety of processed food products (USDA, 2012).

In 2009, the Food and Drug Administration (FDA) in the United States approved the use of HPP for manufacturing low-acid foods, and many food processing industries in the country have since embraced this method. It has also been adopted for various food preparations in Japan and certain regions of Europe. In Europe, HPP is acknowledged as a novel technology and is regulated under the Novel Food Regulation. However, it's important to note that HPP is still an emerging industry in India (Parekh et al., 2017).

Good manufacturing practise (GMP) and industry-specific requirements, like those pertaining to juice and seafood, as well as the Hazard Analysis and Critical Control Points (HACCP) system, must be followed while preparing HP-pasteurized food items. In addition, the Pressure Equipment Directive (PED), which was established in 2002, must be followed by all new pressure vessels used in the European Union (EU). The current CE safety standard, which is currently in use in the EU and is well recognized worldwide, is strengthened by this directive. The PED regulation attempts to establish suitable design standards, GMPs, and thorough safety assessments to ensure the safe operation and maintenance of pressure vessels and their related components because pressure vessels of different kinds use potentially hazardous energy (Tao et al., 2014).

XII. 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):

- Elimination of pathogenic and spoilage microorganisms under elevated 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 exhibit high resistance to pressure levels achievable in commercial settings.
- 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
- The majority of HPP products need to be transported and maintained in a refrigerated environment due to the fact that pressure treatment at room temperature or below has been shown to effectively reduce vegetative pathogens by more than five logs.
- There may be microbiological concerns connected to Clostridium spore survival in low-acid HPP products.
- Because HPP employs water as a pressure transfer medium and things with air bubbles have the potential to distort under pressure, it is not recommended for use with many food products, such as flour or powdered foods with low moisture content and foods containing a lot of air bubbles.
- Since the packaging material used in HPP needs to have a compressibility of at least 15%, only plastic packaging materials are suitable.
- Some regulatory issues.

XIII. FUTURE SCOPE OF HPP

The global market for high-pressure processed (HPP) foods is projected to undergo a compound annual growth rate (CAGR) of 8.60% from 2023 to 2028. This growth is expected to be driven by the increasing consumer demand for convenient, minimally processed foods that preserve the taste, aroma, and freshness of natural products while prolonging shelf life. Factors such as urbanization, evolving lifestyles, rising disposable incomes, and the surge in online food ordering also significantly contribute to the expansion of this market. Following HPP treatment, most vegetative bacteria counts are typically drastically decreased—often by up to 4 log units or more—and enzymes are inactivated with little to no effect on the food's sensory qualities. However, different bacterial and microbe species have varied levels of resistance to high-pressure processing (HPP). Gram-positive bacteria like Listeria monocytogenes, for instance, may show more resistance than gram-negative bacteria like Salmonella. Foods with a high-water content are typically thought to be good HPP options. North America, Latin America, the Middle East, Africa, Europe, and Asia Pacific are the main regions where the HPP industry is present (Global High-pressure Processing (HPP) Foods Market Report and Forecast 2023-2028, n.d.).

Clean label foods are steadily gaining popularity. When a food product is crafted from uncomplicated ingredients with minimal processing and devoid of any chemical additives, it earns the classification of a clean label food. In recent times, an increasing number of global food manufacturers have shown a keen interest in clean label food products. High pressure processing, a method that abstains from chemical usage while preserving essential food quality and microbiological safety, stands out as a pivotal technique for the creation of Clean Label products. High pressure processing, a breakthrough hurdle technology, lessens the need for extra additives and lowers the danger of microbial infection in food. In addition, it prolongs the food's shelf life while preserving its original flavour, colour, and taste.

The integration of HPP technology with recent industry advancements can facilitate the progress of the food industry. High-quality organic food ingredients, fresh local meals with minimal food miles, and functional health foods are some of the upcoming advancements in the field of HPP. 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. Future research and development of healthcare-related components will heavily rely on HPP pre-treatment in order to improve the productivity of functional component manufacturing in the food and pharmaceutical industries (Huang et al., 2017).

XIV. CONCLUSION

The food processing sector has a close relationship with consumer health. As consumer preferences evolve, there is a growing demand for healthier food options characterized by minimal processing and the preservation of natural taste, texture, flavour, aroma, and nutritional value. In response to this demand, high pressure processing (HPP) has emerged as an innovative technology that can partially replace traditional thermal processing methods. HPP offers food manufacturers the opportunity to develop new food products with extended shelf life while preserving their sensory attributes and nutritional qualities. This non-thermal technology aligns with consumer preferences for safe and additive-free food products. Comparing HPP to traditional heat treatments, there are a number of benefits that ensure food safety and quality. Ongoing research and development endeavours are critical to tackle the current constraints linked to HP treatment in the forthcoming times.

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