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Review Article

Healthy expectations of high hydrostatic pressure treatment in food processing industry

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ABSTRACT

High hydrostatic pressure processing (HPP) is a non-thermal pasteurization technology which has already been applied in the food industries. Besides maintaining the food safety and quality, HPP also has potential applications in the enhancement of the health benefits of food products. This study examines the current progress of research on the use of HPP in the development of health foods. Through HPP, the nutritional value of food products can be enhanced or retained, including promotes the biosynthesis of γ-aminobutyric acid (GABA) in the food materials, retains immunoglobulin components in dairy products, increases resistant starch content in cereals, and reduces the glycemic index of fruit and vegetable products, which facilitates better control of blood glucose levels and decreases calorie intake. HPP can also be utilized as a hurdle technology in combination with existing processing technologies for the development of low-sodium food products and the maintenance of microbial safety, thereby lowering the risk of triggering cardiovascular disease. Additionally, HPP can be used to enhance the diversity of probiotic food products. Appropriate sporogenous probiotics can be screened and added to various high-pressure processed food products as a certain bacterial count is still retained in the products after HPP. As HPP causes physical damage to the structures of food products, it can also be used as a synergistic extraction technology to enhance the extraction efficiency of functional components, thereby reducing extraction time. By applying HPP in the extraction of functional components from food waste, the production costs of such components can be effectively reduced. This study provides a summary of the mechanisms by which HPP enhances the health benefits of food products and the current progress of relevant research. HPP possesses huge potential in the development of novel health foods and may provide an abundance of benefits to human health in the future.

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1. Introduction

According to data from the Taiwan Food and Drug Administration, approximately 2000 cases of food poisoning due to the accidental consumption of food products contaminated with pathogenic microbes occur annually. Most food poisoning cases are a result of consuming food products consisting of processed seafood, fruits, or vegetable products, which are consumed raw by a large proportion of consumers. Traditional high-temperature pasteurization is not amendable to retain the original fresh flavors of theses raw ingredients. With a lack of proper pasteurization, there is a higher risk of ingesting pathogenic microbes when consuming such products. This demonstrates the need for diverse pasteurization methods in the food industry to maintain the safety of all products. In addition, modern dietary concepts, which place a greater emphasis on healthy eating, encourage consumers to increase their intake of whole foods or unprocessed food products. Therefore, researchers in the field of food processing hope to achieve the complete or partial replacement of high-temperature pasteurization by physical, biological, or chemical methods for food preservation. With the development of non-thermal pasteurization technologies, the flavor of food products can be maintained, as mild processing methods reduce the use of chemical additives and enhance the preservation of the natural state and freshness of food products. In recent years, the development of non-thermal processing technologies has received great attention from the food processing industry; indeed, non-thermal processing associations around the world now hold annual symposiums to review the progress in various countries on advancements in processing technologies, such as high hydrostatic pressure processing (HPP), pulsed electric field processing, pulsed light processing, electron beam processing, and plasma processing. However, HPP is the only non-thermal processing technology that has been successfully commercialized in the recent decade. HPP involves the application of ultra-high pressure (100–600 MPa) to achieve pasteurization. As it enables the preservation of the natural flavors and nutritional values of raw ingredients, HPP has been recognized as a mild processing technology that can achieve both food safety and flavor retention [1].

The working principle of HPP is as follows: food products that have been hermetically sealed are placed in a thermally insulated airtight vessel and subjected to ultra-high pressure (100–600 MPa) transmitted by a liquid medium (typically water), which provides a pasteurization effect through the uniform and instantaneous application of high pressure. According to the principle of compression heating, an increase in pressure by 100 MPa results in an approximately 3 °C increase in water temperature. The initial pasteurization temperature is controlled within the range of 5–10 °C, meaning that when the pressure is increased to 600 MPa, the water temperature will not exceed 30 °C. Thereby, HPP reduces the influence of temperature on food components. Two basic principles, namely the isostatic principle and Pascal's principle, govern the uniform application of pressure on food products in the sealed vessel. According to the isostatic principle, when pressure is applied to a liquid medium in a closed environment, equal pressure is received by objects within any point in the environment irrespective of object shape or size. Pascal's principle states that the pressure change caused by applying an external force to a fluid at rest in a closed container is transmitted uniformly and without loss to every portion of the fluid and to the walls of the container [2]. Therefore, the effects of high pressure pasteurization are not influenced by the shape and size of the food packages; food products of different volumes can be processed within the same batch. Additionally, preservatives are not required for the maintenance of microbial safety in the food products. HPP is superior to traditional thermal processing technologies in the following aspects: (1) it can be performed at ambient temperature, which eliminates energy consumption required for heating and subsequent cooling; (2) the food products are in their final package during HPP and do not come into direct contact with the processing equipment, which prevents the occurrence of post-pasteurization secondary contamination and enables the recovery and reuse of the pressure-transmitting medium. As HPP possesses the advantages of low energy consumption and low contamination, it is a relatively environmentally friendly processing technology [3].

The development of HPP products has diversified in recent years, with HPP being applied to the development of health foods. HPP has been used to enhance the functional components of food products, develop drinks containing pressure-tolerant Bacillus probiotics, and reduce the additive content in food products, which increases the diversity of product types and enhances the added value of products. Although HPP has already been widely applied in the pasteurization of food products, the high investment costs of HPP equipment result in higher production costs compared with traditional high-temperature pasteurization, causing the average unit price of HPP products to be higher than that of non-HPP products. Therefore, developments in the application of HPP in recent years have been primarily focused on the enhancement of the health benefits to consumers. Adkins et al. [4] reported the use of HPP in cancer immunotherapy to kill tumor cells for the generation of whole cell and dendritic cell-based vaccines. In a review by Pottier et al. [5], the use of high pressure as a hurdle technology to reduce food additives and salt, as well as its potential to improve digestibility and to reduce allergenicity was highlighted. This indicates that high pressure does not merely serve as a pasteurization technology, but can also be potentially used to develop healthier food products. The nutritional value of food products can be enhanced during the pasteurization process, which enables consumers to increase their nutrient intake without having to alter their dietary habits.

2. Characteristics of HPP

2.1. *Effects of high pressure on microorganisms*

Food pasteurization technologies are mainly evaluated based on the tolerance of indicator pathogens; appropriate pasteurization parameters are set based on the conditions of the environments in which the products are distributed. For instance, Clostridium botulinum is used as the indicator pathogen for setting the operating parameters for autoclave pasteurization. Although high pressure is capable of eliminating pathogens, a huge variety of microbes with different physiological characteristics exist in food products, which leads to highly diverse pressure tolerance characteristics among these microbes. Therefore, the cumulative results of extensive microbe pressure tolerance experiments are required for the selection of pressure-tolerant indicator pathogens to ensure that reliable high-pressure pasteurization parameters are set [6]. For instance, the pressure tolerances of common pathogens generally follow these patterns, which must be well-understood when performing studies on high-pressure pasteurization: prokaryotic microbes > eukaryotic microbes; Gram-positive bacteria > Gram-negative bacteria; cocci > bacilli. As HPP is a batchwise pasteurization process, processing time is a key factor that influences output. Although productivity can be increased by decreasing the pasteurization time of each batch of products, this increases the risk of inadequate pasteurization. Therefore, the pH, water activity, and components of food products must be taken into consideration when determining the conditions of high-pressure pasteurization. When the selected conditions are unfavorable for microbial growth, pasteurization efficiency can be increased and pasteurization time can be reduced.

Therefore, the combination of HPP with addition hurdles may act synergistically on the inactivation of microorganisms, such as a low pH value increased HPP inactivation efficiency against pathogenic bacteria in salads (Queirós et al., 2019) [7]. However, there is a great variety of microbes with different physiological characteristics in food products, which leads to diverse pressure tolerance characteristics among the various microbes. An increase in treatment pressure may result in influences of differing extents in the microbes. Therefore, research units and competent health authorities must establish relevant pasteurization process conditions and verification methods for the pasteurization performances of equipment to ensure the safety of HPP products. At present, only a handful of countries have formulated relevant rules or regulations based on the results of microbe pressure tolerance experiments. The operating specifications for HPP products issued by the United States Department of Agriculture (USDA) recommend the use of *Escherichia coli* as the indicator pathogen and at least a 5-log reduction of the indicator pathogen with any time/pressure combination to ensure microbial safety [8]. In particular, for fruit and vegetable juice products, which account for the highest production volume of all HPP products, a 5-log reduction of the indicator pathogen is needed to satisfy the safety requirements of heat-pasteurized juices stated in the Hazard Analysis and Critical Control Point (HACCP) regulation. The competent health authority of Canada, Health Canada, has issued recommendations on the pressure and duration of pressure sustainment for individual products. For instance, a minimum pressure of 600 MPa for a minimum duration of 3 min is required for the effective reduction of *Listeria monocytogenes* in ready-to-eat meat products. As HPP cannot effectively inhibit the growth of microbial spores, the use of HPP for the pasteurization of products distributed at ambient temperature is not recommended. At present, a large number of commercially mass-produced HPP food products are distributed and sold via cold chain systems in many countries, but HPP food products distributed at ambient temperature are not available due to the inability of pressure treatment to completely eliminate microbial spores. Certain bacteria (*Bacillus* and *Clostridium*) form spores as a survival strategy in response to adverse environmental conditions. As the resistance of these spores to stress is much higher than that of vegetative cells of microbes, pressure treatment alone is unable to effectively eliminate microbial spores [1]. Therefore, HPP products must be distributed through cold chain systems as HPP is currently unable to achieve commercial sterility. Recent studies on the development of HPP food products that can be distributed at ambient temperature have shown that a pressure of 600 MPa combined with moderate temperature is required to achieve sterility equivalent to or higher than 12D in canned products and to ensure the quality of food products at ambient temperature.

2.2. *Non-thermal pasteurization*

Traditional pasteurization involves the elimination of pathogenic microbes by high temperature to maintain the quality of products during cold chain distribution. However, high temperatures induce browning and caramelization reactions in food products and destroy the natural flavors of foods. High-pressure pasteurization involves the use of water as a pressure transmission medium to transmit a pressure of 400–600 MPa to packaged food products for the annihilation of pathogens. However, the increase in pressure during HPP generates heat of compression in the transmission medium, leading to a temperature increase within the chamber. When pure water is used as the transmission medium, a 100 MPa increase in pressure leads to an increase of approximately 3 °C in water temperature. Therefore, HPP systems are usually equipped with a water storage system with the water temperature controlled at 5–10 °C, which allows the introduction of low-temperature water into the pressurized chamber during HPP. Consequently, the temperature within the chamber can be maintained below 30 °C even when the pressure has reached 600 MPa, and the natural flavors of food products would not be influenced by an increase in temperature [3].

2.3. *Influence on food components*

HPP achieves pasteurization of food products through hydrostatic pressure within the temperature range of 5–30 °C, which effectively reduces the occurrence of the Maillard and caramelization reactions. Therefore, during the treatment process, new aromatic components are not generated, and the original colors, flavors, quality, and nutrients of food products can be retained to a greater extent compared with traditional thermal processing technologies. It is a known fact that high-temperature pasteurization, even for a short duration, produces influences on the colors and flavors of food products to differing extents; however, HPP also affects microstructures and nutritional contents of different food products to varying degrees. As HPP only influences non-covalent bonds, such as hydrogen bonds, ionic bonds, and hydrophobic bonds, it induces changes in the physicochemical properties and functional activities of biomacromolecules in food products, and may even result in protein denaturation, enzyme deactivation, and microbe inactivation. In contrast, low molecular weight compounds, such as flavor substances, natural nutrients, and aromatic components, are not affected by HPP [9]. High pressure has no significant influence on the primary and secondary structures of protein components in food products. However, the tertiary and quaternary structures of proteins may be altered, causing reversible or irreversible structural modifications in proteins, which consequently result in protein denaturation, aggregation, or gelation. Therefore, HPP can influence enzyme activities in fruits and vegetables and destroy allergenic proteins. HPP has almost no influence on monosaccharides formed by high-energy covalent bonds. However, high pressure can modify carbohydrate molecules formed from the linkage of sugar chains by low-energy bonds. Therefore, HPP causes starch swelling, which may lead to gelatinization that is similar to thermal gelation. Pressure may also cause crystallization of lipid components and changes in biological membranes. This leads to increased permeability and leakage of cell content, ultimately resulting in the accelerated oxidation of food products with high lipid content. The reheating of typical heat-processed foods leads to further destruction of the flavors and textures of the food products [10]. In contrast, high-pressure pasteurization achieves pasteurization and the preservation of original fresh flavors at the same time. Therefore, HPP can be adopted as the pasteurization method for semi-prepared or prepared and ready-to-eat food products, as the fresh flavors of the ingredients and palatability can be retained when they are heated prior to consumption.

2.4. *Hurdle processing*

To satisfy the demands of consumers for natural foods, which includes freshness, stability, safety, tastiness and affordability of food products, food industries tend to adopt a combination of hurdle technologies and various antimicrobial factors for the preservation of food products. The combination of multiple technologies produces a good hurdle effect that inhibits microbial growth while reducing the intensity of the individual processing technologies, dosages of chemical additives, and adverse effects on the original flavors and nutritional contents of food products. As HPP is only performed after packaging, it can serve as the final hurdle technology in a series of bacteria inhibition technologies that reduce microbial risks, prolong the shelf life of stored food products, distribute via cold chain systems, and retain the natural colors and flavors of the food ingredients. With the combined pasteurization effects of other hurdle technologies, the cycle time of HPP equipment can also be reduced, which results in lower production costs. When HPP is utilized as a hurdle technology, the salinity of pickled foods can be reduced while maintaining microbial safety. Therefore, it can potentially be applied to the development of foods for the elderly population or foods with reduced dosages of additives to satisfy the requirements for clean label food production methods [11].

2.5. *Soft packaging*

Several factors must be taken into consideration during the selection of packaging materials for HPP products. The packaging must possess the ability to withstand the operating pressures, sufficient heat sealability, sufficient protective ability to prevent the deterioration of food quality during HPP, and elasticity in at least one side of the packaging to facilitate pressure transmission. Soft polymeric bags, cans, trays, and bottles are commonly used packaging materials for HPP food products. Rigid packaging materials made from metal and glass are unsuitable for HPP, because they are prone to deformation and breakage under high pressure. PET, PE, PP, and EVOH films used singly or in combinations are the most common types of packaging materials adopted for HPP in the food industry. Vacuum packaging is the most common type of packaging used for HPP products, as the residual air in a sealed package possesses higher compressibility compared with the food product within the package. As HPP may potentially lead to uneven processing and package deformation, vacuum packaging can reduce unnecessary physical pressure exerted on the external package by gases within the package [12]. For canned beverages, the space at the top of the can must be minimized during the sealing process to ensure that the packages and the internal space of the pressure chamber can be utilized efficiently to reduce the time required to reach the target treatment pressure during HPP. As the application of pressure causes a temporary volume reduction that is reversed when the pressure is released, the packages of HPP food products must be able to withstand a volume reduction of approximately 15%, maintain seal integrity, and maintain the characteristics of food products after pressure release [13].

3. Influence of HPP on the health benefits of food products

3.1. *Enhancement of antioxidant properties*

As fruits and vegetables are rich in polyphenols, flavonoids, anthocyanins, and lycopene, they possess high antioxidant activity and are a good source of nutrients. Therefore, the protective function of the body against oxidative damage can be enhanced through the intake of fruits and vegetables. However, antioxidant substances in fruits and vegetables may be destroyed at high temperatures during traditional pasteurization processes. Previous studies have indicated that the use of high-pressure pasteurization in place of traditional thermal pasteurization reduces the destruction of antioxidant components (Table 1). Chaikham and Prangthip [14] found that the total phenolic compound content and total flavonoid content of longan flower-honey after pressurization at 500 MPa for 20 min were 71.16 mg GAE/100 g and 58.13 mg QE/100 g, respectively. In contrast, thermal treatment at 50 °C for 5 min reduced the total phenolic compound content and total flavonoid content to 52.16 mg GAE/100 g and 44.96 mg QE/100 g, respectively. In addition, measurements of DPPH radical inhibition (%) and FRAP value (mMFeSO4/g) revealed a higher antioxidant capacity in pressure-treated longan

Table 1 – Comparison of effects of HPP and thermal pasteurization on antioxidant contents in HPP-treated foods.

Foods	Untreated	HPP	Thermal pasteurization	References
Longan flower-honey	–	500 MPa/20 min, total phenols 71.16 mg GAE/100 g, total flavonoids 58.13 mg QE/100 g.	50 °C/5 min, total phenols 52.16 mg GAE/100 g, total flavonoids 44.96 mg QE/100 g.	[14]
strawberry juices	Total monomeric anthocyanins 14.5 mg/100 g, vitamin C 17.0 mg/100 g.	400 MPa/3 min, total monomeric anthocyanins 16.6 mg/100 g, Vitamin C 19.8 mg/100 g.	85 °C/2 min, total monomeric anthocyanins 15.5 mg/100 g, Vitamin C 16.5 mg/100 g,	[15]
soy-smoothies	Total carotenoids 127.4 mg/L, total polyphenol 444 mg GAE/L.	650 MPa/3 min, total carotenoids 136.6 mg/L, total polyphenol 503 mg GAE/L.	80 °C/3 min, total carotenoids 124.1 mg/L, total polyphenol 419 mg GAE/L.	[16]
wheatgrass juice	Vitamin C 9.21 mg/100 mL, total phenolic content 341.8 mg GAE/100 mL	500 MPa/1 min, Vitamin C 9.03 mg/100 mL, total phenolic content 316.1 mg GAE/100 mL	75 °C/15 s, Vitamin C 6.69 mg/100 mL, total phenolic content 218.9 mg GAE/100 mL	[17]
green asparagus juice	Ascorbic acid 108.35 mg/L, total phenolics 301.25 mg/L.	600 MPa/10 min, ascorbic acid 95.86 mg/L, total phenolics 288.48 mg/L.	121 °C/3 min, ascorbic acid 83.43 mg/L, total phenolics 271.64 mg/L.	[18]
Apple juice	Total phenolic content 405.2 mg GAE/kg, flavonoid content 357.8 mg QE/100 g.	600 MPa/50 min, total phenolic content 409.2 mg GAE/kg, flavonoid content 345.8 mg QE/100 g.	80 °C/1 min, total phenolic content 397.4 mg GAE/kg, flavonoid content 353.1 mg QE/100 g.	[19]
beetroot	Betanin 6.4 mg/g DW, total phenolics 11.7 mg gallic acid/100 g, ascorbic acid 6.6 mg/100 g.	650 MPa/3 min, betanin 32.3 mg/g DW, total phenolics 14.7 mg gallic acid/100 g, ascorbic acid 9.1 mg/100 g.	90 °C/7 min, betanin 13.1 mg/g DW, total phenolics 14.1 mg gallic acid/100 g, ascorbic acid 6.3 mg/100 g.	[20]
strawberry purée	Total polyphenols 221.0 mg/100 g, anthocyanins 92.6 mg/100 g.	500 MPa/15 min/50 °C, total polyphenols 213.4 mg/100 g, anthocyanins 79.79 mg/100 g.	90 °C/15 min, otal polyphenols 190.6 mg/100 g, anthocyanins 52.36 mg/100 g.	[21]
grape juice	Total phenolics 23.27 mg/mL, anthocyanins 0.81 mg/mL.	600 MPa/5 min, total phenolics 26.81 mg/mL, Anthocyanins 0.91 mg/mL.	90 °C/1 min, total phenolics 22.34 mg/mL, Anthocyanins 0.86 mg/mL.	[22]
red bean powder	Total phenolic compounds 9.21 mg of GAE/g, total flavonoids content 19.08 mg of CAE/g, proanthocyanin content 7.46 mg of CAE/g.	600 MPa/5 min, total phenolic compounds 6.15 mg of GAE/g, total flavonoids content 14.65 mg of CAE/g, proanthocyanidin content 4.80 mg of CAE/g.	90 °C/15 min, total phenolic compounds 4.47 mg of GAE/g, total flavonoids content 13.09 mg of CAE/g, proanthocyanidin content 3.80 mg of CAE/g.	[23]
açaí juice	Anthocyanins 5.38 mg/g, total phenolic compounds 37.02 mg GAE/g	600 MPa/5 min, anthocyanins 4.62 mg/g, total phenolic compounds 37.97 mg GAE/g.	85 °C/1 min, anthocyanins 3.85 mg/g, total phenolic compounds 31.66 mg GAE/g.	[24]

flower-honey; after being subjected to a storage experiment that lasted for four months, HPP longan flower-honey still possessed a high content of antioxidative constituents. Similar results were obtained in another study on the influence of different pasteurization treatments on beetroot. The contents of betanin, total phenolics, and ascorbic acid increased significantly in beetroot samples subjected to high-pressure treatment at 650 MPa for 3 min compared with untreated beetroot samples. For beetroot samples thermally treated at 90 °C for 7 min, increases in betanin and total phenolic content were also observed; however, the contents were lower than that of beetroot samples subjected to high-pressure treatment. Aaby et al. [15] investigated the influence of different treatment conditions (400 MPa/3 min, 500 MPa/3 min, 600 MPa/3 min, and 85 °C/2 min) on the changes in the total monomeric anthocyanin (TMA) and vitamin C content in strawberry juice during storage at 4 °C for 49 days. Results indicated that different pressures used during HPP did not result in significantly different TMA and vitamin C contents in strawberry juice. However, all high pressure-treated strawberry juice samples had slightly higher TMA content during the storage period compared with the heat-treated strawberry juice samples. The results of a study by Andrés et al. [16] showed that the total polyphenol and total carotenoid contents of soy-smoothies increased after HPP (650 MPa/3 min), with the total polyphenol content increasing from 444 mg GAE/L in the control group to 503 mg GAE/L. The total carotenoid content increased from 127 mg/L to 136 mg/L. In addition, it was observed that higher treatment pressures resulted in greater increases in the total polyphenol and total carotenoid contents. However, thermal treatment at 80 °C for 3 min significantly reduced the total polyphenol and total carotenoid contents to 419 mg GAE/L and 124.1 mg/L, respectively, indicating that the natural nutritional components of food products were retained to a greater extent with HPP. Another study by Ali et al. [17] demonstrated that thermal treatment (75 °C/15 s) resulted in a substantial decrease in the total phenolic content and vitamin C content of wheatgrass juice to 218.9 mg GAE/100 mL and 6.69 mg/100 mL, respectively, which were significantly lower than that of the control group (341.8 mg GAE/100 mL and 9.21 mg/100 mL, respectively) and the high pressure-treated group (316.1 mg GAE/100 mL and 9.03 mg/100 mL, respectively). The research results discussed above indicate that HPP promotes the extraction of antioxidant substances, enables the retention of functional components, and reduces the destruction of natural nutrients in fruits and vegetables, which makes it a suitable technology for the pasteurization of heat-sensitive food products (see Tables 2 and 3).

3.2. *Increase of resistant starch content*

Based on the rate of digestion in the human body, starch can be classified into rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS). In general, SDS is the most ideal type of dietary starch, as it reduces the rate of starch digestion in the small intestine and lowers postprandial blood glucose levels. High hydrostatic pressure (HHP) treatment significantly reduces the enthalpy change of retrograded starch and converts freezable water to non-freezable water during the retrogradation process. This indicates that the percentage of SDS is not positively correlated with the degree of starch retrogradation. A study by Tian et al. [25] showed that HPP decreased the non-waxy and waxy starch content of rice from 19.5% to 12.1% and 15.7%–11.4%, respectively, while increasing the imperfect crystallites in the starches from 26.4% to 30.7% and 28.6%–31.3%, respectively. In a study by Li et al. [26] on the influence of high-pressure treatment on the physicochemical and structural properties of red bean starch, it was found that an increase in treatment pressure (150–600 MPa) promoted starch gelatinization, which reduced the degree of crystallinity and gelatinization temperature. In particular, treatment at 600 MPa for 15 min resulted in complete starch gelatinization and loss of birefringence. Other studies have indicated that high pressure also promotes the gelatinization of chickpeas [27] and peas [28]. Guo et al. [29] found that HPP treatment resulted in the formation of amylose–long-chain fatty acid complexes, which is defined as type-5 of resistant starch. The lotus starch will completely gelatinize under 600 MPa pressure treatment, while lotus amylose can form complex with saturated and unsaturated fatty acids at 500 MPa [30]. Furthermore, it was found that the solubility of starch under different temperatures (50–90 °C) also increased with an increase in the pressure used during high-pressure treatment. At 50–60 °C, the 600 MPa treatment group showed the highest swelling capacity, but the opposite was observed when the temperature was increased to 70–90 °C. Solubility and swelling capacity reflects the degree of interactions between the amorphous and crystalline regions of starch granules. At lower temperatures, straight-chain starch forms crystals with lipids, which prevents excessive granule swelling. When high pressure is applied, straight-chain starch molecules aggregate and reduce the degree of binding between straight-chain starch and lipids, resulting in higher water-holding and swelling capacities. An increase in temperature leads to the rearrangement of starch molecules, which produces an inhibitive effect on swelling. In a study by Li et al. [31] on the influence of high-pressure gelatinization on the physicochemical properties of mung bean starch during the retrogradation process, it was found that mung bean starch could be fully retrograded after high-pressure treatment at 600 MPa for 15 min. Analysis of XRD spectra revealed a reduced degree of crystallinity and the disappearance of C-type crystals. As retrogradation time increased, the degree of crystallinity and morphology of starch gradually reverted to the initial state. In addition, it was found that a pressure of 600 MPa enhanced the content of RS in starch to approximately three times that of the original starch and that the RS content continuously increased during the retrogradation process. Another study by Liu et al. [32] showed that HPP promoted interactions between straight-chain starch and branched-chain starch, and between straight-chain starch and lipids, thereby reducing the release of straight-chain starch during the gelatinization process and leading to higher retention of straight-chain starch content. This constituted the key reason for an increase in starch resistance with HPP. Similar results were obtained in a study on tartary buckwheat starch. Compared with starch granules cooked in boiling water, HHP-treated starch granules exhibit intact structures, which hinder the entry of enzymes into the

Table 2 – Increase in nutritional value of cereals.

Samples	Processing conditions	Achievements	References
rice	600 MPa, 30 min	HPP reduced the contents of non-waxy and waxy starches from 19.5% to 12.1% and from 15.7% to 11.4%, respectively, while increasing the proportion of crystallites, thereby increasing the content of slowly digestible starch (SDS).	[25]
Sorghum starch	600 MPa, 20 min	HPP resulted in lower *in vitro* hydrolysis in sorghum starch and reduced the amount of digestible starch through the increase of the SDS and RS fractions.	[32]
brown rice	300 MPa, 10 min	As treatment pressure increased, the bio-accessibility of brown rice increased, and RS and free amino acid content was significantly increased.	[34]
soybean	200 MPa, 10min	High-pressure pasteurization (HPP) on soybean soaked in sodium glutamate solution resulted in cell structure damage, an increase in free amino acids in the soaking solution, and the accumulation of γ-aminobutyric acid (GABA); these events can be regarded as the high-pressure induced transformation of soybean.	[37]
rough rice	30 MPa, 24 or 48 h	HPP significantly increased the content of functional components, such as c-oryzanol, GABA, total arabinoxylan, tricin 40-O-(threo-b-guaiacylglyceryl) ether, vitamin B, and vitamin E in germinated rough rice.	[39]
brown rice	50 MPa, 20 min	HPP resulted in a 25% increase in the GABA content of brown rice.	[40]
corn starch	600 MPa, 15 min	HPP increased the degree of crystallinity of normal and waxy corn starches, thereby increasing the content of resistant starch (RS).	[41]
buckwheat starch	600 MPa, 20 min	HPP-modified buckwheat starch had lower *in vitro* hydrolysis, a reduced amount of rapidly digestible starch (RDS), as well as higher levels of SDS and RS.	[42]
Coffee beans	600 MPa, 5 min	HPP enhanced glutamate decarboxylase (GAD) activity and promoted the conversion of glutamic acid to GABA in coffee beans. Compared with untreated coffee beans, the GABA content of HPP coffee beans was increased by approximately two times ($P < 0.05$).	[43]

granules and impede starch hydrolysis. Colussi et al. [33] found that high-pressure treatment with 3 cycles at 600 MPa in combination with retrogradation led to a 10–15% reduction in the absorption of potato starch in the small intestine, which was mainly due to slower glucose release. It was also observed that RDS content decreased significantly, while SDS and RS levels increased with an increase in pressure during HPP. Compared with other starchy foods, rice has a higher glycemic index (GI). In addition to the source of starch, the proportions of straight-chain and branched-chain starch content, average molecular weight, processing technology, and the presence of other components in the food matrix influence the rate of starch hydrolysis. For instance, the germination of brown rice substantially increases the rate of starch digestion through enzymatic hydrolysis. However, HPP increases the RS content in germinated brown rice and reduces the starch digestion rate. Therefore, HPP may be potentially applied to control blood sugar levels [34].

3.3. *Reduction of glycemic index*

The GI is a measure of the increase in blood glucose levels after the intake of saccharide-containing foods. The consumption of low GI foods may help prevent diseases associated with insulin resistance and diabetes mellitus. Elizondo-Montemayor et al. [35] studied the effects of HHP processing of fresh mango puree on the GIs and postprandial glycemic responses of 38 healthy Mexican subjects in a randomized cross-over clinical trial. The mean GI for HHP processed mango puree was significantly lower (32.7) than that of unprocessed mango puree (42.7). None of the subjects in the HHP processed mango puree group showed a high GI, compared to a significantly higher proportion of high GI in the unprocessed mango puree group. In addition, the viscosity and alcohol insoluble residue (AIR) solubility values of the HHP-treated mango puree samples were significantly higher. The results of this study show that low GI fruits are appropriate for glycemic control and that mango may be included as part of the diet for healthy subjects and type 2 diabetes mellitus (T2DM) subjects. Furthermore, HHP processing of mangos may offer additional benefits for glycemic control, as it is able to lower the GI of mango puree. Similar results were obtained in another study on high-pressure pasteurization of atemoya puree by Chou [36]. The postprandial blood glucose concentrations of rats fed with puree treated with pressures of 300 MPa and 600 MPa were significantly lower than that of the control group. GIs of untreated puree and puree treated with pressures of 100 MPa, 300 MPa, and 600 MPa were 65.4, 66.3, 55.4, and 49.8, respectively, which indicated that GI decreases with an increase in treatment pressure.

3.4. *Increase of GABA content*

γ-aminobutyric acid (GABA) is a non-protein amino acid widely distributed in prokaryotic and eukaryotic organisms. It is a key inhibitory neurotransmitter in the sympathetic nervous system and plays a critical role in the regulation of cardiovascular function. HPP may cause partial destruction of cellular structures, including the internal cellular structures of cereals and the cell membrane of plant cells. This destruction leads to accelerated material transport in plant cells subjected to high pressure and accelerated biochemical reactions

Table 3 – Health effects of extracts obtained by high pressure methods.

Samples	Processing conditions	Achievements	References
Tomato pulp	450 MPa, 10 min, 20 °C	By utilizing response surface methodology (RSM) to determine the optimum conditions for HPE, the maximum extraction yield (8.71%), flavonoid content (21.52 ± 0.09 mg QE/g FW), and lycopene content (2.01 ± 0.09 mg QE/100 g FW) were achieved.	[55]
Ginseng	100 MPa, 24 h, 50 °C	The contents of total phenolics, saponins, and acidic polysaccharides of high hydrostatic pressure extract of ginseng (PEG) were higher than those of hot water extract of ginseng (WEG). When fed to rats, PEG reduced the body weight and white adipose tissue mass of rats. PEG increased fecal triacylglycerol, whereas WEG did not. PEG reduced mRNA levels of adipogenic genes, such as peroxisome proliferator-activated receptor (PPAR)γ and aP2. The mRNA levels of pro-inflammatory genes, tumor necrosis factor (TNF)-α, interleukin (IL)-6, and monocyte chemoattractant protein (MCP)-1, were down-regulated by PEG but not by WEG.	[57]
Ginseng	200 MPa, 5 min, 60 °C	Compared with microwave extraction, ultrasound extraction, Soxhlet extraction, and heat reflux extraction (HRE) methods, high-pressure extraction (HPE) achieved the highest extraction yield of ginsenoside and the shortest extraction time.	[59]
Ginseng	600 MPa, 5–15 min	The extraction yields of ginseng extract (312.2–387.1 mg/g ginseng) and crude saponin (19.3–32.6 mg/g ginseng) obtained with HPE were higher than that of the control group (189.9 and 17.5 mg/g ginseng, respectively).	[60]
Onion	500 MPa, 10 min	Onion extracts obtained by HPE were fed to high cholesterol diet-fed rats. Results indicated that the HPE extracts significantly increased fecal lipid and cholesterol levels, and reduced LDL levels in blood and hepatic lipid levels, which demonstrates the application potential of HPE in the prevention of hyperlipidemia.	[61]
longan pulp	407 MPa, 6 min	Ultrahigh pressure-assisted enzymatic treatment achieved the maximum polysaccharide yield (8.55%) without altering the original polysaccharide structure, and exhibited significant inhibitory activity towards the enzyme, acetylcholinesterase. This technology can be potentially applied in the fields of medicine and functional foods.	[62]
Red macroalgae	400 MPa, 20 min	High hydrostatic pressure-assisted enzymatic treatment improved the extraction of specific molecules such as proteins, polyphenols, and polysaccharides, and improved the antioxidant activity of extracted fractions by over 2.8 times.	[63]
pomegranate peel	300 or 600 MPa, 15 min	HPE at 300 MPa resulted in the maximum level of total phenolic content and antioxidant capacity in pomegranate peel extracts, as well as optimum inhibitory effects against the pathogens Bacillus cereus and *Pseudomonas aeruginosa*, without affecting the growth of beneficial microbes.	[64]

through the maintenance of enzymatic activity. Thus, HPP induces the conversion of glutamic acid to GABA through enzymatic reactions [37]. The combination of HPP and initial germination in brown rice increases the activity of enzymes related to the biosynthesis of GABA, which activates the metabolic pathways related with GABA and glutamic acid and results in an increase in the GABA content of germinated brown rice. Therefore, germination combined with HPP can be used as an effective means of enhancing the ability of functional component extraction due to the increase of enzymatic reaction rates and acceleration of the biosynthesis of physiological metabolites. Shigematsu et al. [38] reported that HPP at 200 MPa induced the conversion of glutamic acid to GABA in brown rice. When the pressure-treated brown rice was stored at 25 °C for 4 days, the concentrations of certain amino acids, including GABA, increased with storage time. The same was not observed in the samples of the untreated control group. The experimental results provide feasibility for a novel use of HPP technology to alter the metabolic pathways in a cellular biological material and to accumulate useful metabolites. Kim et al. [39] also observed that high-pressure treatment had enhancement effects on the nutritional components of germinated rough rice. Rough rice was germinated at 37 °C and subjected to high-pressure treatment at 30 MPa for 24 h (HP24) and 48 h (HP48). Results indicated that the highest GABA, total arabinoxylan, and tricin 4′-O-(threo-β-guaiacyl-glyceryl) ether, and γ-Oryzanol contents were achieved after HP48 for 2 days. The highest vitamin B (60.99 mg/100 g) and E (4.07 mg/100 g) contents were observed after HP24 for 5 and 2 days, respectively. These experimental results suggest that a combination of high-pressure treatment and germination efficiently enhances the functional characteristics of rough rice. Xia et al. [40] also observed that wholegrain brown rice that was first subjected to HHP treatment (50–350 MPa/20 min) and subsequently incubated at 37 °C to obtain germinated grains after a 2-day soaking period exhibited a significant increase in GABA content. Compared with the control group, grains treated with a pressure of 50 MPa showed a 25% increase in GABA content.

3.5. *Retention of lactoferrin*

Dairy products contain various types of immunoglobulins that are beneficial to human health. For instance, immunoglobulin

A (IgA), which is present in colostrum and cow milk, provides protection for the gastrointestinal system. Currently, high-temperature short-time (HTST) pasteurization is adopted during the processing of dairy products to prolong shelf life and minimize the risks of pathogen infections. However, thermal treatment reduces the nutrient content and immunological characteristics of dairy products. As human and animal immunoglobulins have low thermal stability, denaturation can be observed after the pasteurization process. HPP is a non-thermal processing technology that only causes minimum destruction of macromolecules in food products. At a low temperature (8 °C), high-pressure treatment at 200 MPa for 2.5, 15, and 30 min did not produce a significant influence on the IgA content of human colostrum. An increase in the treatment pressure to 400 MPa at a low temperature for 2.5–30 min also had no significant influence on the IgA content of human breast milk [44]. HPP at 400 MPa and above reduced the total viable count and Enterobacteriaceae count to undetectable levels [45], while HPP at 400 MPa and below also had protective effects towards other immunoglobulins, such as IgM and IgG; the experimental results showed that pressure treatments at 200 MPa and 400 MPa for 2.5, 15, and 30 min did not significantly lower IgM and IgG content [46]. Therefore, the replacement of traditional thermal pasteurization with HPP enables the maintenance of immunoglobulin content in dairy products. As immunoglobulins possess a wide variety of functional characteristics in humans and animals, including anti-microbial, anti-inflammatory, anti-tumor, and immunomodulatory activities, they are regarded as highly valuable proteins in the food industry. High pressure also improves the solubility, foamability and emulsifiability of immunoglobulins. Studies have shown that high-pressure treatment at 400 MPa for 30 min and 300 MPa for 60 min result in the formation of a molten globule state in immunoglobulins, which is an intermediate conformational state between the secondary and tertiary structures of proteins. Consequently, the solubility, foamability, and foam stability of immunoglobulins can be substantially increased [47]. Col-plus cow milk in New Zealand, which undergoes HPP instead of thermal pasteurization, has a heat-sensitive immunoglobulin content that is 2.5 times that of heat-pasteurized cow milk.

3.6. *Reduction of sodium content*

To maintain good texture and water-holding capacity in meat products, a certain amount of salt must be added during the production process. Salt is also commonly used in the production of various processed foods due to its multiple functions. However, as consumers become more health-conscious and increasingly concerned about the use of food additives, they tend to purchase natural, additive-free, and health-oriented mildly-processed food products, which leads to a decreased demand for products with high salt content. Therefore, food product manufacturers have begun to develop products with reduced or low salt content to decrease the sodium intake of consumers [10]. Methods commonly adopted to reduce sodium content include the replacement of sodium chloride with other chloride salts or binding agents, or the use of alternative processing technologies. However, the addition of salt not only increases the savoriness of meat products, but also influences water-holding capacity, product quality, and microbial growth in meat products. The non-addition of nitrites to meat products may lead to concerns about microbial food safety and poorer flavor. To address the possible food safety risks and changes in product quality associated with reduced salt and additive content in meat products, HPP may be adopted in the production process for the improvement of product quality. Tamm et al. [48] investigated the effects of replacing sodium chloride (NaCl) with potassium chloride (KCl) and the use of HPP on the reduction of sodium content in cooked ham. Results indicated that a reduction of up to 1.1% NaCl was possible by replacing NaCl with KCl (0.2%) in combination with HPP. Stollewerk et al. [49] found that the non-addition of NaCl to dry-cured ham in combination with HPP at 600 MPa effectively inhibited the growth of Listeria monocytogenes and Salmonella enterica. Compared with the standard processing method (NaCl addition), the combined NaCl-free and HPP method achieved better inhibitive effects on pathogens and produced healthier meat products. Similar results were obtained by Pietrasik et al. [50], who investigated the combined effect of partial salt replacement with modified KCl and HPP (600 MPa for 3 min at 8 °C) on the quality and shelf life of cooked ham. After 12 weeks of storage, the total aerobic plate and lactic acid bacteria counts of the treated ham were still close to the detectable level of 1.0 log CFU/g. Consumer acceptability test results also indicated no significant differences between HPP ham and non-HPP ham. Therefore, HPP could extend the shelf life of cooked ham without effects on quality. Rodrigues et al. [51] reported that the use of HPP at 600 MPa for 5 min to treat marinated beef resulted in the reduction of salt content by 1%, inhibition of the growth of Listeria innocua and Enterococcus faecium, and prolongation of shelf life to 14 days. When the same processing method was applied to breakfast sausages, a treatment pressure of 150 MPa led to a 1.5% reduction in the amount of salt while maintaining the same flavors as breakfast sausages produced using the traditional processing method [52].

3.7. *Development of probiotic products*

Plant-derived foods, such as fruits, are regarded as good culture media for probiotics, as they contain nutrients necessary for probiotic growth. In addition, as plant-derived foods possess attractive appearances and appealing flavors, the use of fruits as carriers of probiotics for consumption has been recommended. Compared with thermal processing, HPP not only annihilates unwanted microbes in juices, but also enables the maintenance of the nutrition characteristics and sensory qualities of juices. Consumers have also shown a preference for HPP products over heat-treated products. In addition, HPP effectively protects Lactobacillus rhamnosus GG, a probiotic strain present in fruit-based food products; studies have shown that the concentration of Lactobacillus rhamnosus GG in HPP products could be maintained above 108 CFU/mL, even after 30 days of storage [53]. Ganeden, Inc. is a world-renowned United States probiotic ingredient manufacturer and a leader in probiotics research and probiotic product development. Its patented probiotic, GanedenBC30 (Bacillus coagulans strain GBI-30, 6086), has been added to fruit juices for the production of HPP organic cold pressed fruit

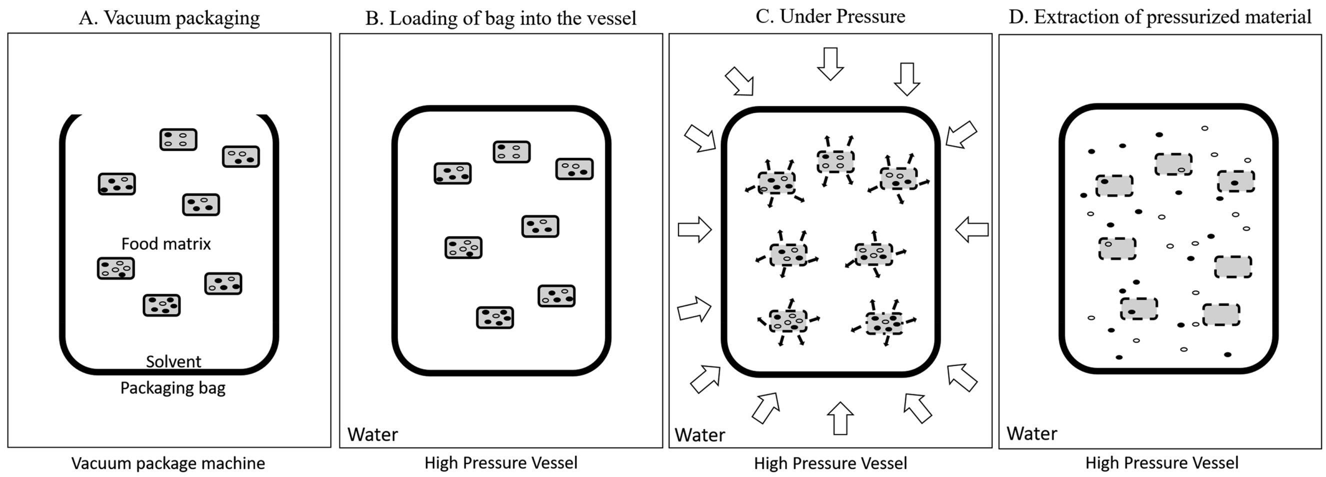

Fig. 1 – Schematic diagram of high-pressure extraction. (A) The solvent and food matrices are placed in a packaging bag for vacuum packaging. (B) The sealed bag is loaded into a high-pressure vessel, and the pressure-transmitting medium (water) is subsequently introduced into the vessel. (C) High pressure is applied to the vessel, which causes mechanical damage and breakage of cells within the food matrices. This enables the rapid penetration of the solvent into the cells, and results in the dissolution and extraction of intracellular substances. (D) Extraction is complete, with the solvent containing a high concentration of extracts.

juices with floral scents. As GanedenBC30 remains viable after HPP, these fruit juices are the first Bacillus coagulans-containing HPP juice products in the market. Three of the seven juice products, namely Green Harmony, Appleade, and Turmeric Tonic, have each been fortified with one billion CFU of GanedenBC30 (GanedenBC30.com).

3.8. *Extraction of functional food components*

High-pressure extraction (HPE) is a novel technology used in the extraction of active substances from animal and plant materials. HPE involves the use of high hydraulic pressure to induce physical damage in animal and plant cells, which facilitates the penetration of solvents into cells, increases mass transfer rates, and promotes the release of extracts. Compared with traditional extraction technologies, HPE enhances the extractability of effective components and reduces extraction time (Fig. 1). It can be used for the recovery of functional components from food processing wastes, such as the extraction of antioxidant compounds and sulforaphane from papaya seeds [54], the extraction of lycopene from tomato waste [55], and the enhancement of the nutritional value of processed products. Lee et al. [56] compared the efficiencies of saponin extraction from ginseng using heat reflux extraction, high-pressure extraction, ultrasonic extraction, and microwave-assisted extraction. Results indicated that HPE achieved a higher saponin concentration within a shorter period of time. With HPE, 16.59 mg/g saponin could be obtained after 15 min, compared with 14.86 mg/g after 40 min for ultrasonic extraction, 13.68 mg/g after 24 h for heat reflux extraction, and 8.57 mg/g after 1 min for microwave-assisted extraction. In a study by Jung et al. [57], HHP extract of ginseng (PEG) and hot water extract of ginseng (WEG) were fed to high-fat diet induced obese rats. The total phenolics, saponins, and acidic polysaccharides contents of PEG were higher than those of WEG. PEG reduced the body weight and white adipose tissue mass of rats; in addition, PEG increased fecal triacylglycerol, whereas WEG did not. The experimental results also showed that PEG downregulated the mRNA levels of pro-inflammatory genes, such as TNF-α, IL-6, and MCP-1, whereas WEG did not exhibit the same effects. The prickly pears treated by HPP can enhance their health potential by increasing the extractability of bioactive compounds, including phenolic acids, isorhamnetin glucosyl-rhamnosyl-rhamnoside and isorhamnetin glucosyl-rhamnoside [58].

4. Conclusions

In the past, HPP has been utilized for the elimination of pathogens in the food industry, as it is a particularly suitable technology for the pasteurization of heat-sensitive foods. However, due to the high investment costs of HPP equipment, the production costs of HPP products are slightly higher than that of non-HPP products, resulting in a higher average unit price for HPP products. Therefore, the utilization of HPP for pasteurization in the food industry is much lower than that of traditional thermal pasteurization. Due to the differences in production costs, different market positioning strategies must be adopted for HPP products and thermally pasteurized products. At present, health foods are the most widely accepted high-priced food products among consumers. With the aging population becoming a global issue, the concept of preventive health care has gradually gained popularity in recent years, thereby providing a favorable environment for the global development of health foods. However, most health food products on the market come in the form of capsules or tablets, which are relatively expensive and unsuitable for consumption by certain consumers. Therefore, the development of health foods with a wider variety of forms is necessary. In actuality, the most convenient and cost-saving method for the consumption of health foods is direct intake through a balanced diet without an alteration of dietary habits. As high pressure has been proven to enhance the health-promoting components of foods, it is able to satisfy the needs of most consumers; therefore, the development of food products with health benefits will constitute the future trend of HPP product development. At present, pressure-tolerant probiotics have already been widely applied in a variety of HPP products, including fruit and vegetable juices, cold brew coffee, and cereal milk, which makes the consumption of probiotics possible for vegetarian consumers. Natural health-promoting materials extracted from medicinal herbs, plants, and animals are suitable for incorporation into HPP products, and the extraction costs of these materials can be reduced through the utilization of high-pressure extraction.

As a fixed customer base exists for various health food products and the relatively high prices of these products are generally accepted by consumers, the development of HPP health food products should be aimed towards the enhancement of nutrient intake by consumers without an alteration of dietary habits. Besides the retention of natural flavors and reduction of additives, the improvement of the health-promoting effects of various food components will serve as a key strategy for enhancing the attractiveness of HPP products. Through the review of the aforementioned literature, it can be concluded that high pressure can be potentially applied in the development of health foods. The ability of HPP to maintain microbial safety while increasing the nutritional value of food products will contribute to its applicability in the food or biotechnological industry.

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