High Pressure Processing for Gelatinization and Nutrients Infusion

Subjects: Engineering, Chemical
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High pressure processing (HPP) is a novel technology that involves subjecting foods to high hydrostatic pressures of the order of 100–600 MPa. This technology has been proven successful for inactivation of numerous microorganisms, spores and enzymes in foods, leading to increased shelf life. HPP is not limited to cold pasteurization but has many other applications. The focus of this entry is to explore other applications of HPP, such as gelatinization, forced water absorption and infusion of nutrients. The use of high pressure in producing cold gelatinizing effects, imparting unique properties to food and improving food quality has also been discussed, highlighting the latest published studies and the innovative methods adopted.

high pressure processing (HPP) gelatinization infusion quality improvement

1. Introduction

High pressure processing (HPP) or high hydrostatic pressure (HHP) are terms that describe subjecting foods to pressures in the order of thousands of atmospheric pressures. The foods are usually vacuum packed and placed into a basket, which is then loaded into the HPP machine, as shown in **Figure 1**.

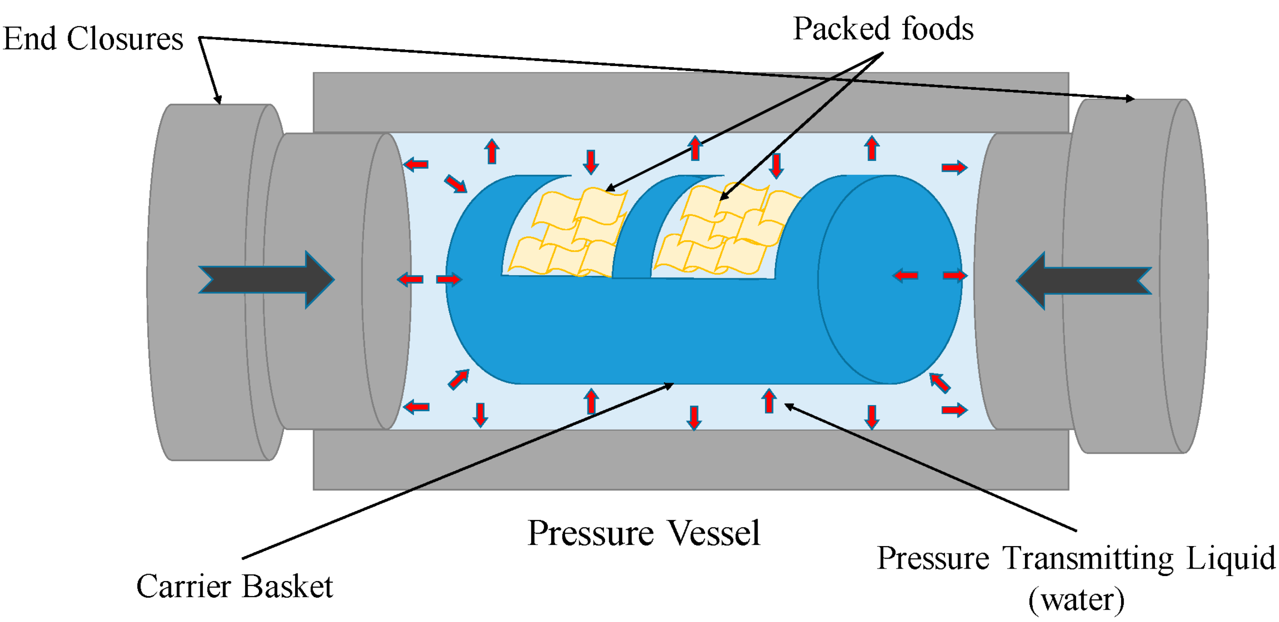

Figure 1. Schematic representation of a high pressure processing (HPP) vessel.

The two openings are closed with end closures and a pressure transmitting liquid, which is usually water, is used to pressurize the vessel. The combined effect of a high pressure pump(s) with a pressure intensifier(s) is used to generate the required pressure. The foods are then held at a particular pressure for a specified duration. This is followed by a quick decompression and unloading. Under compression, there is an increase in water temperature of up to 3 °C for every 100 MPa increase in pressure. Lipid-based foods experience a slightly higher increase in temperature with pressure [1]. The temperature returns to close to the initial temperature upon depressurization. HPP has been widely investigated for increasing the shelf life of foods through the inactivation of microorganisms [2], spores [3] and enzymes [4] present in foods. HPP can also be used for functional and physical modifications of foods [5][6]. It has also been tested for creating pressure-shift freezing and thawing, which is outside of the scope of this review. This review covers the application of HPP for inducing low temperature gelatinization, changing food properties and enhancing food quality. Some of the prior review works have been exclusively done on high pressure gelatinization of pure starch [7][8] and on high pressure infusions [9].

2. High Pressure Gelatinization

2.1. Starch Gelatinization

Starch is a polymeric carbohydrate that consists of two types of molecules, amylose and amylopectin (**Figure 2**). When starch granules swell up in the presence of water and heat, the process is called gelatinization. During this process, water molecules are adsorbed onto the amylose and amylopectin molecules, breaking the intermolecular hydrogen bonds present in starch. On cooling, starch loses water and reformation of hydrogen bonds takes place; this is called retrogradation. High pressure processing causes cold gelatinization of starches. Pea starch gelatinizes at 25 °C and pressures above 400 MPa. The presence of water is necessary, without which there will be no effect of pressure on starch [10].

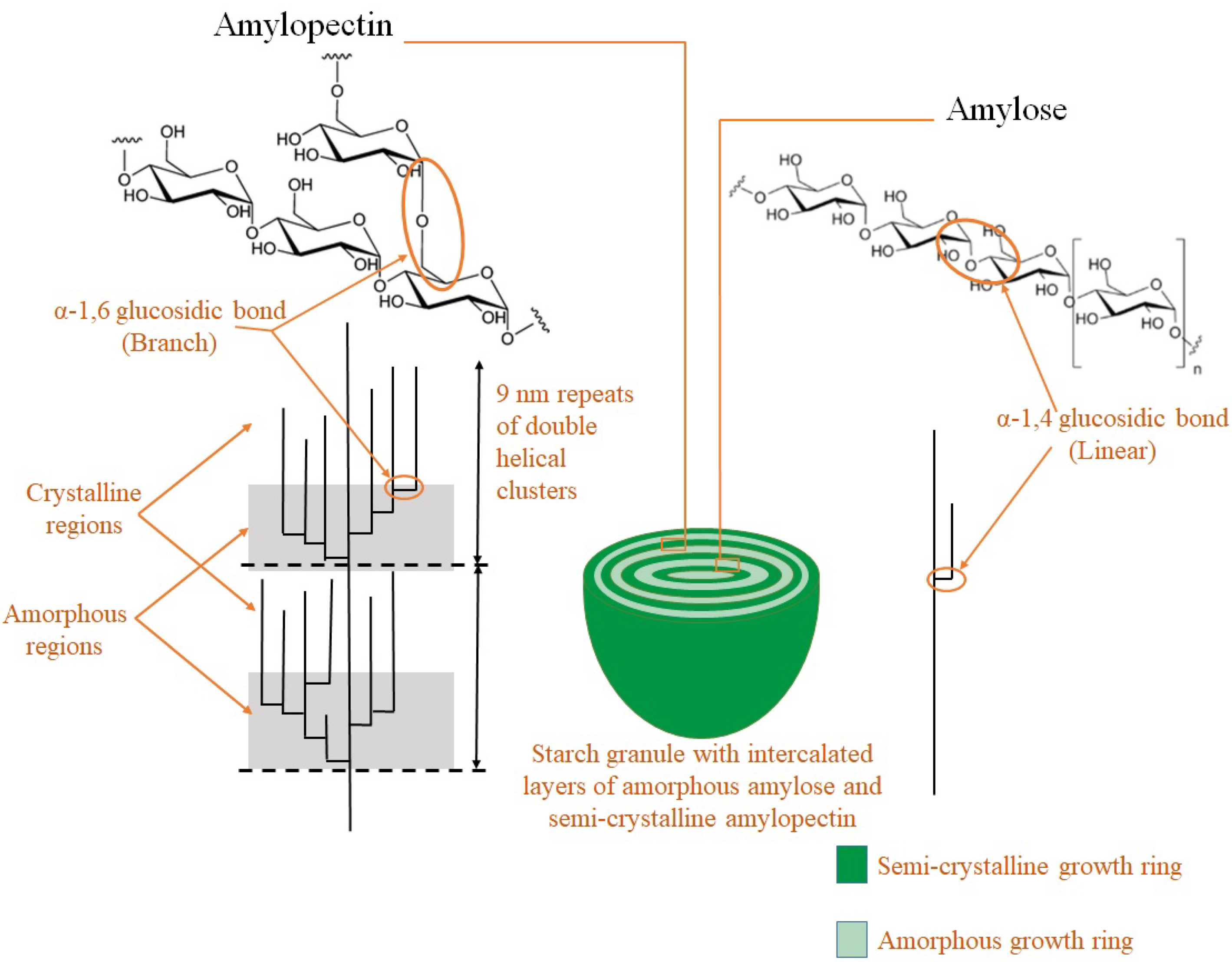

Figure 2. Schematic representation of a starch granule with its structure and types (redrawn from O'Neill and Field [11] and Raguin and Ebenhöh, 2017 [12]).

2.2. Gelatinization of Collagen

Gelatinization is not only restricted to starch. Gelatin or gelatine, commonly used as a gelling agent in foods, is made from collagen derived from animals. Collagen is a triple-helical heterotrimer and is stabilized by hydrogen bonds [13]. Collagen is treated with dilute acid or alkali for several days so that the hydrogen bonds and other interlinks present in the coils are cleaved such that water-soluble gelatin is produced. This is gelatin or gelatinized collagen (**Figure 3**). There have also been a few studies on the gelatinization of collagen using HPP. The use of HPP in gelatinization of collagen with acid as the pressure transmitting medium dramatically reduces the processing time. An investigation compared the traditional method of acid treatment with the high pressure method [13]. Results showed that HPP gelatinization carried out at 500 MPa reduced the processing time from more than 26 h to 15 min. Though the pressure treated collagen had a comparatively lower yield than the traditional method, the physical properties of the HPP treated gels were superior. The gel strength and rheological properties of high pressure processed gelatins were better than the traditionally prepared gelatins. The hardness, gumminess, chewiness and adhesiveness of the jelly made from HPP treated gelatin were greater than the commercial gelatin, while cohesiveness and springiness were similar [14]. Increasing acid strength for extraction increases the yield but slightly reduces gel strength [15].

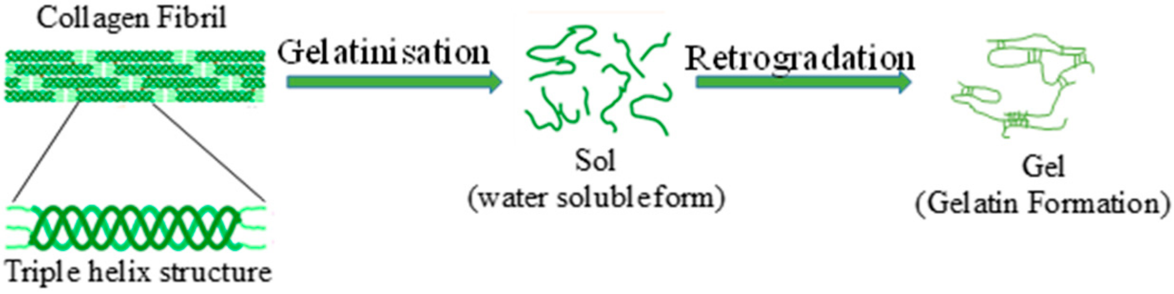

Figure 3. Gelatin made from collagen gelatinization (redrawn from von Endt and Baker 1991 [16]).

3. Forced Water Absorption in Foods Using HPP

Starch is one of the primary components in foods, but there has been some research on the effect of HPP treatment on the properties of whole foods as well. The process of immersion of foods into liquids for softening is called soaking. The process of soaking is generally long, and HPP has been used to fasten the process (**Figure 4**). High pressure conditions can change many physico-chemical properties of foods such as the changes in diffusivities, nutritional and anti-nutritional compound levels, etc.

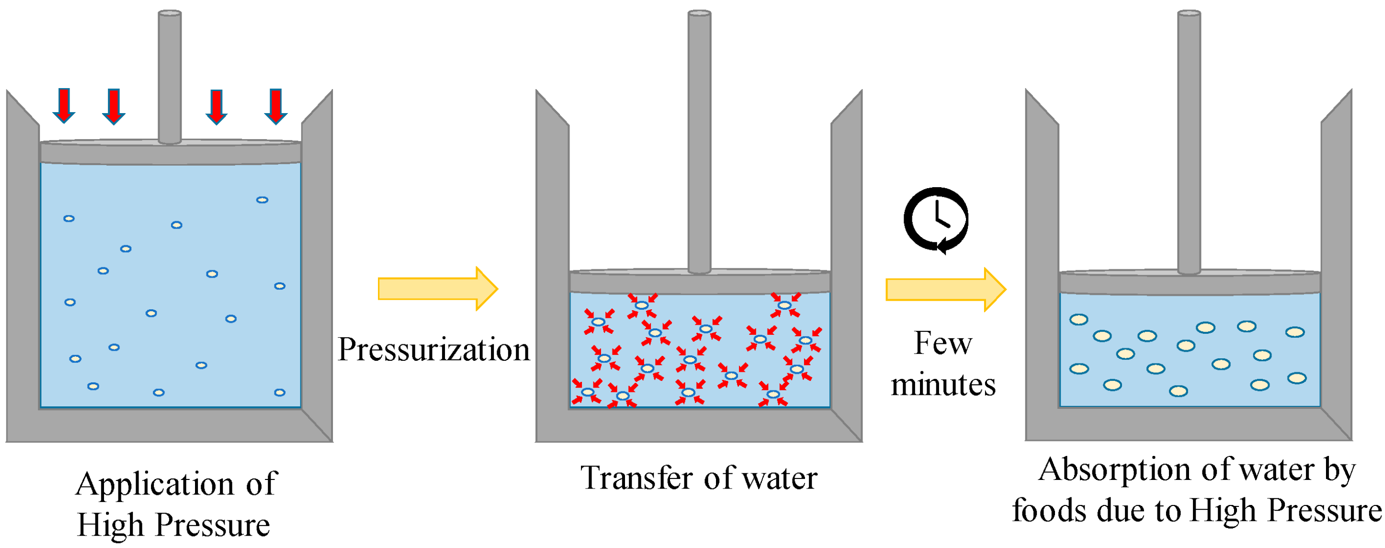

Figure 4. Representation of forced water absorption by foods under high pressure.

When whole grain glutinous rice was subjected to HPP, it was observed that the diffusion coefficient of water increased with temperature up to 300 MPa, after which temperature had no significant effect [17]. The effective diffusion coefficient of water also increased from 20 °C to 50 °C after which it decreased. The explanation stated for this phenomenon was the occurrence of gelatinization. The gelatinization of the rice granules restricts the transport (diffusion) of water. However, irrespective of the change in the diffusion coefficient, the quantity of water absorbed by the rice and the rate of its absorption increased with pressure and temperature. The effect of presoaking for 30 min, followed by high pressure treatment at 400 MPa for 10 min and final soaking overnight led to a rice variety that had enhanced properties [18]. The HPP processed rice had higher digestibility and starch with higher swelling capabilities. HPP led to a higher degree of water penetration in the rice, thus causing a higher level of gelatinization to the starch (**Figure 5**). The rice was claimed to have more palatable properties. A similar study conducted by Zhu et al. [19], recommended the combination of HPP and partial milling of brown rice to enhance its processing efficiency and quality. Foxtail millet, a type of cereal grain, was subjected to long durations of HPP [20]. There was a drop in the effective diffusion coefficient observed above 200 MPa for germinated and 600 MPa for non-germinated grains. The degree of gelatinization and water uptake increased with pressure, temperature and time. In addition, the nutritional components such as antioxidants and total phenolic activity were enhanced, whereas anti-nutritional compounds such as tannin and phytic acid decreased with high pressure.

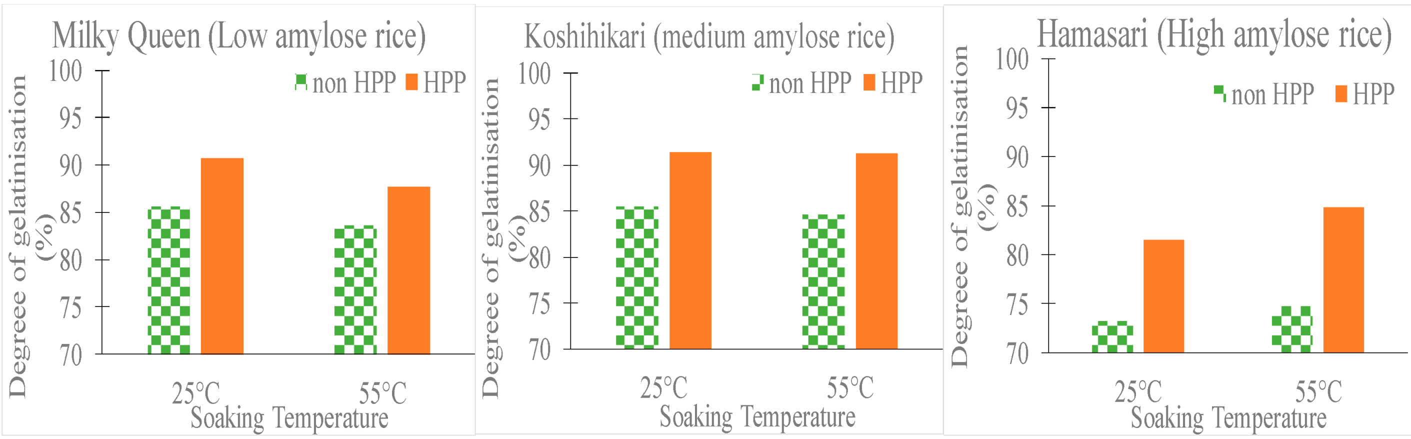

Figure 5. Comparison of the degree of gelatinization after cooking of three varieties of rice with different levels of amylose with their HPP treated counterparts (plotted using the data from Yamakura et al., 2005 [18]).

In another study, paddy grains of the Basmati variety were subjected to HPP with pressure, temperature and time in the range of 350–550 MPa, 30–50 °C and 5–30 min respectively [21]. This was done to establish the water absorption and gelatinization kinetics. The effect of presoaking was also studied. The non-soaked grains showed a higher rate of water uptake, whereas the presoaked grains showed a higher degree of gelatinization with the maximum at the highest level of pressure and temperature studied, i.e., 500 MPa, 50 °C. Temperature and pressure were shown to have a synergistic action on water absorption. Results showed that under the influence of high pressure, the water absorption and diffusivity were much higher compared to grains soaked at atmospheric pressure. Presoaked grains exhibited a higher saturation moisture content, whereas the non-soaked grains showed higher diffusivities (**Figure 6**). A first-order kinetic model was used to describe gelatinization. Based on the energy of activation (E_a) and activation volume (ΔV), adverse effects of pressure on gelatinization was observed at extreme high pressure. Ravichandran et al. [21] further explained that the progressing of gelatinization depends on the first order rate constant (k). k is related to E_a and ΔV by the Arrhenius and Eyring equations respectively. An increase in the value of E_a leads to a subsequent decrease in k. In thermal gelatinization, the value of E_a

decreases with increase in temperatures above 60 °C. This eases the process of gelatinization at high temperatures. In pressure gelatinization, an increase in pressure leads to the rise in E_a. The ease of gelatinization is hence lower. This is because an increase in pressure restricts starch granule swelling. Negative values of ΔV were observed which indicated the sensitivity of the grains to pressure. This meant the occurrence of compression of grains during pressure treatment. The negative value of ΔV further sustained the explanation of the restriction of starch granule swelling due to pressure. Hence, a lower pressure of 450 MPa for treatment was suggested. The conclusion of the study was that this method of using HPP was a better alternative to thermal soaking because it reduces soaking time and also induces partial gelatinization in the paddy grains.

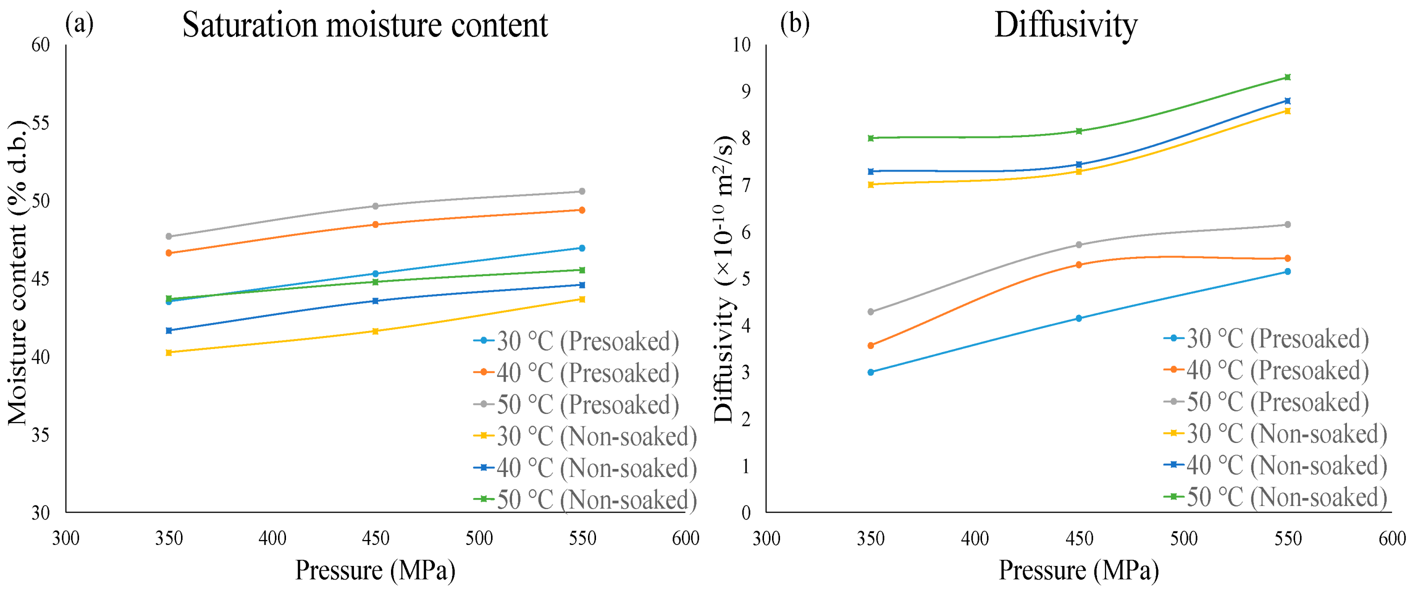

Figure 6. (**a**) Water uptake and (**b**) water diffusivity in presoaked and nonsoaked paddy grains subjected to HPP (plotted using the data from Ravichandran, Purohit and Rao, 2018 [21]).

Dried beans were initially soaked and then treated with a high pressure of 600 MPa for different durations. This was then compared with thermally treated (HT) (95 °C) and high pressure/high temperature process (HPHT) (600 MPa, 95 °C) [23]. Softening of the beans is an important process before eating. This is because raw beans are too hard to be disintegrated by mere chewing and the softness is an indicator of the suitability for consumption. The results showed that the high pressure process alone was not able to reduce the hardness of the bean even after long processing times. The presence of heat with or without pressure is necessary to soften the bean. This was attributed to thermal pectin solubilization. Although the HPHT was found to have a higher degree of starch hydrolysis than HT samples, the process did not impart enough enhancement of any property to make the process economically viable.

HPP has been used to treat cut pieces of tubers and the process has been shown to alter some of the properties. When potato discs were subjected to moderate heat and pressure treatment (MHPT) (75–95 °C, 100 MPa), the firmness increased at the temperature range of 75–85 °C. MHPT also slightly increased tissue sloughing while undergoing colour change similar to that of heat treatment [23]. Amylase acts on gelatinized starch and causes saccharification of the starch. Sweet potatoes contain internal amylases. If the starch present in sweet potato is gelatinized, the internal amylases can cause saccharification and this would give a higher yield of reduced sugars in extraction. However, the internal amylases are inactivated at high temperatures near 100 °C. An experiment on using HPP to cause gelatinization in sweet potato was carried out [24]. Treatments were conducted at different levels of pressure and temperatures for different durations. The process did not affect the amylase activity, but the reducing sugars extracted from the pressure treated samples were similar or slightly lesser in quantity than that extracted from untreated sweet potato pieces. This indicated insufficient gelatinization for saccharification. The process of HPP showed an inhibitory effect on the gelatinization and/or saccharification at lower pressures of 100 MPa and 200 MPa. The reduced sugar content in the samples treated at high pressures of 500 MPa and 70 °C were comparable but were still lower than those treated at atmospheric pressure at 80 °C for the same duration. The reason behind this anomaly of the initial fall in the reducing sugar content with pressure remained unclear.

4. Pressure Assisted Infusion in Foods

When the process of soaking (carried out at atmospheric pressure) is used to transfer some compounds of value to foods, the transfer occurs through the process of osmosis, where there are two components; the solvent (usually water) and the solute (the component intended for transfer). The concentration of solute in the soaking solution can be increased only up to a critical concentration. On exceeding that concentration, the moisture gets driven out, dehydrating the food that is not generally desirable. In such situations, high hydrostatic pressures can be used to force the transfer of the food value compounds.

Using high pressure processing of foods can osmotically induce a mass transfer process to drive certain compounds of value into or out of foods according to the requirements. The diffusion of both the solvent and solute happens simultaneously during soaking, and the directions of diffusion can be the same or opposite depending on the osmotic potentials. This feature can be effectively made use of to increase the quality of foods in terms of nutritional content and flavour enhancement. If a food item is placed in a nutritive medium followed by HPP of the sample, the nutrients can be driven into the food while maintaining the moisture in them. The mechanism for the transfer is not well understood. A research on HPP treatment of brown rice suggested that HPP creates some microfractures on the surfaces of grain, facilitating water transport [25]. This can be taken as a plausible explanation for the transport of nutrients along with water. However, this is a low moisture content grain and developing cracks cannot be the mechanism for high moisture foods. When high moisture fruits were processed for nutrient transfer using HPP, two explanations have been hypothesized for the mechanism of transfer. High pressure conditions affect the cell structures of fruits or vegetables, thereby affecting their permeability and allowing them to uptake nutritional compounds from the surrounding medium [26][27]. However, for quercetin-infused cranberries, Mahadevan et al. [28] reported that even though the cell permeabilization does play some role in increasing the transfer, this effect is not dominant. Osmosis has been stated to be mainly responsible for diffusion. This conclusion was supported by showing a similar degree of cell permeability in samples before and after HPP. One interesting point to note in this experiment is that the cranberries were impermeable to quercetin initially and had to be scarified before HPP treatment. This shows that, regardless of whether cell permeabilization is dominant or not, cell permeabilization is necessary for nutrient transfer. HPP can create cell ruptures in some foods while in others, external scarification may be necessary. Overall, the process of HPP preserves the main solid matrix of foods when transferring components to different phases.

4.1. Aroma Infusion

HPP has had some application in binding different aromas to foods. Some common odorants were mixed with maize starch in native form, with HPP treated maize starch and with maize starch during HPP treatment at 650 MPa for 9 min [29]. Different maize starches with varying amylose content were studied for comparison. The binding extent of these different methods was then analyzed. Hylon VII, a high amylose maize starch, showed similar or slightly enhanced binding characteristics after it was treated with HPP (**Figure 7a**). However, when it was mixed with odorants during HPP, the binding was poorer for most varieties of the odorants excepting hexanol, guaiacol, methyl anthranilate, and octanol. Guaiacol and methyl anthranilate had very poor binding characteristics for native starch. In waxy maize starch with no amylose, there were a few compounds whose sorption reduced in the HPP treated starch. Although the overall average sorption of odorants reduced for both types of HPP treatments, hexanol, guaiacol, methyl anthranilate, and octanol, along with a few more compounds, showed enhanced sorption characteristics during HPP treatment (**Figure 7b**). The process of HPP also led to gelatinization of starch and was inversely related to the amylose content.

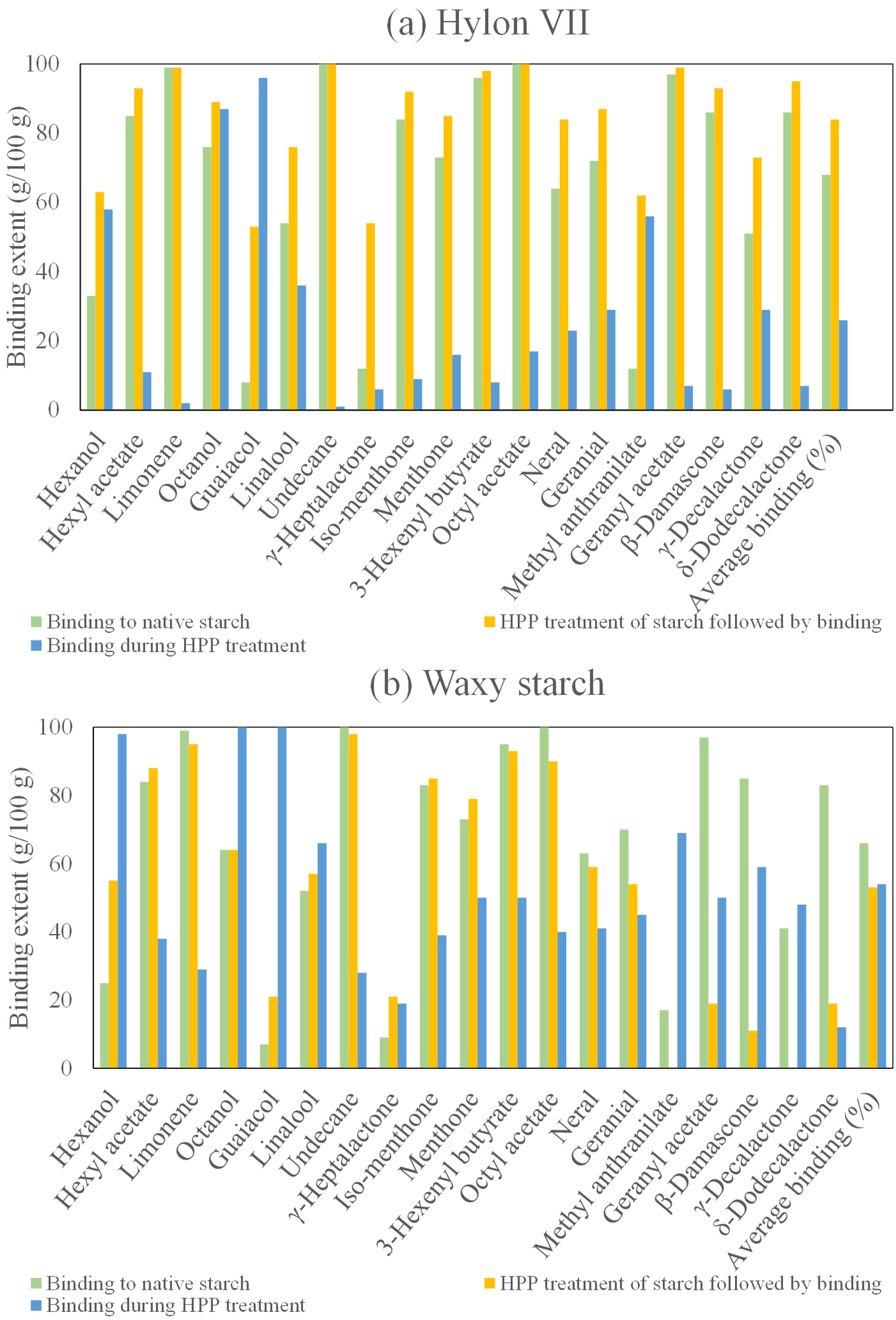

Figure 7. Comparison of binding properties of different odorants to (**a**) high amylose maize starch (Hylon VII), (**b**) no amylose maize starch (waxy starch) treated in various ways (plotted using the data from Błaszczak, Misharina, Yuryev, and Fornal, 2007 [30]).

4.2. High Pressure Impregnation (HPI)

When any compound is used in the liquid form or in a dissolved form for infusion by pressure into a solid food (generally a solid porous matrix), it has been referred to as high pressure impregnation or HPI. Vatankhah and Ramaswamy [30] used HPI for the impregnation of ascorbic acid in apple cubes. They found the ascorbic acid content in the apple pieces increased with pressure. They also checked the effect of viscosity in HPI by making use of different concentrations of chitosan. The result showed a decrease in the level of mass intake of chitosan with an increase in its concentration. The impregnation of chitosan also increased the pressure stability of the apple, which would otherwise collapse under high pressure due to the presence of small air pockets. Osmotic dehydration (OD) was compared with vacuum impregnation (VI) and high pressure impregnation by adding sucrose and calcium lactate in unripened and ripened mango chunks [31]. All samples after OD, VI or HPI were subjected to further OD for up to 4 h before the examination. The effect of the presence of pectin methylesterase (PME), which is generally used for improving food firmness, was also evaluated. It was found that both VI and HPI led to an increase in the soluble solids gain and lower water loss in comparison to OD alone. HPI, however, had lesser pronounced effects than VI. The presence of PME for all cases led to a slight increase in firmness and work of shear. The soluble solids gain, with or without the presence of PME, increased in the unripened mango but decreased in ripened mangoes. This was because of two reasons; the sturdy cellular structure of unripened mangoes and the lower sugar content in them. When water leaves the fruit tissue, the susceptibility of the tissues structure to collapse in unripened mangoes is much lower than ripened ones. The collapse of tissue structure can lead to physical hindrance of the osmotic solution from entering the fruit. In addition, lower sugar content in unripened mangoes results in a greater concentration gradient with the osmotic solution, thereby promoting a higher soluble solids gain. PME-pretreated baby carrots with HPP treatment with calcium lactate gluconate (CLG) showed that the high pressures increased their calcium content by almost seven times [32]. The HPP-treated baby carrots had calcium contents of more than three times that obtained by soaking at atmospheric pressure or with vacuum infusion techniques. Experiments using Box-Behnken design showed that the pressure level, processing time and CLG concentration are directly related to the increase in the calcium content and hardness of the carrots. The application of cyclic pressures also causes a significant increase in calcium. The follow-up study using SEM imaging showed that HPP caused cell damage in the carrots [33]. The extraction of beta carotene from the carrots increased by three to five times in comparison to the untreated variety. The effects of individual processing variables, i.e., pressure, processing time, CLG concentration and PME pretreatment on the amount of beta carotene extracted were not significant. HPP also led to a mild to moderate darkening of the carrots after infusion.

Another study using HPI was done to impregnate oil into selected fruits through water-based emulsions [34]. Oil and Tween 80, an edible emulsifier, were used in different ratios to form different emulsified oil mixtures. Twenty per cent of these emulsified oil mixtures were homogenized along with 80% water to form the infusate. It was found that the presence of hydrophilic emulsifiers in the solutions facilitated the transport of oil into the inner layers. Without the presence of emulsifiers, oil transfer in fruits was not very efficient. In addition, the higher the concentration of the emulsifier, the lower the transport, whereas higher oil concentration gave higher transfer. This method could prove to be a very efficient method for the fortification of foods with lipid-soluble vitamins, such as vitamin A, vitamin K, etc. in foods [34].

A unique study involving a combination of high pressure gelatinization and high pressure infusion was carried out with paddy rice [35]. Rice loses most of its thiamine, present in the bran and germ layers, during its processing from brown rice to white rice. Parboiled rice, however, has much of the thiamine retained in it. Rice undergoes gelatinization during parboiling and gelatinization facilitates the process of thiamine transfer. Since high pressure environments have shown to cause gelatinization, paddy rice was subjected to pressures of 450 MPa and 600 MPa at the temperatures of 50 °C and 70 °C for 15 min and 30 min. The results showed that HPP caused a higher transfer of thiamine as the pressure and temperature increased. Long processing times, however, led to its degradation. The HPP treated rice maintained the grain dimensions whilst parboiling rendered the rice shorter and broader.

4.3. Flavour Infusion

HPP has been used to impart flavours to foods. Villacís, Rastogi, and Balasubramaniam [36] demonstrated the use of HPP for adding salt and moisture to turkey breast while improving its textural properties. Lemus-Mondaca et al. [37] also used HPP to impregnate salt and water into jumbo squid to enhance sensory characteristics. The Weibull model was reported as the best fit for the mass transfer of compounds into the jumbo squid. When the flavour from solid foods like lemon needs to be infused into any drink, the flavour imparting substance must be placed in the target liquid. On the application of high pressure, the flavour components will be transferred to the drink. The brewing of coffee or tea needs to be done at high temperatures. Cold brewed beverages take considerably longer times to reach similar infusion levels. If a pot of hot brewed coffee takes five to ten minutes for preparation, the cold brewed variety can take several hours [38]. Thus, HPP can make the infusion process faster and much more effective. Hence, a design for the infusion of alcoholic beverages with at least 20% alcohol content was carried out with the HPP technology, as shown in (**Figure 8**) [38]. This technology can be effectively applied in the near future for the enhancement of flavours in the beverage industry.

Figure 8. High pressure infusion (HPI) of flavour into beverages (redrawn from U.S. Patent No. 15/975,989, 2018 [38]).

5. Conclusions

High pressure processing has many unexplored possibilities for food quality improvements. A significant amount of work has been done in the area of high pressure gelatinization but with limited industrial-scale applications. The niche market for high pressure infusions and high pressure impregnations is an upcoming method, leading to a high potential for food quality enhancements. The ability to make use of the three parameters of pressure, temperature and time can be optimized for the design of food products with specific properties. Since HPP also inactivates most pathogens, it can be very useful for the production of final packaged ready-to-consume foods that undergo gelatinization and/or infusion during pressure treatment. The impregnation of vital nutrients such as vitamins, flavours and stabilizers into foods are other beneficial applications of this method. Although aroma binding to foods is an innovative idea for augmenting the sensory attributes of foods, the application of HPP in this field has not been extensively studied yet. The simultaneous quality enrichment, along with microbial inactivation, would be very useful in developing processed foods and making the overall expensive process of HPP viable.

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