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REVIEW



Effect of high hydrostatic pressure on the edible quality, health and safety attributes of plant-based foods represented by cereals and legumes: a review

Yangyue Ding^a, Qingfeng Ban^{a,b}, Yue Wu^a, Yuxue Sun^a, Zhihao Zhou^b, Qi Wang^b, Jianjun Cheng^a and Hang Xiao^b 

^aCollege of Food Science, Northeast Agricultural University, Harbin, Heilongjiang, China; ^bDepartment of Food Science, University of Massachusetts, Amherst, MA, USA

ABSTRACT

Consumers today are increasingly willing to reduce their meat consumption and adopt plant-based alternatives in their diet. As a main source of plant-based foods, cereals and legumes (CLs) together could make up for all the essential nutrients that humans consume daily. However, the consumption of CLs and their derivatives is facing many challenges, such as the poor palatability of coarse grains and vegetarian meat, the presence of anti-nutritional factors, and allergenic proteins in CLs, and the vulnerability of plant-based foods to microbial contamination. Recently, high hydrostatic pressure (HHP) technology has been used to tailor the techno-functionality of plant proteins and induce cold gelatinization of starch in CLs to improve the edible quality of plant-based products. The nutritional value (e.g., the bioavailability of vitamins and minerals, reduction of anti-nutritional factors of legume proteins) and bio-functional properties (e.g., production of bioactive peptides, increasing the content of γ -aminobutyric acid) of CLs were significantly improved as affected by HHP. Moreover, the food safety of plant-based products could be significantly improved as well. HHP lowered the risk of microbial contamination through the inactivation of numerous microorganisms, spores, and enzymes in CLs and alleviated the allergy symptoms from consumption of plant-based foods.

KEYWORDS

Edible quality;
high hydrostatic pressure;
legumes;
microbial safety;
nutrition attributes;
plant-based foods

Introduction

Plant-based foods have attracted growing attention in food industries due to their advantages over their animal counterparts, such as a lower risk of environmental pollution and health problems, less religious food habit limitations, targeting vegetarian consumers, along with their versatility and lower cost (Joshi and Kumar 2015; Nasrabadi, Doost, and Mezzenga 2021).

As a major source of plant-based foods, cereals and legumes (CLs) together could make up for all the essential nutrients that humans consume daily, i.e., carbohydrates, protein, lipids, vitamins and minerals (Gulati, Brahma, and Rose 2020). However, the consumption of plant-based products, represented by CLs and their derivatives, also faces many challenges: (i) *The edible quality of plant-based foods needs to be improved*: The poor palatability of coarse grains limits their consumption. For example, although brown rice has high nutritional value, it is not widely consumed because of its long cooking time, high hardness and chewiness, and undesirable rice bran odor (Y. Li et al. 2021). The utilization of legumes is also challenged by the phenomenon of hard-to-cook defects, which are developed during storage periods under noncontrolled temperature and relative humidity

conditions. (Coelho et al. 2007). In general, plant-based meat analogues are different from meat because they lack the fibrous structure, bite, and juicy mouth feel of meat (Sun et al. 2021). The acidification of plant proteins in plant-based yogurts often leads to weak gel formation and phase separation, which deteriorates the edible quality of plant-based dairy products (Sim, Hua, and Henry 2020). (ii) *The nutritional attributes of plant-based products need enrichment*: Leguminous crops such as soybean, pea, lentil, and chickpea have received interest due to their sustainability benefits, high nutritional values, and techno-functional properties for producing plant-based proteins. For example, soybean protein and pea protein are primarily used to replace and blend with animal muscle proteins for meat formulations. However, the limited consumption of legumes is mainly due to the presence of anti-nutritional factors such as protease inhibitors, lectins, tannins, and phytic acid, which impede the utilization, absorption, and digestion of nutrients (Linsberger-Martin et al. 2013); in addition, due to consumer's increasing attention to plant-based foods, the research on the bioavailability, enrichment, and extraction of nutrients and bioactive substances in CLs is increasing in recent years (Xia, Wang, et al. 2017). (iii) *The safety of plant-based foods needs to be strengthened*: The most used

proteins in plant-based products come from soy, peas, peanuts, and wheat; unfortunately, all of these grains, except peas, are among the eight major allergens. Specifically, ingestion of soy-containing food can cause immunological symptoms in soy-allergic individuals. These symptoms include urticaria, rhinitis, itching, asthma, anaphylactic shock, or even death (Yang et al. 2015). Wheat allergy, as one of the most common causes of food allergies in children, usually begins in early childhood; peanut allergy is also very prevalent in Western countries; CLs (e.g., rice, wheat, maize, soybean, peanut, barley, and oat) and derived products (e.g., flour, flakes, peanut butter, and beer) are often contaminated with microorganisms during harvesting, transportation, and storage, which decrease the safety of plant-based products. There is potent evidence showing the microorganism contamination of plant-based foods could induce the serious effects of immunosuppression, carcinogenesis, mutagenesis, and teratogenesis on human health (Mirza Alizadeh et al. 2021).

In recent years, there are increasing studies on the application of non-thermal processing techniques (e.g., ultrasound, irradiation, pulsed electric fields, low-temperature plasma, and high hydrostatic pressure) to improve the quality of plant-based foods (Bai et al. 2021; Borsato et al. 2019; Ferreira et al. 2021; Meng et al. 2019; Park, Puligundla, and Mok 2020). However, high hydrostatic pressure (HHP) is the most successful non-thermal technology commercialized in the last decade (Huang, Hsu, and Wang 2020). HHP technology is widely used in the processing of fruits and vegetables, cereals, dairy, meat, and seafood. This technique mainly employs water (typically water mixed with a small percentage of soluble oil for lubrication and anti-corrosion purposes) as a medium to transmit pressure (100–600 MPa) throughout the food system, aiming to produce products with high edible quality, microbial safety, and nutritional enrichment (Xia et al. 2019). The main advantages of HHP, such as instantaneous and homogenous transmittance of pressure in the treated food and the possibility of processing at ambient temperatures, represent a promising tool to implement mild post packaging processing for a broad range of plant-based foods (Koutchma 2014a).

The functionality and interactions of proteins and starch directly affect the sensory quality of plant-based foods. The sensitivity of protein structure to HHP is mainly due to weakening of hydrophobic and electrostatic bonds. In such cases, protein aggregates (e.g., casein micelles) separate into their subunits even at relatively low pressure (150 MPa). In general, when the pressure is higher than 300 MPa, the pressure will have irreversible effects on the protein, but not on the covalent bond; when it is higher than 700 MPa, the pressure has the potential to act on the secondary structure of the protein (Chauhan 2019). In addition, high pressure causes cold gelatinization of starch and preserves the starch granular integrity (especially when consumed as whole grain) due to the restricted swelling, which is important for improving the edible quality of coarse grains (Zhu et al. 2016). As far as healthy plant-based foods are concerned, HHP can increase the content or bioavailability of nutrients

and bioactive compounds (e.g., bioactive peptide, γ -aminobutyric acid, indispensable amino acids, vitamin B and E, mineral elements, resistant starch, and polyphenols, etc.) in CL matrix (Xia, Wang, et al. 2017). HHP also has the potential to reduce protein immunoreactivity by disrupting conformational epitopes and other mechanisms such as protein cross-linking or epitope masking (Lavilla, Puértolas, and Orcajo 2020). In terms of the microbial safety of plant-based foods, HHP can inactivate mycotoxins, and microbial enzymes and consequently can increase their shelf life (Mirza Alizadeh et al. 2021).

This review proposes to comprehend and synthesize the effects of HHP technology on the edible quality, health and safety attributes of plant-based foods represented by CLs, the great potential of HHP treatment lies in: (i) Improving the edible quality of plant-based foods by tailoring the techno-functionality of plant proteins, inducing cold gelatinization of starch in CLs, and increasing the content of volatile flavor substances. (ii) Enhancing health attributes of CLs by increasing the content or bioavailability of nutrients and bioactive compounds. (iii) Reducing the risk of allergy and microbial contamination.

Fundamentals of high hydrostatic pressure

Principles on the effects of HHP on plant-based foods

Plant-based foods are numerous with varying shapes, sizes, and packaging forms. According to the isostatic principle, pressure is instantaneously and evenly transmitted throughout the foods, independently of the size and geometry of the food. Thus, the product will return to its original shape after decompression (Abera 2019). Unlike thermal processing, where heat is transferred gradually through the food system, the instantaneous pressure transfer reduces processing time, processing energy, and the risk of over-processing of foods (Barba et al. 2015). In particular, food materials, whether in direct contact with the pressure medium or sealed in a flexible package, are applicable to this law.

The effect of HHP on biomolecules in plant-based foods also obeys Le Chatelier's law. The principle is under equilibrium conditions, any chemical reaction, phase transition, molecular transformation, etc., that indicates a decrease in volume is favored when the pressure increases (Chawla, Patil, and Singh 2011). The breaking of ionic bonds is increased by HHP, as this results in a volume decrease due to the electrostriction of water. In addition, hydrogen bonds are stabilized by HHP, as their formation involves a volume decrease. Therefore, biomacromolecules, such as proteins and starch, can tailor their structure and techno-functional properties subjected to HHP, due to changes in non-covalent bonds, such as hydrogen, ionic, and hydrophobic bonds, which are more sensitive to pressure (Barba et al. 2015). However, pressure usually does not affect covalent bonds, and thus HHP-treated CLs can retain their color, aroma, flavor, and nutrients (Koutchma 2014b).

HHP system and processing procedures for plant-based foods

HHP was first applied at a laboratory scale by Hite in 1899 to destroy microorganisms in milk to improve its shelf-life. The technology was considered an emerging process since the first industrial-scale systems were available in 1990 in Japan. The main components of an HHP system include a pressure vessel, which is a forged monotone cylindrical vessel that can be operated under different pressure conditions according to the inner diameter of the vessel (Sehrawat et al. 2021); closures for sealing the vessel; a device for holding the closures in place while the vessel is under pressure (e.g., yoke); an intensifier, or high-pressure pump to build up the pressure using a food-grade hydraulic oil; a system for controlling and monitoring the pressure and temperature, and a product-handling system for transferring product to and from the pressure vessel (Figure 1A) (Koutchma 2014c).

The HHP operation starts with loading prepacked foods (flexible packaging materials filled with liquid or solid foods) in perforated baskets, which are transported into the vessel and then pressurized by a pressure transmitting fluid (typically water mixed with a small percentage of soluble oil for lubrication and anti-corrosion purposes) (Huang, Hsu, and Wang 2020). In industrial-scale systems, the combined effect of a high-pressure pump with an intensifier is used to pump a pressure transmitting fluid directly into the vessel to achieve a pre-set pressure (indirect compression) (Balakrishna, Wazed, and Farid 2020). The foods are then held at a particular pressure for a specified duration. HHP process is environment-friendly as compared with the thermal process: once the pressure has been reached, no additional energy is required to maintain the pressure. This is followed by a quick decompression in seconds to minutes (Yamamoto 2017). The discharge valves then open, followed by the plugs, which are put back into their original position.

The vessel moves back to the loading/unloading position. Once in this position, the processed batch carriers are pushed into the unloading line, while the next batch of carriers is automatically loaded, ready for a new processing cycle (Figure 1B) (Proctor 2018).

Effect of HHP on the edible quality of plant-based foods

Tailor the techno-functionality of plant proteins

The functionalities of legume protein or cereal protein, such as water-holding capacity, solubility, emulsification, foaming, gelation properties, etc., are essential for plant protein-based foods. However, most plant-based proteins are limited in their application due to their poor water solubility, complexity, and susceptibility to pH, ionic strength, and temperature and often cannot substitute the function of animal proteins without subsequent processing (Nasrabadi, Doost, and Mezzenga 2021).

Plant protein solubility is an important parameter because it is related to other functional attributes, such as water-holding capacity, emulsification, foaming, gelling, and influences the palatability of many plant-based foods, including tenderness, juiciness, chewiness, and viscosity (Kyriakopoulou, Dekkers, and van der Goot 2019). An earlier study compared the effects of thermal treatment and HHP treatment on calcium-added soybean protein 1% (w/w) aqueous dispersions at pH 7.0. The results of this work showed that HHP treatment improved the solubility and colloidal stability of proteins, whereas conventional heat treatment did not. In addition, The HHP-treated samples also form transparent cold-set gels with great water holding capacity (Piccini, Scilingo, and Speroni 2019). The combination of HHP and the pH-shifting increased the solubility of soybean protein isolate (SPI) (Tan et al. 2021). The increase in the solubility of SPI is mainly due to the above

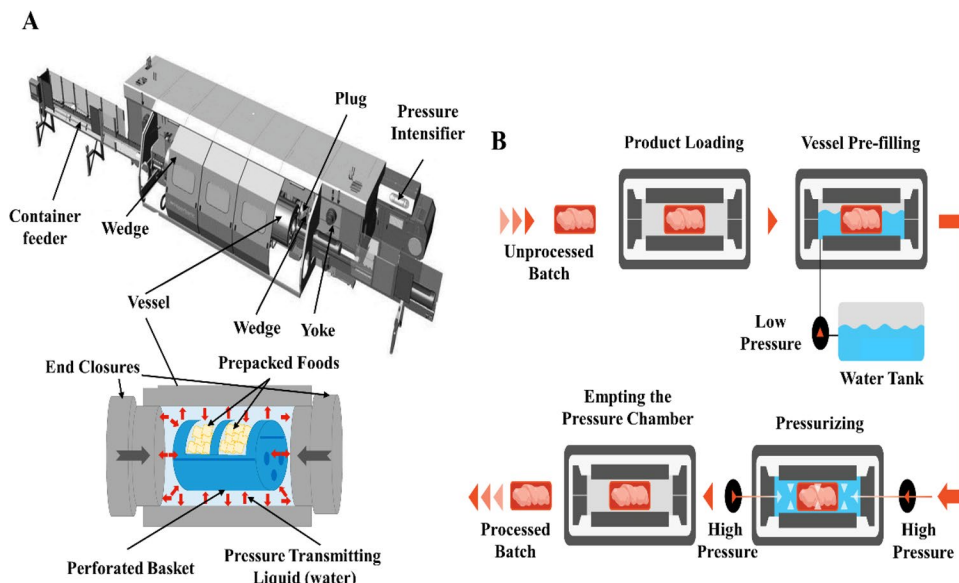


Figure 1. Basic components of a Hiperbaric HHP machine with pressure intensifiers (A); diagram of operation of an HHP unit (B) (Proctor 2018; Balakrishna, Wazed, and Farid 2020).

treatment inducing partial unfolding of the protein structure and changing the surface charge of the protein, thus facilitating the interaction of the protein with water. The increase in solubility may also be due to the increased conversion of insoluble aggregates to stable soluble aggregates, which can be attributed to the low molecular weight protein after HHP treatment (Gharibzahedi and Smith 2021). However, higher pressure levels (i.e., > 400 MPa) may reduce the solubility of plant proteins due to the exposure of buried sulfhydryl groups and insoluble macro-aggregate (Nasrabadi, Doost, and Mezzenga 2021).

Plant proteins are widely added to the emulsion-type systems (e.g., plant-based cream) as emulsifiers to facilitate droplet breakdown and maintain physical stability (Ningtyas, Bhandari, and Prakash 2021). However, due to their poor emulsification, a large number of plant proteins are still underutilized in food formulations (Kutzli, Weiss, and Gibis 2021). HHP appears as a good strategy to manipulate the surfactant properties of the proteins and their ability to facilitate the formation of dispersed food systems such as emulsions and foams, and to stabilize them (Queirós, Saraiva, and da Silva 2018). According to Chao, Jung, and Aluko (2018), at pH 3.0, the HHP-treated isolated pea proteins formed significantly higher quality emulsions with oil droplet sizes ($d_{4,3}$) of 26–68 μm compared to 52–92 μm for the control isolated pea proteins. HHP treatments facilitated the molecular diffusion of interior hydrophobic groups on the surface of smaller soluble particles to adsorb more oil droplets at the interface (Gharibzahedi and Smith 2021).

The demand for plant-based alternatives to dairy products has been increasing to alleviate the intense strain of animal husbandry on the environment. In recent years, the consumption of plant-based yogurt has been increasing and such products are mainly made through the fermentation of legume milk. In an early study, HHP of all legume protein samples (mung bean, chickpea, pea, lentil, and faba bean proteins) formed viscoelastic gels ($G' > G''$) with gel strengths ($G' \sim 102\text{--}103\text{ Pa}$; $\tan \delta \sim 0.2\text{--}0.3$) comparable to those of commercial dairy yogurt (Sim, Hua, and Henry 2020). HHP can form a uniform plant protein gel in the package with minimal ingredients and much faster than fermentation, making it a suitable structural alternative to plant-based yogurt (Queirós, Saraiva, and da Silva 2018).

Facilitate hydration and starch gelatinization

If water diffusion into the grains is inadequate, the starch located in the central part of the grain may not be completely gelatinized during cooking, resulting in a hard texture. The use of HHP is an alternative approach for accelerating hydration. The mechanism by which HHP promotes hydration of CLs is not thoroughly understood, but it is speculated that the mechanism may be similar to ultrasound treatment. Hydration is a mass transfer unit operation, and pressure may accelerate this transport phenomenon. Its effect is related to pressure travel through CL tissue, which causes expansion and contraction. These alternative changes cause the CL matrix to behave as a sponge, thus

improving mass transfer (Vásquez, Siche, and Miano 2021). Pressure can destroy the bran and germ (raphe and hilum) of cereals (legumes), creating new channels where water can penetrate. In addition, starch granules in CLs have pores and channels; some channels can extend into the hilum (Dhital, Brennan, and Gidley 2019). HHP may induce the dissociation of protein and lipids from within the pores and channels, thus facilitating water migration.

The cooking of CLs is a process of starch absorbing water, swelling and gelatinization, accompanied by protein denaturation. In other words, the palatability of CLs is dependent on the pasting and thermal properties of starch. HHP affects the multi-scale structure of starch by facilitating water molecules into the starch granules, weakening the double helix in the crystalline region and destroying the internal crystalline structure (Zhang et al. 2019; Han, Shi, and Sun 2020; P. L. Liu, Hu, and Shen 2010). Due to the key role of starch multi-scale structure in starch pasting and aggregation, their alteration may affect the edible quality of CLs. Therefore, HHP can be used as an innovative technology to obtain plant-based products with novel cooking/texture properties. Table 1 summarizes several results concerning the effect of HHP on hydration and starch gelatinization of CLs.

Rice (*Oryza sativa* L.) is the most consumed cereal crop worldwide. Although refined rice is easy to cook, brown rice and black rice are rich in fiber, which hinders water absorption and heat transfer during the cooking process. In addition, instant rice is still beset by problems including long rehydration time and inferior quality as compared to traditional cooked rice. Therefore, they are difficult to be accepted by most consumers as a staple food and a new processing technology is urgently needed to improve their eating quality. The effect of HHP treatment on the gelatinization degree of starch strongly depends on the pressure levels. In an early study, when the pressure reached 300 MPa, more hollows appeared in germinated brown rice (GBR) (Figure 2 A c) and starch gelatinization occurred, while when the pressure was increased to 500 MPa, brown rice exhibited greater cell sizes due to the endosperm cell expansion caused by the gelatinization of intercellular starch and water absorption after HHP (Xia, Tao, et al. 2017). However, the reduction of moisture and space within the kernels caused by extreme pressure limited the starch gelatinization (Xu et al. 2019). This may be due to the contraction or even disappearance of cracks in the kernel, which affected the water distribution. Moreover, based on the activation energy (E_a) and activation volume (ΔV), adverse effects of pressure on starch gelatinization were observed at extremely high pressure (Ravichandran, Purohit, and Rao 2018).

Common beans (*Phaseolus vulgaris* L.) are the most consumed legume crop worldwide. HHP can alter the hydration and drying rates of common beans. It was shown that HHP improved the beans hydration (4.7-fold faster), drying (27% higher water diffusion in 600 MPa-treated samples), and even rehydration (2.1-fold faster) (Belmiro, Tribst, and Cristianini 2018). In addition, the HHP-treated samples have higher initial hydration rate, firstly, because of the high pressure promoting the filling of capillary and intermicellar

Table 1. Effect of HHP on the edible quality of cereals and legumes.

Cereals and legumes	Treatment parameters	Main findings	References
Brown rice	Pressure range: 200–500 MPa, holding time: 5–15 min.	HHP promoted rice hydration with restricted swelling and intact starch granules. The gelatinization degree of brown rice, medium-milled rice, and fully milled rice was 41.2%, 50.2%, and 39.9%, respectively, after being treated with 400 MPa for 10 min.	Zhu et al. (2016)
Brown rice	Pressure range: 200–600 MPa, holding time: 0–20 min.	HHP shorten the cooking time of brown rice from 34 to 14 min. The hardness of brown rice treated with HHP was lower than that of soaked brown rice, similar to that of refined rice. When the pressure exceeded 500 MPa, the gumminess and springiness of brown rice decreased.	Y. Yu et al. (2015)
Brown rice	Germination duration: 36 h, germination rates: 95%, pressure range: 100–500 MPa, holding time: 10 min, temperature: 18 °C.	SEM images showed that starch granules gelatinized at 300 MPa, especially when the pressure increased to 500 MPa. Starch gelatinization reduced the hardness of germinated brown rice, simultaneously accompanied by the decrease of cohesiveness, gumminess, and resilience.	Xia, Tao, et al. (2017)
Brown rice	Pressure range: 100–500 MPa, holding time: 15 min, temperature: 20 °C. Germination condition: 37 °C/36 h.	The formation of aldehydes, alcohols, and ketones in germinated brown rice was enhanced by the HHP process, improving flavor. (E,E)-2,4-decadienal, (E)-2-hexenal, (E,E)-2,4-heptadienal, and benzyl alcohol were thought of as volatile biomarkers of high pressure.	Xia, Mei, et al. (2017)
Rice	Pressure range: 100–500 MPa, holding time: 30 min, temperature: 25 °C.	The water adsorption increased, and cooking time decreased. Parboiled rice (PR) samples presented higher lightness scores and had lower color intensity. HHP-treated rice showed a reduction of hardness values from 0.69 to 32.99%. The DSC results showed that the enthalpy of PR samples decreased after HHP soaking. The molecular structure of parboiled rice confirmed that HHP soaking could decrease the retrogradation level.	Wu et al. (2021)
Normal rice and waxy rice	Pressure: 300 MPa and 400 MPa, holding time: 25 min, temperature: 55 °C.	The hardness of rice decreased, while the springiness and cohesiveness increased after soaking in HHP. HHP reduced the retrogradation of cooked rice.	Y. Q. Tian et al. (2014)
Paddy rice	Pressure range: 100–600 MPa, holding time: 30 min, temperature: 25 °C.	HHP promoted the uniform distribution of water in rice grain and eliminated the “white-core” phenomenon. HHP reduced starch enthalpy.	Xu et al. (2019)
Long grain paddy	Pressure range: 350–550 MPa, holding time: 300–1200s, temperature: 30–50 °C.	In order to fully absorb water (40%, db) and partially gelatinize (16%), the recommended treatment conditions are 30 °C, 450 MPa, 600 s. Based on the energy of activation (Ea) and activation volume (ΔV), adverse effects of pressure on gelatinization were observed at extremely high pressure.	Ravichandran, Purohit, and Rao (2018)
Japonica rice and Jasmine rice	Pressure range: 200–600 MPa, holding time: 10 min, temperature: 25 °C.	Both 200 MPa and 400 MPa promoted alcohols, ketones, esters, and olefins while they caused a loss in heterocycles, alkanes, and arenes. Based on the changes in the three key flavor compounds in rice (aldehydes, alcohols, and ketones), the HHP process could be a suitable alternative to traditional pretreatment for improving the flavor in cooked rice.	Deng et al. (2013)
Jasmine rice	Pressure range: 300–570 MPa, holding time: 2–20 min, cycle mode: single or two cycles, temperature: 25 °C.	Jasmine rice that had been HHP processed and then microwaves heated for 1.5 min was more valued than jasmine rice just heated by microwave oven for 10 min, in terms of the grain shape, adhesiveness, cohesiveness, texture, and overall quality.	Boluda-Aguilar et al. (2013)
Black rice	Pressure range: 200–400 MPa, holding time: 15 min, temperature: 25 °C.	HHP improved the water absorption and texture characteristics of the cooked black rice and decreased the leached amylose. In addition, the retrogradation degree of HHP-soaked samples was lower than that of the control group (from 91 to 71%, storage for 21 days).	Meng et al. (2018)
Black rice	Pressure range: 200–500 MPa, holding time: 15 min, temperature: 25 °C.	The total content of three key flavor components in cooked black rice (alcohols, ketones, and aldehydes) following by HHP treatment increased. T_{21} value decreased with the increase of pressure, indicating that HHP reduced the retrogradation degree of cooked black rice.	Meng et al. (2020)
Common beans	Pressure range: 50–600 MPa, holding time: 1 min and 10 min.	HHP improved the common beans hydration (up to 4.7 times faster), drying (water diffusivity was 27% higher for sample processed at 600 MPa) and even rehydration (up to 2.1 times faster). Additionally, HHP reduced the cooking time of the beans in 15 min, due to the higher initial hydration.	Belmiro, Tribst, and Cristianini (2018).
Adzuki Beans	Pressure parameter: 200 MPa, pressure increase rate: 3.0–3.7 MPa/s, holding time: 10 min, temperature: 20 °C.	About 30% of adzuki bean seed coat was damaged, which was equivalent to the surface area of some peeled adzuki beans. HHP was confirmed to promote mass transfer to the cotyledon of legumes with a tight testa. HHP caused an increase in the effective diffusion coefficient of adzuki beans, thereby decreasing the water absorption time.	Ueno et al. (2015).
Foxtail millet	Pressure range: 200–600 MPa, holding time: 30–120 min, temperature: 20–80 °C.	HHP soaking improves the water absorption of germinated grains, thus increasing the starch gelatinization degree of flour, with the maximum value of 64.93%. The maximum value of effective diffusion coefficient of water was $6.77 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ at 200 MPa and 60 °C.	Sharma et al. (2018)

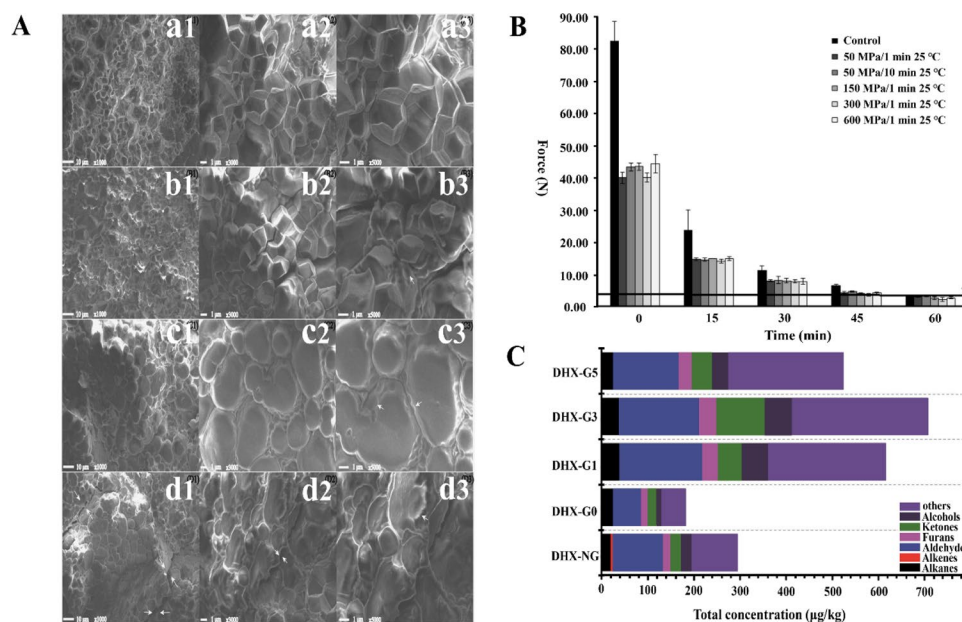


Figure 2. SEM images visualizing the different types of endosperm cells after HHP processing: a, GBR0 (0.1 MPa), b, GBR1 (100 MPa), c, GBR3 (300 MPa), d, GBR5 (500 MPa). a1–d1 (1000 ×), a2–d2 (3000 ×), and a3–d3 (5000 ×) (A) (Xia, Tao, et al. 2017); cooking of common beans, *black line means the expected texture obtained by using a pressurized pan at 121 °C /15 min (B) (Belmiro, Tribst, and Cristianini 2018); distribution of different chemical groups and total concentrations of the volatile organic compounds detected in differentially treated indica rice (Daohuaxiang JZX, DHX), NG: Non-germinated samples, G0–G5: 0.1–500 MPa (C) (Xia, Mei, et al. 2017).

spaces, and secondly, due to the promotion of the rapid transition of the husk from the glassy to the rubbery state, which can lead to significant improvements in the cooking characteristics of the beans. Hardness is usually used to define the cooking time of a product. As shown in Figure 2 B, the degree of hardness reduction during the cooking process was similar for all pressurized-common beans, which reached the desired hardness around 15 min before the unprocessed one.

Legumes have a more complex seed coat structure compared to cereal grains. This structure can be entirely or partially impermeable to water, depending on its composition and structure (Miano and Augusto 2018). After HHP treatment, about 30% of the adzuki bean seed coat was removed, which was equivalent to the surface area of some peeled adzuki beans (Ueno et al. 2015). Once the residual seed coat is hydrated from inside, it also becomes permeable to water (Miano and Augusto 2018). Therefore, HHP was shown to facilitate mass transfer to the cotyledon of legumes with a tight testa. In contrast, Balakrishna, Wazed, and Farid (2020) reported that HHP treatment alone did not reduce the hardness of the beans, even after a long processing time. The presence of heat is necessary to soften the beans with or without pressure. This processing prior to HHP treatment is to dissolve the pectin. The above-mentioned reports on the different effects of HHP treatments on the hardness of legumes may be due to differences in pressure levels and legume varieties. To further improve the textural properties of the HHP-treated legumes, the legumes can be presoaked at high temperature for a short period of time to serve to soften the seed coat and remove the pectin.

Increase the content of volatile flavor compounds

Aroma is one of the main factors affecting taste and consumer acceptance. HHP has a stabilizing effect on low-molecular-weight volatiles and is considered an effective process for improving product flavor (Xia and Li 2018b). HHP has been found to have an indirect effect on the formation of volatile flavor compounds due to enzymatic or non-enzymatic chemical reactions (e.g., Maillard reactions, alcohol oxidoreduction, and lipoxygenase pathway) induced by high pressure (Xia, Mei, et al. 2017). In addition, the binding ability of small volatile components to starch/protein mixtures, the synergistic effect between different volatiles, and changes in starch structure may be the factors that influence the formation and release of headspace components from cooked CLs.

As shown in Figure 2 C, HHP increased the volatile contents of aldehydes, ketones, and alcohols, which are the most abundant volatiles in terms of quality and quantity, giving the rice its characteristic taste and odor. Among them, HHP exerted the most significant effect on aldehydes. Hexanal, the most abundant aldehyde compound in rice, is formed through the oxidation of unsaturated fatty acids such as linoleic and linolenic acids, catalyzed by lipoxygenase and hydroperoxide lyase (Viljanen et al. 2011). HHP causes the breakdown of the cell structure, thus allowing the enzyme to enter the extracellular environment and combine with fatty acids for conversion reactions. The increases in Ketone content may be due to modifications of protein aggregation, the folded-unfolded equilibrium of proteins, electrostatic and hydrophobic interactions, and on the thiol/disulfide exchange reactions or enzymatic inactivation

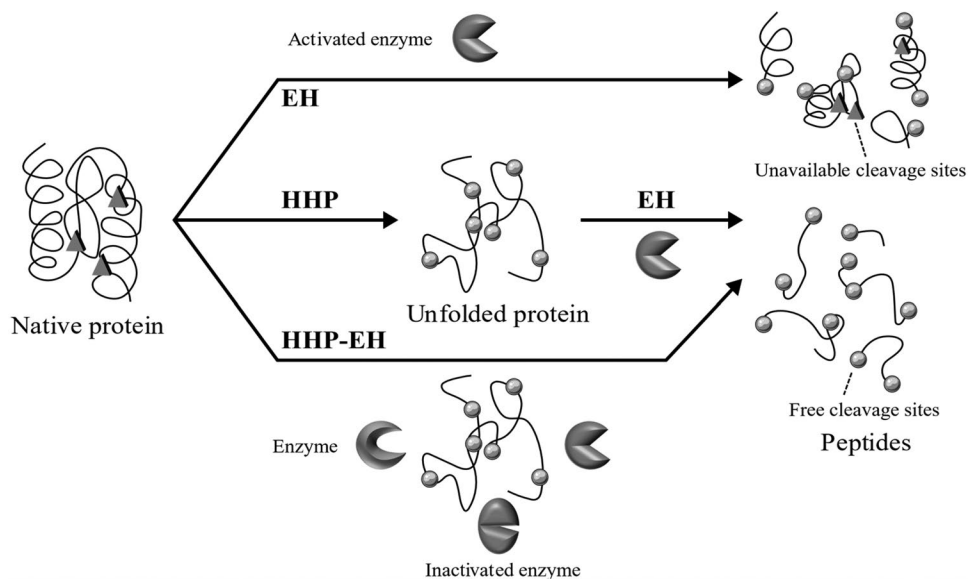


Figure 3. Mechanisms of improvement of enzymatic hydrolysis (EH) of plant proteins assisted by HHP (pretreatment – HHP + EH, or simultaneously HHP-EH) for the production of peptides (Marciniak et al. 2018).

caused by HHP (Deng et al. 2013). Overall, HHP increased total concentrations of aroma compounds in pressurized germinated brown rice (GBR), which was 523.63–706.03 $\mu\text{g}\cdot\text{kg}^{-1}$ for pressurized GBR, compared with the values of 181.24 for untreated GBR (Xia, Mei, et al. 2017). In a similar study, presoaked samples were cooked by HHP treatment at 200–600 MPa for 10 min (Deng et al. 2013), resulting in increased alcohols, ketones, esters, and olefins, but decreased heterocycles, alkanes, and arenes contents in Japonica rice and Jasmine rice. The degree of variation in volatile components depended on the pressure level and rice cultivars.

Effect of HHP on the bioactive substances and nutrients of plant-based foods

Facilitate protein hydrolysis and bioactive peptide production

HHP processing is a valuable tool for fortifying nutritional and functional properties and even potentially improving bioaccessibility/bioavailability. Table 2 provides a summary of recent findings on using HHP to improve the health benefits of CLs. Bioactive peptides have biological activities such as anti-inflammatory, antioxidant, antihypertensive, hypoglycemic, antibacterial, and immunomodulatory properties (Ulug, Jahandideh, and Wu 2021). HHP can lead to protein unfolding and improve its sensitivity to enzymatic hydrolysis by exposing enzyme access sites. Thus, pretreatment of proteins with HHP prior to enzyme treatment, especially when using pressure-sensitive enzymes, such as Trypsin or Alkaline Protease® or protein hydrolysis under HHP (simultaneous pressurization and hydrolysis), can be efficient strategies to produce bioactive peptides from plant proteins (Marciniak et al. 2018) (Figure 3). However, it has also been reported that enzymatic hydrolysis of proteins during HHP treatment not only weakens the economic

advantage due to the long processing time but also reduces the process efficiency related to enzyme instability (Gharibzadeh and Smith 2021). Additionally, proteins should be hydrolyzed immediately after HHP treatment since the susceptibility of HHP-treated proteins to hydrolysis is reduced with time.

M. Y. Kim, Jang, et al. (2017) detected the maximum content of < 3 and < 10 kDa peptides (60.46 and 88.47 mg) in the protein extracts of pre-germinated soybeans subjected to HHP (150 MPa), and low molecular weight peptides had a positive effect on the anti-inflammatory activity of the extracts. They also suggested that the HHP increases the conversion of tripeptides and proteins, which may have a positive effect on anti-inflammatory activity (M. Y. Kim et al. 2018). In another study, pinto bean protein concentrate was hydrolyzed by subtilisins at 0.1–200 MPa (Garcia-Mora et al. 2016). They found that alcalase hydrolysis increased the content of small peptides, flavonoids, and total phenolic compounds, as well as oxygen radical absorbance capacity of hydrolysates at 200 MPa. Similarly, soybean protein hydrolysates treated at high pressure at 200 MPa for 4 h to obtain active peptides with high antioxidant activity and angiotensin-converting enzyme inhibitory activity (Guan et al. 2018). We can find that a mild pressure (≤ 200 MPa) is more suitable for the production of bioactive peptides, which may be due to the over-pressurization that may cause protein aggregation and reduce the hydrolysis rate.

Increase of GABA content

Gamma-Aminobutyric acid (GABA) is a non-protein-free amino acid that can reduce blood pressure, control obesity, relieve anxiety, and boost immunity. In CLs, GABA is mainly produced from glutamate (Glu) via the catalyzation of glutamate decarboxylase (GAD) (Zhao et al. 2017). HHP promotes the activity of GAD and thus enhances the accumulation of GABA in plant tissues.

Table 2. Effect of HHP on the health attributes of cereals and legumes.

Cereals and legumes	Treatment parameters	Main findings	References
Black soybean	Germination time: 4 days, pressure: 150 MPa, holding time: 24 h.	Germinated black soybean has anti-inflammatory activity. HHP enhances this activity and increases the conversion of marker compounds (tripeptides, anti-inflammatory active tripeptides, and Arg-Asp-Gly) and proteins, which may have a positive effect on physiological activity.	M. Y. Kim et al. (2018)
Black soybean	Germination condition: 20°C/2 or 4 days, 95% relative humidity, pressure range: 0.1–150 MPa, holding time: 12 or 24 h, temperature: 25°C.	Pre-germinated soybean extracts treated with HHP processing inhibited the expression of pro-inflammatory cytokines (TNF- α , IL-1 β , and IL-6) in LPS-induced RAW 264.7 macrophages.	M. Y. Kim, Jang, et al. (2017)
Pinto bean	Pressure range: 100–300 MPa, holding time: 15 min, enzymatic reactions: Alcalase and Savinase (0.1 U/mg protein), temperature: 80°C, time: 15 min.	Alcalase hydrolysis at 100 MPa or 200 MPa led to a higher angiotensin-converting enzyme inhibition, reducing power, and free radical scavenging activity of hydrolyzates. In particular, alcalase hydrolysis increased the content of small peptides, flavonoids, and total phenolic compounds of hydrolyzates at 200 MPa.	Garcia-Mora et al. (2016)
Soybean	Enzymatic reactions: Corolase PP (4000 U/g)/ 50°C, pressure range: 80–300 MPa, holding time: 1–5 h, temperature: 50°C.	Hydrolysates obtained at 200 MPa for 4 h had higher bioactivities (e.g., reducing power, ABTS radical-scavenging, and ACE inhibitory activities).	Guan et al. (2018)
Brown rice	Germination condition: 37°C/36 h, pressure range: 100–500 MPa, holding time: 10 min, temperature: 18°C.	The in vitro bioavailability of Ca and Cu was increased by 12.59–52.17% and 2.87–23.06%, respectively, after HHP treatment. Additionally, HHP increased essential amino acids and GABA contents, as well as the total antioxidant activity and starch anti-enzymatic capacity.	Xia, Wang, et al. (2017)
Brown rice	Pressure range: 50–350 MPa, holding time: 20 min, germination condition: 37°C/48 h.	The GABA contents depended on the pressure applied, showing a 25% increment in 50 MPa-stressed grains compared to the control.	Xia, Wang, and Li (2018)
Brown rice	Pressure: 30–90 MPa, holding time: 5 min, temperature: 21°C, germination condition: 37°C/52 h.	Moderate high pressure can act as a stress factor to increase GABA by inducing an adaptive response to HHP shock during germination. HHP pretreatments at mild pressures also favored the retention of Zn and Fe. In addition, HHP improved bioaccessible free amino acids during in vitro digestion.	Xia and Li (2018a)
Soybean	Pressure: 30 MPa, holding time: 5 min, germination condition: 37°C/48 h.	The highest GABA concentration was 12.35 μ mol/g (dry basis) in Glu-soaked pressurized soybean at 2 days, while that in water-soaked at 0 day was 0.90 μ mol/g, which indicates that HHP processing promoted the proteolysis and specific Glu metabolism.	Ueno et al. (2010)
Brown rice	Germination condition: 37°C/48 h, 80% relative humidity, pressure range: 0.1–100 MPa, holding time: 24 h, temperature: 37°C.	The total polyphenol content and of GABA and γ -oryzanol in germinated brown rice was maximum at 30 MPa and 50 MPa, respectively. While the phytic acid content of germinated brown rice was decreased from 6.1 and 4.2 mg/g at 0.1 MPa to 3.0 and 1.1 mg/g at 100 MPa.	M. Y. Kim, Lee, Jang, Li, et al. (2015)
Brown rice	Germination condition: 37°C/1–6 days, 80% relative humidity, pressure: 30 MPa, holding time: 24 or 48 h, temperature: 37°C.	The combination of germination and HHP was shown to enhance GABA accumulation in brown rice. The highest GABA content of 121.21 mg/100 g was found in 2-day-old germinated seeds treated with high pressure (30 MPa, 48 h). The highest vitamin E content was observed after HHP treatment at 30 MPa for 24 h (4.07 mg/100 g) with 2 days of germination.	M. Y. Kim, Lee, Jang, Park, et al. (2015)
Rice	Pressure: 600 MPa, holding time: 30 min, temperature: 30°C, retrogradation: 0–14 days, 4°C.	After 7 days of retrogradation, the SDS content of HHP-gelatinized non-waxy starch (36.7%) was higher than that of heat-gelatinized starch (33.9%).	Y. Tian et al. (2014)
Tartary buckwheat	Pressure range: 120–600 MPa, holding time: 20 min.	HHP-600 MPa had the lowest RDS content (17.0%) and the highest SDS (50.5%) and RS (6.7%) levels.	H. Liu et al. (2016)
Dry bean	Pressure range: 150–600 MPa, holding time: 5–15 min, temperature: 25°C.	HHP-600 MPa led to insoluble dietary fiber reduction, including RS, whereas 150–450 MPa increased RS, without modifying soluble and insoluble dietary fiber.	Lin et al. (2020)
Waxy corn	Pressure: 300–600 MPa, pressure increase rate: 350 MPa/min, holding time: 15 min.	HHP increased the crystallinity of normal corn starch and waxy corn starch, thus enhancing the RS content. HHP gelatinized waxy corn starch gel requires a longer retrogradation time to obtain a higher RS yield.	Li et al. (2016)
Rough rice	Germination condition: 37°C/2 days, 80% relative humidity, pressure range: 0.1–100 MPa, holding time: 24 h, temperature: 37°C.	The total phenolic acid content of brown rice increased from 85.37 μ g/g at 0.1 MPa to 183.52 μ g/g at 100 MPa. The combined treatment of germination and HHP increased the vitamin E content in rough rice compared to germination treatment alone.	M. Y. Kim, Lee, et al. (2017)
Rice	Pressure: 450 MPa and 600 MPa, holding time: 15 min and 30 min, temperature: 50°C and 70°C.	Pressure and temperature increased the vitamin B1 content in rice, but the rice was exposed to high pressure for a long time, resulting in some degradation of vitamin B1. The removal of the bran layer after HHP treatment assured palatability while retaining some of the vitamin B1.	Balakrishna and Farid (2020)

Split peas and whole white beans	Pressure: 100 and 600 MPa, holding time: 30 and 60 min, temperature: 20 and 60 °C.	HHP treatment reduced oligosaccharides, phytic acid and trypsin inhibitor activity in split peas and whole white beans.	Linsberger-Martin et al. (2013)
Red bean	Pressure range: 400–600 MPa, holding time: 5 min.	An effective reduction of trypsin inhibitor activity and phytic acid content was achieved using HHP at 600 MPa for 5 min. Total phenols, flavonoids, proanthocyanidins and total antioxidant capacity were more preserved in HHP-treated sample than in heat-treated sample.	H. Lee et al. (2018)
Chickpeas	Pressure range: 100–600 MPa, holding time: 10 min.	HHP processing reduced tannin to 25 mg CE/ 100 g and phytic acid to 0.2% levels which were about one fifth of their content in raw chickpeas and significantly lower than in overnight soaked sample.	Alsaman and Ramaswamy (2020)
Common beans	Pressure: 50 MPa and 600 MPa, holding time: 1 min and 10 min, temperature: 25 °C.	The phytic acid content of common beans did not change after HHP treatment, but the tannin content decreased (probably due to leaching).	Belmiro, Tribst, and Cristianini (2020)
Red kidney bean	Pressure: 50–450 MPa, pressure increase rate: 100 MPa/min, holding time: 15 min.	The hemagglutination activity of phytohemagglutinin decreased significantly when the pressure was increased to 450 MPa. The results show that the phytohemagglutinin undergoes unfolding at pressures < 450 MPa and aggregates at 450 MPa.	C. C. Liu et al. (2013)

The potential pathways of GABA accumulation in CL tissues promoted by HHP is illustrated in Figure 4 (adapted from Poojary et al. [2017]). (i) Moderate pressure causing metabolic and/or mechanical disruptions, leading to an increase in cytoplasmic proton (H^+) concentration, inducing an acidic pH-dependent activation of GAD and GABA synthesis. (ii) Increased cytosolic Ca^{2+} forms complexes with calmodulin (CaM), and Ca^{2+} /CaM activates GAD in the physiological pH range. The pressure causes structural changes in Ca^{2+} channel proteins, which in turn promote GABA synthesis (Kinnersley and Turano 2000). (iii) In addition, HHP can disrupt cellular structures by activating cellulase or mechanical forces; therefore, it can accelerate the mass transfer of Glu or GAD and contribute to the enhancement of the interaction between Glu and GAD, which may facilitate the accumulation of GABA (Poojary et al. 2017).

According to Xia, Wang, et al. (2017), a pressure (> 100 MPa) may not increase GABA content in CL tissues.

They found a 25% increase in GABA content in the grains treated with 50 MPa compared to the control group. However, when the pressure was increased to 200 MPa, the GABA content in germinated-brown rice started to decrease (Xia, Wang, and Li 2018). They also suggested that the moderate HHP shock facilitated biotransformation of GABA during germination, which is likely to act as a stress protector conferring high-pressure stress tolerance (Xia and Li 2018a). In a similar study, the GABA content in germinated brown rice reached a maximum at 50 MPa (111.4 mg/100 g) and then decreased to 93.2 mg/100 g at 100 MPa (M. Y. Kim, Lee, Jang, Li, et al. 2015). They also reported that the maximum GABA content of 121.21 mg/100 g was found in 2-day-old germinated brown rice treated with high pressure (30 MPa, 48 h) (M. Y. Kim, Lee, Jang, Park, et al. 2015). In another study, HHP of soybean in Glu solution caused higher accumulation of GABA, which suggests that both proteolysis and specific Glu metabolism were accelerated by HHP (Ueno et al. 2010).

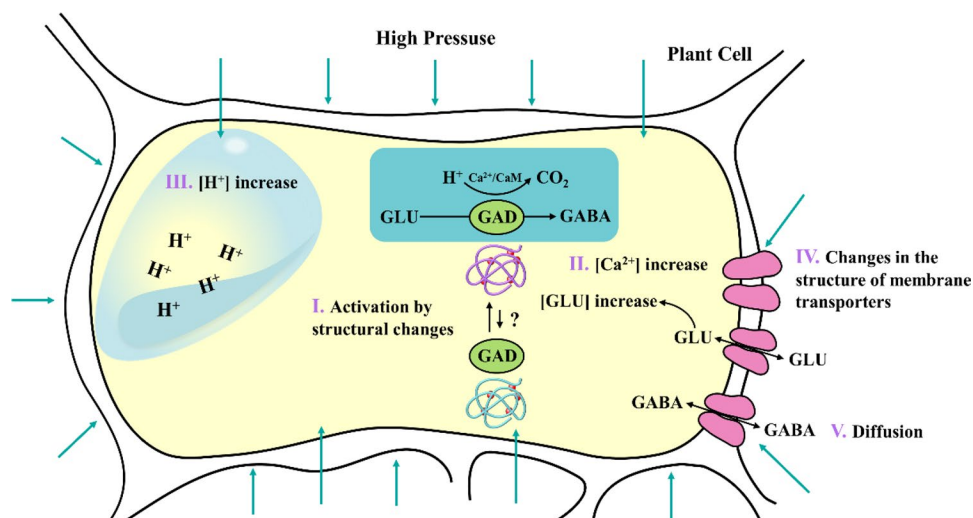


Figure 4. Potential mechanisms for HHP-induced GABA accumulation in CLs adapted from Poojary et al. (2017), glutamate (GLU), glutamate decarboxylase (GAD).

Increase of slowly digestible starch and resistant starch fractions

During heat gelatinization, starch granules absorb water and swell, and the growth rings and crystalline features disappear. In contrast, during pressurized gelatinization, starch granules can swell but tend to maintain their granule shape and lamellar structure (Figure 5) (Yamamoto et al. 2006). Thus, the HHP-treated starch granules exhibit an intact structure, which prevents the enzymes from entering the granules and hinders starch hydrolysis. In addition, HHP facilitates the formation of amylose-lipid complexes (i.e., RS type 5). The formation of the complex inhibits the swelling of starch granules and prevents them from being hydrolyzed (Guo et al. 2018). Castro et al. (2020) also reported that the amylose content and crystallinity of pressurized starches were superior to the native starch, resulting in a lower hydrolysis rate.

Y. Tian et al. (2014) found that HHP completely gelatinized the non-waxy rice starch granules, but the pressurized starch retained intact granules. The SDS content of HHP-gelatinized non-waxy starch (36.7%) was higher than that of heat-gelatinized starch (33.9%) after 7 days of retrogradation. In another study, HHP increased the crystallinity of corn starch, thus enhancing the RS content. HHP gelatinized waxy corn starch gel requires a longer retrogradation time to obtain a higher RS yield (W. Li et al. 2016). The effect of HHP on RS content was also dependent on the applied pressure level. HHP-600 MPa led to insoluble dietary fiber (IDF) reduction, including RS, whereas 150–450 MPa increased RS, without modifying IDF content. The increase of RS may be due to the tightly-packed complexes of globular starch granules-protein cell wall fiber formed at HHP $\leq$ 450 MPa (Lin et al. 2020).

Improve the bioavailability of minerals and vitamins

Phytic acid molecules are negatively charged at physiological pH, and they can bind to important divalent cations such

as Fe, Zn, Mg, and Ca form insoluble complexes, thus inhibiting the bioavailability of minerals (H. Lee et al. 2018). HHP treatment is effective in reducing the phytic acid content in CLs, thus also improving the bioavailability of mineral materials. According to Xia, Wang, et al. (2017), HHP treatment increased the in vitro bioavailability of Ca and Cu in brown rice by 12.59–52.17% and 2.87–23.06% after HHP treatment at 0.1–500 MPa, respectively. In a subsequent study, they found that HHP treatment under mild pressure (30–90 MPa) facilitated the retention of Zn and Fe in brown rice (Xia and Li 2018a). They also reported an increase in the bioavailability of minerals at a pressure of 300 MPa due to cell disruption, which resulted in the release of minerals into the extracellular environment; however, as the pressure increased, the bioavailability of minerals decreased due to the encapsulation from gelatinized starch (Xia, Tao, et al. 2017).

The combined treatment of germination and HHP increased the vitamin E content in rough rice compared to germination treatment alone (M. Y. Kim, Lee, et al. 2017). In another study, pressure and temperature increased the vitamin B1 content in rice, but the rice was exposed to high pressure for a long time, resulting in some degradation of vitamin B1. The removal of bran layer after HHP treatment assured the palatability while retaining some of the vitamin B1 (Balakrishna and Farid 2020). Prior to milling, the rice is soaked under pressure in order to transfer the vitamins and minerals from the bran layer into its white kernel itself, and/or all the vitamins and minerals in the cooked rice should be assembled from its bran layer (Hashimoto et al. 2020).

Reduce the anti-nutritional factors in legumes

The nutritional values of legumes are reduced due to the presence of several anti-nutritional factors. These include tannins, phytic acid, lectins, trypsin inhibitors and flatulence-causing oligosaccharides (Khattab and Arntfield

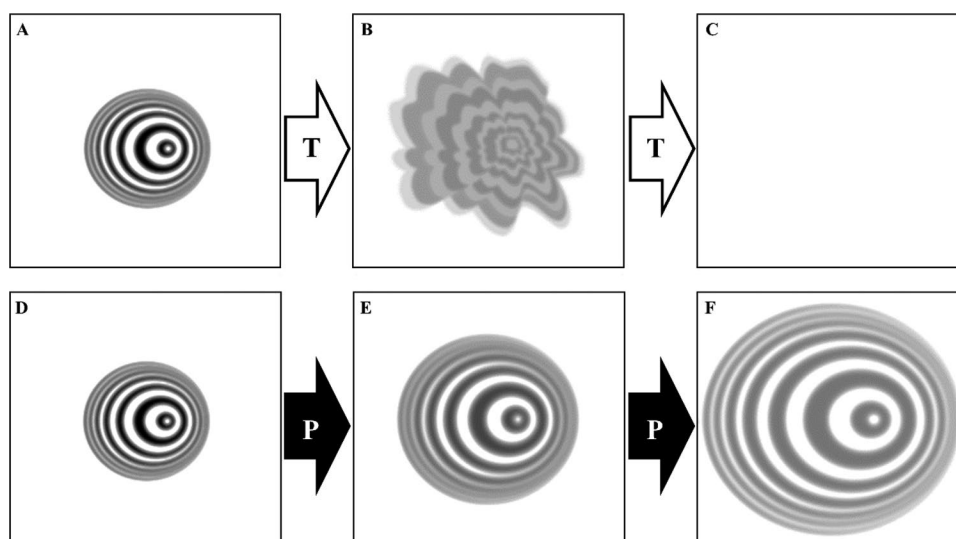


Figure 5. Schematic diagram of heat gelatinization of a starch granule (A–C); Schematic diagram of pressure gelatinization of a starch granule (D–F) (Yamamoto et al. 2006).

2009). In addition, the digestibility of legume proteins is lower than other animal proteins mainly due to intrinsic structural factors and anti-nutritional factors. Boiling reduces phytic acid and tannins in legumes and inactivates trypsin inhibitors and lectins in legumes. However, increasing the time and temperature of cooking can reduce the nutritive value of legumes. In recent years, HHP treatment as a non-thermal technique has been shown to be effective in removing anti-nutritional factors from legumes.

Linsberger-Martin et al. (2013) showed that phytic acid was reduced by HHP processing by up to 36% in split peas and 11% in whole white beans. Regardless of the duration, the protein digestibility of beans could be increased by up to 8.7% at 600 MPa and 60 °C treatment, and that of peas could be increased by 4.3% at 600 MPa and 60 °C treatment for 60 min. H. Lee et al. (2018) investigated the effect of HHP on the anti-nutritional factors of red bean flour. The results showed that the use of HHP at 600 MPa reduced the activity of trypsin inhibitors by 80.5% while preserving the sensory and nutritional quality. In addition, the phytic acid contents of HHP in 600 MPa processed samples decreased to 8.19%, compared with the control samples. The decrease in phytic acid may be related to the hydrolase activity of phytase, or it may be due to insoluble complexes formed by phytic acid with other components. In a similar study, the HHP processing reduced the tannin content to 25 mg CE/100g and the phytic acid content to 0.2%, about 1/5 of the raw chickpea content, significantly lower than the overnight soaked samples (Alsaman and Ramaswamy 2020). Legumes are rich in lectins, but kidney beans contain more lectins than other beans. The lectin extracted from red kidney beans is known as phytohaemagglutinin (PHA), and the anti-nutritional effect of PHA is manifested by reduced epithelial resistance to digestive enzymes, which occasionally leads to acute gastroenteritis. According to C. C. Liu et al. (2013), HHP increased the crude extract yield of PHA and decreased its haemagglutination activity. For purified samples, the PHA yield was not affected at pressures < 450 MPa, while the haemagglutination activity was reduced at 450 MPa.

Effect of HHP on the safety attributes of plant-based foods

Reduce the allergenicity of plant proteins

Food allergies have become a growing concern, affecting about 10% of the population according to the latest estimates, with a higher prevalence in infants and children, especially in developed countries (Vanga et al. 2019). The main CLs causing allergies are soybean, peanuts, and wheat, but the incidence of allergy to other legumes (e.g., lentils, peas, and lupins) is also increasing in some specific countries. Table 3 provides a summary of recent findings on using HHP to improve the safety attributes of CLs.

HHP reduces the allergenicity of allergens through different mechanisms, such as protein denaturation, protein aggregation or cross-linking, allergen extraction, protein conformational changes, and increasing enzymatic proteolysis

(Figure 6). The major allergenic proteins share some common characteristics: the allergenic proteins are relatively stable to heat treatment, acids, and resistant to proteolysis. However, further aspects such as food preparation, food matrix, and food processing can also affect allergenicity (Huang et al. 2014). The tertiary structure of proteins is critical for allergenicity, and thus HHP processing has an advantage in reducing protein immunoreactivity by disrupting conformational epitopes and other mechanisms (e.g., epitope masking or facilitating enzymatic hydrolysis) (Lavilla, Puértolas, and Orcajo 2020).

β -conglycinin is a strongly antigenic protein in soybeans, accounting for about 20–30% of the total soybean protein. β -conglycinin is a heat-stable protein, heat treatment can change its molecular structure and reduce its allergenicity to some extent, but the effect is usually not satisfactory. HHP combined with heat treatment changed the secondary structure of the protein from ordered to disordered and altered the degree of polymerization of the protein. These structural changes may have led to the reduction of β -accompanin antigenicity (Bu et al. 2020). Xi and He (2018) reported that the antigenicity inhibition of β -conglycinin decreased from 92.72 to 55.15% after treatment with 400 MPa for 15 min. When the peptide synthesis was performed on the antigenic region, they also found that the peptide did not react with the antiserum against β -conglycinin, i.e., the area did not contain a linear epitope, which indicated that HHP processing changed the conformational structure of β -conglycinin and thus reduced its antigenicity (Xi, He, and Pi 2019). H. J. Li et al. (2018) performed ELISA on sera from Chinese children with a soy allergy and showed that HHP reduced the allergenicity of soybean protein isolate for infant formula by 45.5%. They also found that HHP processing resulted in the loss of allergenicity of the α and α' subunits of 7S globulin and the A1 and A1a subunits of 11S globulin implying that other allergens can tolerate the HHP process.

Peanuts are one of the major allergenic sources that can cause severe reactions and death. Ara h 1 is a major peanut allergen, accounting for 12–16% of total peanut protein, and induces more than 90% peanut-sensitive individual reactions. Pan et al. (2020) showed that the immunoreactivity of Ara h 1 was reduced after HHP processing (≥ 400 MPa). The maximum reduction was 74.32% at 600 MPa treatment for 1200s. The decrease in Ara h 1 immunoreactivity may be due to the change in the secondary/tertiary structure and the formation of new multimers, resulting in the inactivation of immunoreactive sites. Long et al. (2016) used indirect ELISA and PCR to study the effects of HHP and heat treatment on peanut Ara h 2 allergenicity and the effect of Ara h 2 treatment on the reduction of peanut allergenicity in animal models. At 55 °C and 600 MPa treatment for more than 10 min, the samples showed a significant decrease in IgE binding compared to heat treatment. In addition, in a BALB/c mouse allergy model, a significant reduction in specific IgE titers were observed in mice fed with HHP- and heat-treated peanuts, along with a decrease in serum histamine levels. Polyphenol

Table 3. Effect of HHP on the allergenicity of plant proteins and microbiological safety of cereals and legumes.

Samples	Treatment parameters	Main findings	References
Soybean protein	Pressure range: 100–600 MPa, holding time: 20 min; temperature: 60–100 °C, time: 20 min.	The antigenicity of β -conglycinin was reduced by 87.04% at 400 MPa and 100 °C for 20 min compared to the untreated sample.	Bu et al. (2020)
Soy protein isolate	Pressure range: 200–500 MPa, holding time: 5–20 min, temperature: 20 °C.	The antigenicity inhibition of β -conglycinin decreased from 92.72 to 55.15% after treatment with 400 MPa for 15 min. HHP induced structural modification of β -conglycinin and changed the antigenicity of β -conglycinin.	Xi and He (2018)
Soy protein isolate	Pressure range: 200–500 MPa, holding time: 5–20 min.	HHP at 300 MPa for 15 min reduced allergenicity by 45.5%. Western blotting and mass spectrometry analysis showed that HHP treatment altered the sensitization of α and α' subunits of 7S globulin and A1 and A1a subunits of 11S globulin. HHP may improve the safe use of soybean protein isolate in infant formulas.	H. J. Li et al. (2018)
Soybean protein	Pressure: 300 MPa, holding time: 15 min, temperature: 40 °C.	A significant decrease in antigenicity was observed in the sprouts obtained from HHP-treated soybean seeds. The total essential amino acid content and nutritional value, however, were reduced only by 18%.	Penas et al. (2011)
Peanut protein	Pressure range: 200–600 MPa, holding time: 150–1200s, temperature: 20 °C.	HHP treatment (≥ 400 MPa) combined with a longer duration reduced the immunoreactivity of Ara h1, with the highest reduction rate of 74.7% at 600 MPa (1200s).	Pan et al. (2020)
Peanut protein	Pressure range: 200–800 MPa, holding time: 5 and 10 min.	Ara h 1 and Ara h 2 immunoreactivities in crushed peanuts were reduced by 73.3% at 800 MPa. Peanuts treated with 600 MPa and 800 MPa had considerably lower aflatoxin levels, 0.26 mg/g, and 0.22 mg/g on a wet basis, respectively, than the control peanut aflatoxin level (9.08 mg/g) on day 30.	Huang, Yang, et al. (2014)
Peanut protein	Pressure range: 100–600 MPa, holding time: 5 and 10 min.	A significant reduction in IgE binding was observed when samples were treated at 55 °C and 600 MPa for more than 10 min compared to boiling treatment. In a BALB/c mouse model of allergy, a reduction in specific IgE titers was observed in peanut treated with high pressure and thermal fed mice, accompanied by reduced histamine levels in serum.	Long et al. (2016)
Peanut protein	Pressure: 300 MPa and 500 MPa, holding time: 3 and 10 min, temperature: 37 °C; polyphenol oxidase: 40 units.	HHP at 500 MPa combined with polyphenol oxidase induced an increase in cross-linking of allergens and a reduction (approximately 2-fold) in IgE binding, as compared to polyphenol oxidase alone.	Chung, Houska, and Reed (2013)
Buckwheat protein	Pressure range: 100–600 MPa, holding time: 1–30 min.	The IgE binding of buckwheat protein hydrolyzed with alkaline protease following HHP decreased by 83.8 to 100%.	C. Lee et al. (2017)
Rice	Pressure range: 200–600 MPa, pressure increase rate: 1000 MPa/min, holding time: 10 min.	With pressures of 400 MPa and 600 MPa, cooked samples remained unspoiled after 8 weeks of storage at 25 °C with sequences representing DNA from a highly heterogeneous mix of nonviable bacterial cells.	L. Yu et al. (2018)
Wheat	Pressure range: 100–300 MPa, holding time: 10–600s, temperature: 30 °C.	HHP (300 MPa, 10 min) terminated in mycotoxin content under the detection limit (0.5 mg/kg) for mycotoxins analyzed after storage of cereal grains (0 and 6 weeks).	Schmidt, Zannini, and Arendt (2019)
Maize	Pressure range: 100–600 MPa, holding time: 20 min, temperature: 45 °C.	The maximum reduction in ZEA and DON levels (caused by <i>Fusarium graminearum</i>) was obtained in maize grains when HHP (550 MPa) was utilized with heating at 45 °C and holding time 20 min.	Kalagatur et al. (2018)
Green bean	Pressure: 600 MPa, holding time: 10 min, temperature: 25 °C.	HHP resulted in a 3.7-log CFU/g reduction in <i>L. innocua</i> ATCC 51742, whereas microwave-assisted pasteurization processing showed a 9.0-log CFU/g reduction.	Inanoglu et al. (2021)
Red bean powder	Pressure range: 400–600 MPa, holding time: 5 min.	Microbial counts in the red bean flour were reduced to 1.83, 1.55, and 1.05 log CFU/g using HHP 400, 500, and 600 MPa.	H. Lee et al. (2018)
Grass pea	Pressure: 200–600 MPa, holding time: 5–25 min.	The reduction in β -diaminopropionic acid ranged from 36.00–71.22% compared to the untreated grass pea samples. Soaked-HHP treatment at 600 MPa with 9 h soaking time and 15 min pressurization time maximized the reduction of β -diaminopropionic acid.	Buta et al. (2019)

oxidase has been reported to cross-link proteins in the presence of caffeic acid, resulting in reduced allergenicity of the major peanut allergens. HHP at 500 MPa combined with polyphenol oxidase induced an increase in cross-linking of allergens and a reduction (approximately 2-fold) in IgE binding, as compared to polyphenol oxidase alone (Chung, Houska, and Reed 2013).

Wheat is also one of the eight allergenic foods; however, we did not find any reports of HHP reducing its allergenicity. HHP can improve the proteolysis of wheat gluten,

suggesting that this technique may be an effective method to obtain hypoallergenic hydrolysates (N. Kim 2017). Buckwheat allergy appears to be rather common among adults in certain Southeast Asian countries. C. Lee et al. (2017) indicated that HHP processing combined with alkaline protease hydrolysis prevented the IgE binding of buckwheat protein. Among them, the IgE binding of buckwheat protein decreased to normal levels in 11 patients' serum samples, and the IgE binding of serum samples decreased by 83.8 to 98.2% in 3 cases.

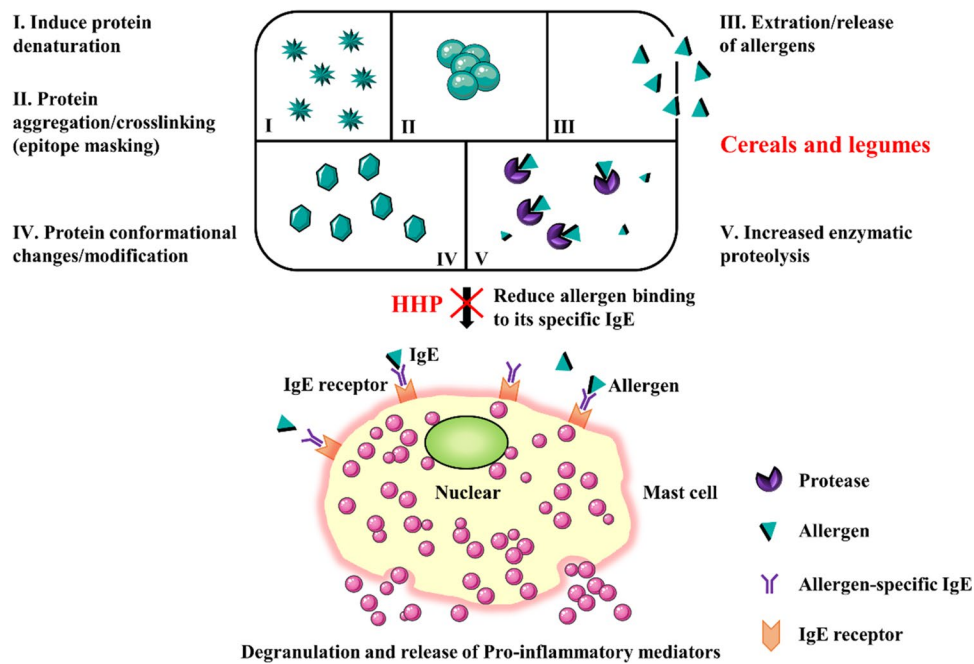


Figure 6. Mechanisms of HHP in reducing allergenicity of food allergen. Figure adapted from Huang, Yang, et al. (2014).

Inactivate microorganisms in cereals and legumes

CLs are susceptible to infection from various microorganisms (e.g., mycotoxin) on the farm or after harvest and storage. Some of the physicochemical properties of CLs, including pH, chemical composition, and water activity, are increasing the occurrence of microorganisms (Khodaei, Javanmardi, and Khaneghah 2021). The lethal impact of HHP on microbial populations are mainly due to simultaneous effects on cell membrane permeability, alteration of cell morphology, modification of biochemical reactions, and interference with genetic mechanisms occurring within microbial cells (e.g., disintegration of ribosomes in their subunits) (Figure 7) (Sehrawat et al. 2021). In addition, changes in intracellular pH caused by enzyme inactivation and damage to cell membranes induced microbial cell death.

The most common pathogen associated with cooked rice is *Bacillus cereus*, which, when present at high levels (usually $>10^5$ – 10^6 CFU/g), can cause vomiting or diarrhea-type illness. The cooked rice remained unspoiled after 8 weeks of storage at 25°C under pressures of 400 MPa and 600 MPa, with sequences representing DNA from a highly heterogeneous mix of nonviable bacterial cells (Yu et al. 2018). Another study reported that HHP treatment had a bactericidal effect on the microbial content (0 log CFU/g) in all varieties of rice and was better than atmospheric pressure plasma (APP) in regulating microorganisms. APP only sterilizes microorganisms on the rice surface that can come in contact with the plasma gas, which may be the reason for its lower sterilization rate than HHP (J. H. Lee et al. 2019). Kalagatur et al. (2018) studied the effect of thermal variation and HHP processing on the content of deoxynivalenol (DON) and zearalenone (ZEA) in maize kernels using response surface methodology. The maximum reduction in ZEA and DON contents (caused by *Fusarium graminearum*)

in maize kernels was observed when HHP (550 MPa) was heated at 45°C and held for 20 min.

Inanoglu et al. (2021) reported that microwave-assisted pasteurization processing (MAPS) resulted in 9.0–log CFU/g reduction of *L. innocua* ATCC 51742 in green bean broth, whereas the HHP treatment resulted in a 3.7–log CFU/g reduction. These results may be due to the higher resistance to pressure of *L. innocua* ATCC 51742 compared with that of *L. monocytogenes*. Thus, the MAPS treatment was more efficient in inactivating *L. innocua* ATCC 51742. Red bean powder (RBP) is widely added to bread, soups, and other snacks due to its sweet taste. However, food powders are generally produced without microbial control, and drying conditions and milling processes allow microbial growth due to cross-contamination. According to H. Lee et al. (2018), microbial counts in the RBP were reduced to 1.83, 1.55, and 1.05 log CFU/g using HHP 400, 500, and 600 MPa. The reduction in microbial population was most effective when treated at 600 MPa for 5 min, which was similar to the effect of heat treatment at 90°C for 15 min. The contamination of peanuts with aflatoxins is one of the most serious safety concerns in the world. Huang, Yang, and Wang (2014) indicated that peanuts treated with 600 MPa and 800 MPa had considerably lower aflatoxin levels, 0.26 mg/g and 0.22 mg/g in a wet basis, respectively, than the control peanut aflatoxin level (9.08 mg/g) on day 30. It is noteworthy that HHP processing cannot directly destroy aflatoxin, but it can still reduce the accumulation of aflatoxin by inhibiting *A. flavus* growth.

Limitations of HHP technology in plant-based food processing

HHP processing offers numerous advantages for a wide range of plant-based foods, but the application of HHP

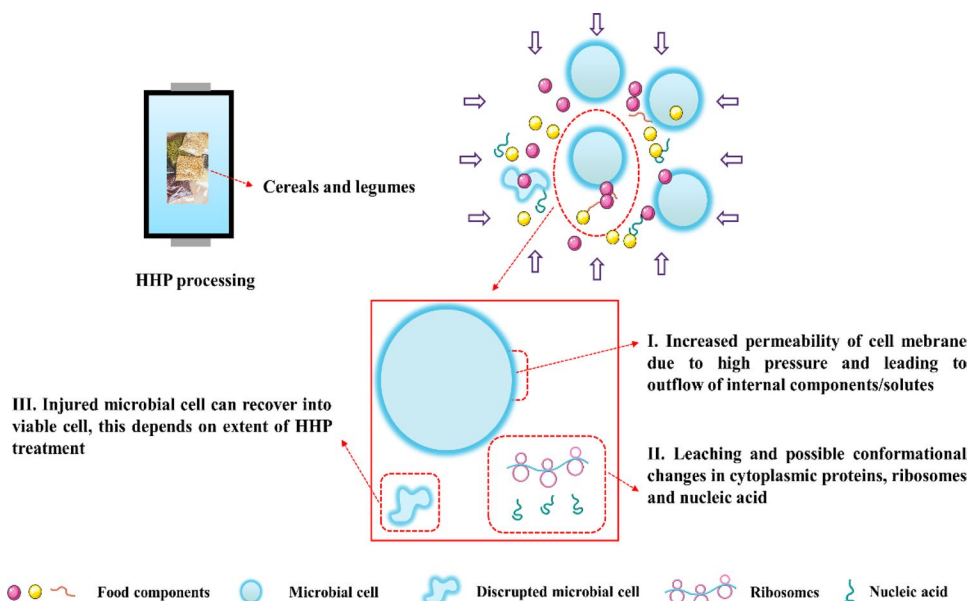


Figure 7. Schematic diagram representing cell membrane modification on high-pressure processing. Figure adapted from Rachna Sehrawat et al. (2021).

technology in the processing of such foods also faces some challenges: (i) High equipment costs limit the application of this technology. Specifically, the cost of the initial investment in equipment is estimated at \$0.6 to \$4 million, accounting for 75–80% of the investment (Ulug, Jahandideh, and Wu 2021). The cost of HHP per kg of food processed is significantly higher than the cost of heat treatment (5–10 times) (Proctor 2018). (ii) High-pressure equipment is at risk of pressure leaks. (iii) Higher pressure levels (i.e., > 400 MPa) may reduce the solubility of plant proteins due to the exposure of buried sulfhydryl groups and protein aggregation (Nasrabadi, Doost, and Mezzenga 2021). (iv) Due to the complexity of chemical reactions (denaturation and renaturation) involved in the pressurization and decompression processes, the protein aggregation caused by HHP may not achieve the expected hydrolysis. (v) This technique is not suitable for flour with a low water content, dried grains, or material containing large amounts of air bubbles because HHP requires water as the pressure transfer medium, and products containing air bubbles will be deformed under pressure (Huang et al. 2017). (vi) HHP treatment usually only alters non-covalent bonds, and enzymatic involvement is still required for the regulation of protein structure/conformation. (vii) In order to inactivate spores in plant-based foods, a combination of pressure (600 MPa) and temperature (> 100 °C) would be needed. The drawback is that the high temperatures that are applied alter the nutritional and organoleptic properties of the plant-based foods. These issues still need to be addressed for the widespread application of HHP technology to the processing of plant-based foods.

Conclusions and prospects

This review systemically summarizes the effects of HHP technology on the edible quality, health and safety attributes of

plant-based foods represented by cereals and legumes. HHP improves the palatability of plant-based products such as vegetarian meat and plant-based yogurt by adjusting the techno-functionalities of plant proteins (e.g., solubility and emulsification, etc.). HHP also promotes the cold gelatinization of starch within CLs, ensuring the edible quality of coarse grains. In terms of health attributes, HHP can increase the content and bioavailability of nutrients and bioactive compounds (e.g., bioactive peptide, GABA, vitamin B and E, mineral elements, and resistant starch, etc.) in CLs. In addition, the HHP treatment effectively reduces the allergenicity of plant proteins and inhibits the occurrence of mycotoxins, ensuring the safety of plant-based products for consumption.

The combination between HHP and germination has been well studied and showed a strong ability to improve the edible quality and bio-functions of CLs. However, the researches on other processing techniques with HHP (e.g., infrared sterilization, pulsed electric field, ultrasound, and UV-TiO₂ photocatalysis, etc.) are still scarce. By combining these technologies, the edible quality and food safety of plant-based foods can be further enhanced. For example, recent reports show that the combined treatment of UV-TiO₂ photocatalysis and high hydrostatic pressure can effectively inactivate spores that are highly resistant to pressure (J. U. Kim et al. 2021; Shahbaz et al. 2016).

HHP technology has become an industrial reality, and although there are still many aspects under research. Varieties of cereal or legume-based foods processed by HHP are commercially available in North America, Europe, Oceania, and Asia. Currently, commercially available plant-based (cereals or legumes) foods processed under HHP mainly include: plant-based milks and yogurts, plant-based meat, instant rice, plant-based dips and ready-to-eat porridge (Table 4).

The growth rate for the U.S. plant-based food market more than doubled in 2020, as sales surged 27% to \$7 billion, according to the Plant Based Foods Association

Table 4. Effect of HHP treatment on commercially available cereal and legume based foods.

Foods	Countries	Main benefits	Information sources
Rice cake	Japan	<i>Mochi</i> is a Japanese rice cake usually mixed with green herbs, which are susceptible to microbial contamination, and thus they are HHP-treated for enhanced food safety instead of heat treatment which damages their fresh color, flavor, and nutrients.	Yamamoto (2017)
Parboiled rice	Japan	Parboiled rice products are HHP-treated for improved water impregnation into the grains so that the texture should be improved.	Yamamoto (2017)
Pea protein-based meats	US	ARKK food company offers a variety of plant-based meats (Skinny Butcher brand), such as “chicken” breasts, ground “turkey” or “turkey” strips. The company can place these products in the market with a shelf-life of 75 days under refrigeration (not frozen) thanks to HHP.	https://skinnybutcher.com/
Hummus	US	Important companies such as Fresh Innovations and Ithaca Hummus have found in Hiperbaric's HHP technology an opportunity for success: from offering a product that maintains all the freshness and color of a freshly made one, but with a shelf life of more than 60 days, to guarantee total protection of the brand, avoiding contamination or recalls, since HHP processing is applied on the product already packaged.	https://www.fresh-innovations.com/ https://ithacahummus.com/
Ready-to-eat oats	US	MUSH Foods is a manufacturer and distributor of ready-to-eat oats. With HHP the company was able to increase the shelf-life of the product from one to eight weeks, without the addition of preservatives. In addition, HHP treatment can modify the native structure of starches, leading to gelatinization and enhancing the texture of certain products. Consequently, there is no need for fillers and/or binders to improve the consistency, as HHP contributes to a pudding-like texture.	https://eatmush.com/
Plant protein-based milks and yogurts	Canada	Plant Veda Foods Ltd. uses HHP to produce plant-based milks and yogurts. HHP treatment extends the shelf life of these plant protein-based beverages, improves their quality, and increases production efficiency.	https://www.plantveda.com/

(PBFA). HHP treatment is a useful technology to improve the formulation of plant-based products. HHP improves food safety and quality, extends shelf-life, and allows for a cleaner label with fewer ingredients. Therefore, the application of HHP technology for plant-based food production will be increasing in the near future. As advertised by Hiperbaric, there is a growing number of customers using their HHP equipment to process plant-based foods. However, the application of HHP technology in plant-based foods is still limited by high processing costs and difficulty in inactivating spores. Solving these problems will accelerate the application of this technology in plant-based food processing.

Author's contributions

Yangyue Ding, Qingfeng Ban, Jianjun Cheng, and Hang Xiao conceived and designed the review. Yue Wu and Yuexue Sun collected the literature. Yangyue Ding drafted the manuscript. Hang Xiao, Zhihao Zhou, Qi Wang, and Jianjun Cheng reviewed and edited the manuscript. All authors read and approved the manuscript.

Disclosure statement

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ORCID

Hang Xiao  <http://orcid.org/0000-0001-6194-2796>

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