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High-Pressure Homogenization: Principles and Applications Beyond Microbial Inactivation

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Abstract

(Ultra) high-pressure homogenization ((U)HPH) is one of the emerging technologies being studied and developed for various applications in the food industry. (U)HPH was suggested as an effective tool for achieving microbial safety and extending the product shelf life of liquid foods in a continuous process while minimizing some negative attributes of thermal processing. The valve geometry, pressure level, inlet temperature, and the number of homogenization cycles are all factors affecting the level of microbial inactivation and the extent of the techno-functionalities of food biopolymers and matrices. Turbulence, high shear, cavitation, and temperature increase induced by (U)HPH treatments enhance emulsion stability, stabilize proteins in solutions, reduce particle size distributions, and increase the accessibility of health-promoting compounds. This review is a comprehensive and updated overview of the engineering aspects of the (U)HPH process, specifically focusing on (U)HPH modification of food components such as polysaccharides, proteins, and bioactive compounds. A detailed description of the potential applications in food products beyond microbial inactivation is also included.

Keywords High-pressure homogenization · Polysaccharide structure modification · Protein structure modification · Emerging food processing technology · Bioactive compounds properties

Introduction

In recent years, the food industry is rapidly evolving and facing new consumers' demands and global food trends. Nowadays, consumers are looking for healthier and safe food with minimal or no-added food preservatives and extended shelf life, together with the demand for more sustainable food resources (plant-based proteins, for example). Although conventional thermal processing methods are verified tools for ensuring microbiological food safety [18], the intense heat used in these methods can cause nutrient degradation (e.g., vitamins and volatile aroma compounds) and result in the formation of unwanted compounds and off-flavors, for example, acrylamide, chloropropanols, and furan [95, 127, 141]. Emerging technologies are often investigated as a replacement of conventional methods to minimize the effect of heat on food components while ensuring microbial safety and preserving nutrients as well as sensorial properties, and, in some cases, improve techno-functional properties. These technologies include high hydrostatic pressure (HHP), high-pressure homogenization (HPH), ohmic heating, pulsed electric fields (PEF), microwave heating, cold plasma, gamma irradiation, UV processing, and ultrasound [5, 40, 107, 134, 175, 183, 212].

In HHP processing, the pressure is applied uniformly and transmitted to the pre-packed product by the pressure-transmitting medium at ambient or subambient temperature for several minutes, without inducing a shearing effect. Although many products are commercially being treated with HHP for pasteurization (fruit and vegetable beverages, for example) [13, 130], this process is not continuous and thus only a relatively low processing volume is possible. On the other hand, HPH, also known as dynamic high-pressure homogenization or high-pressure valve homogenization, is an emerging continuous flow process technology enabling the homogenization and pasteurization, and in some cases sterilization, of fluids in one single step [122, 210], while the fluid is being subjected to high pressure for less than a second [166, 187].

Homogenization is a physical process in which a dispersed system, suspension or emulsion, is forced to flow at a high velocity through a narrow passage, a disruption valve, producing a smaller and narrow particle size distribution [12].

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Conventional homogenization, usually up to 50 MPa [9], is widely utilized in the food industry to stabilize emulsions by preventing creaming and coalescence, to reduce particle size (dispersion) and to mix ingredients [12]. In contrast to (ultra) high-pressure homogenization ((U)HPH), conventional homogenization has no preservation effect on the treated fluid. A major difference between (U)HPH and conventional homogenization is the maximum pressure level reached, and it is dependent on the homogenizer design and characteristics such as gap size, seals, and valve geometry. UHPH reaches pressure levels up to 400 MPa [10, 210], while HPH reaches pressure levels between 50 and 200 MPa [63]. It should be noted that some authors differ on the cut-off point between HPH and UHPH [49, 166, 210]. High-pressure jet (HPJ) technology is a similar technology reported to reach up to 500–600 MPa by utilization of a nozzle (from diamond, sapphire, or ruby) restricting the flow and forcing the fluid to form a jet stream that hits the air around it and transforms the liquid into aerosols. Immediately after the nozzle, a heat exchanger is connected, allowing those aerosols to coalesce back to liquid by hitting the wall of the heat exchanger [72, 76, 77, 185].

(U)HPH has been demonstrated as a valuable tool with two main impacts, the first, mainly focuses on the physical changes of the fluid after being subjected to the treatment. Such changes have crucial importance in various applications, such as preparation and stabilization of emulsions and nanoemulsions, reduction in droplets, and particle size of emulsions and suspensions together with a narrower size distribution, changes in the techno-functional properties of proteins and polysaccharides, texture modification and changes, and improvement in rheological properties of fluids [9, 21, 70, 79, 122, 174, 210]. In the pharmaceutical, cosmetics, and biochemical industries, it can be a tool for handling solid lipid nanoparticles and crystalline solids, dispersions, emulsions with controlled droplet size, drug nanoparticles, and nanosuspension [24, 46, 88, 91, 131, 187, 188]. The effect of cell disruption induced by (U)HPH can also be used as a tool for improved extraction of intra-cellular compounds (e.g., proteins, enzymes, fatty acids) in bioengineering-related industries [11, 14, 90, 125]. The second major application is microbial inactivation. (U)HPH can induce a reduction of the microbial load of food products to the level of pasteurization and even sterilization [9, 42, 62, 100, 101, 134, 145, 210], depending on process parameters such as pressure level and the number of passes, process temperature (inlet and maximal temperature), high-pressure valve design, and the properties of the treated fluid itself [122, 187, 210].

(U)HPH applications for enzyme inactivation and improvement of techno-functional properties of food components have been also explored. More recently, an increased scientific focus has been given to the direct and indirect effects of (U)HPH on bioactive compounds. Currently, the majority of (U)HPH utilization in many aspects is still in a laboratory or pilot scale. The industrial usage of commercially available (U)HPH units is limited, due to operation, usually at the maximal achievable pressure levels with flow rates less than the industrial requirements and, in some cases, high energy consumption [49, 122, 166]. A comprehensive review of the main engineering aspects and the physics behind (U)HPH, along with opportunities in scaling up of the process to commercial scale, was recently published by Martínez-Monteagudo et al. [122]. The utilization of (U)HPH for pasteurization, sterilization, and enzyme inactivation, especially in the beverage industry, has been previously reviewed [9, 43, 46, 49, 63, 70, 122, 137, 154, 166, 187, 210], while others have reviewed the impact of (U)HPH on emulsion stability [16, 49, 52, 70, 122, 135, 174, 210]. In addition to the interest in the opportunities of (U)HPH in microbial inactivation, including patents on the topic [30, 117, 124], the technology was also studied regarding the influence on the techno-functional properties of proteins and polysaccharides and the manufacture of food products with improved functionality. The focus of this publication is an updated review of the engineering aspects of (U)HPH and the potential of this emerging technology for applications beyond microbial inactivation. Technological aspects, detailed descriptions, and working principles as related to applications in the development of novel food products are also discussed.

Principles of (Ultra) High-Pressure Homogenization

The design of high-pressure homogenizer usually consists of one or two stages restricting the fluid flow, depending on the desired application and the properties of the final product [70]. The recent developments of designs (intensifiers, different valve, and homogenization chamber geometries) and various high-pressure-resistant materials (e.g., ceramic, diamond, sapphire, seals) allow operating pressure levels of up to 400 MPa and process temperatures of up to 140–150 °C [10, 49, 166]. Commercially available units differ mostly in their high-pressure valve design affecting the pressure range and applicable flow rates at the laboratory, pilot, and industrial scale [49, 166]. Valve design and geometry were reported to influence vegetative microorganisms' inactivation [45] and the formation of food nanoemulsions [47] even when the same pressure was used.

Two-stage (U)HPH systems are usually equipped with a positive displacement pump, intensifier, and heat exchangers before and/or after the high-pressure valve. The first stage is the high-pressure valve, and the second stage is the low-pressure valve. A schematic diagram of a two-stage (U)HPH system design is presented in Fig. 1. The fluid, depending on the processing objective (pasteurization, sterilization, emulsification), is pre-chilled or pre-heated to the desired inlet

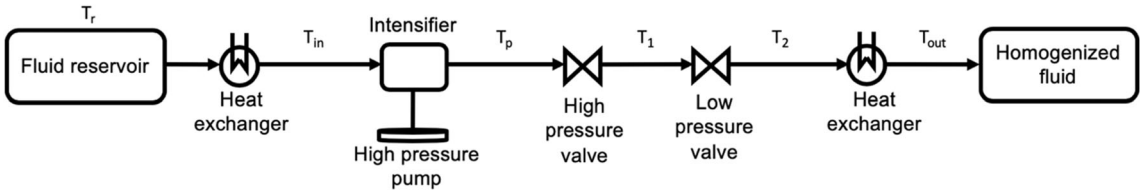

Fig. 1 A schematic flow diagram of a two-stage high-pressure homogenization processing system. T_r is the temperature of the fluid reservoir; T_{in} is the fluid inlet temperature before increasing pressure to the homogenization pressure p; T_p is the fluid temperature after hydrostatic compression; T_1 is the fluid temperature after the high-pressure valve;T_2 is the fluid temperature after the low-pressure valve; T_{out} is the final fluid temperature after cooling in the heat exchanger. Based on [46, 49, 70, 122, 210]

temperature by a heat exchanger. Then, it is pressurized by a pressure intensifier, to the required pressure, usually up to 400 MPa, and consequently, the fluid temperature rises due to hydrostatic compression. Afterward, the fluid is depressurized by passing through the high-pressure homogenization valve reaching after the first stage, a depressurization to 10–20 MPa. Due to the pressure drop, part of the kinetic energy is converted to heat, resulting in a temperature increase [49, 122, 210]. The second homogenization valve, the low-pressure valve, reduces the fluid pressure to atmospheric pressure and disrupts agglomerates that might have been formed during the first homogenization valve discharge. As the final product temperature can be high, immediate cooling by a heat exchanger is often employed after homogenization to minimize damage to thermolabile components.

Valve Design and Temperature Increase

Valve geometry and design are crucial parameters affecting the process performance and characteristics of the final product. During (U)HPH, the fluid is forced to flow through the high-pressure valve passing a minute orifice (width of a few micrometers), increasing the fluid's velocity. The disruption of the fluid particles (emulsion or suspensions) is mostly influenced by the valve geometry and the homogenization pressure level selected. The fluid itself is exposed to high pressure for a very short period, less than a second, and therefore hydrostatic effects are relatively small [166, 187]. Adjusting the initial fluid temperature, the pressure, the number of passes, and valve design may help to achieve the desired physical changes and process temperature [122]. Various valve geometries and designs are commercially available aiming for specific final applications [122]. Different commercial high-pressure homogenizers exist for laboratory and pilot-scale and a few ones fitting industrial requirements [122, 166, 210]. The three main types of valve geometries are counter jet, radial diffusers, and axial flow valves. While comprehensive descriptions of available homogenization valves are available [46, 122, 187, 210], Fig. 2 describes the most reported valve geometries [46, 70]. A nozzle-type geometry (Fig. 2a) was reported to be effective in the applications of droplet disruption [178], microbial inactivation, and cell rupture [152, 159]. The conical piston valve (Fig. 2b) was reported to be effective for breaking cell structures [20, 61, 103, 126], preparation of nanosuspensions [128] and nanoemulsions [47], solid lipid nanoparticles [177], and microbial inactivation [45, 57, 169]. The ceramic needle and seat (Fig. 2c) were reported to be effective for cell disruption [42, 57, 169, 193], preparation of nanosuspensions [59, 74, 186], protein denaturation [136], and microbial inactivation [51, 190]. Microfluidics (Fig. 2d) was reported to effectively disrupt cells, with relatively larger particles compared with the conical piston [61], heat denaturation of proteins [80], and formation of nanoparticles [99], and fine emulsion formation [24].

Velocity and Temperature Increase

In (U)HPH, the fluid is simultaneously subjected to homogenization and pressure effects. As the fluid depressurizes after the first homogenization valve and passes through a minute gap, the fluid velocity increases due to the tubing size reduction along with the corresponding drop in fluid pressure [49]. The patterns of fluid flow together with the velocity profile have been previously reviewed [122]. The increment in fluid velocity results in intense turbulence contributing to the disruption of the fluid dispersed phase and the homogenization effect. Forcing the fluid to pass through the small gap while the valve restricts its motion results in shearing between the fluid and the valve seat. Shear has a large effect on the droplet disruption. It was previously reported that the inertial and surface forces could be characterized by the Weber number (*We* in Eq. (1)) described before for disruption of a particle in a laminar flow [122, 195]. But for (U)HPH, the relation between the surface tension depends on the pressure and the temperature during homogenization (Eq. (2)) [122].

$$W_e = \frac{\rho \times v^2 \times l}{\gamma} \tag{1}$$

$$\left(\frac{\partial \gamma}{\partial p}\right)_{T,A} = \left(\frac{\partial V}{\partial A}\right)_{p,T} \tag{2}$$

where ρ is the fluid density, v is the fluid velocity, l is the

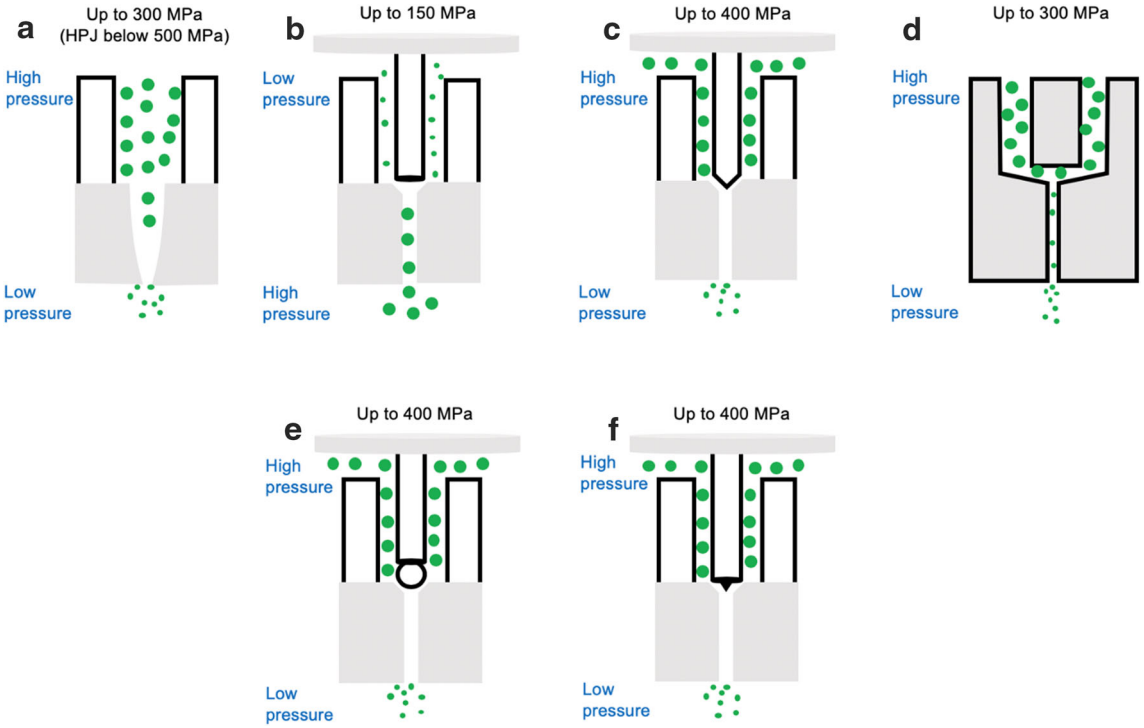

Fig. 2 Schematic representation of common high-pressure valves. **a** Nozzle. **b** Needle and seat. **c** Conical piston. **d** Microfluidics. **e** Ball and seat. **f** Sharp angle. Drawings do not represent real scale. Based on [46, 49, 70, 122, 210]

typical length, γ is the surface tension, p is the pressure of the system, V the total volume of the system, A total surface area, and T is the system temperature.

Mixing, emulsifying, and homogenization in the (U)HPH valves are considered to occur due to the turbulence created by the restricted fluid flow, leading to the increment in its velocity. The generated turbulence dissipates kinetic energy into heat, leading to an increase in fluid temperature [29, 78, 122]. The third phenomenon happening after the first (U)HPH valve is cavitation due to the sudden pressure drop [122]. Cavitation refers to the formation of air bubbles in the fluid and their subsequent collapse. Quantification and prediction of cavitation are possible using two dimensionless numbers: cavitation (C_v, Eq. (3)) and cavitation inception (C_{in}, Eq. (4)):

$$C_v = \frac{p_2}{p_1} \tag{3}$$

$$C_{in} = \frac{p_2 - p_v}{0.5 \times \rho \times {v_{\max}}^2} \tag{4}$$

where p_2 is the pressure after homogenization valve, p_1 is the pressure before homogenization valve, p_v is the liquid vapor pressure, ρ is the fluid density, and v_{max} is the fluid maximum velocity. The combination of three phenomena, turbulence, high shear, and cavitation, is mainly responsible for the effect of mixing, dispersion, emulsification, and reduction in particle size [29, 78, 122].

The total increment in temperature reflects two factors: heat compression and the combined effect of shearing turbulence and mixing (as a result of the instantaneous pressure drop). The rapid pressurization generated during the pressure build-up in the intensifier causes heat compression and an increase in temperature at a range of 2–3 °C per 100 MPa, depending on the fluid characteristics while this increment is reversible upon pressure release [46, 49, 122]. Due to the isotactic pressure and the work done during the pressure discharge through the homogenization valves, the kinetic energy of the fluid is lost in the form of heat and the fluid temperature increases irreversibly by 14–25 °C per 100 MPa, depending on the physicochemical properties of the fluid, the fluid inlet temperature, and the homogenizer design [46, 49, 122, 166, 187, 210]. For example, it was reported that the range of increasing temperature per 100 MPa for bovine milk was 16.6–19.5 °C when the inlet temperature ranged from 4 to 50 °C [73, 139, 142, 182]. For fruit juices and plant-based beverages, the increment was reported to be 15.0–22.6 °C per 100 MPa when inlet temperature ranged from 4 to 75 °C [143, 180, 189]. The increment in fluid temperature is mostly dependent on the homogenization pressure at a specific inlet temperature [210]. This increment was described to be a linear or polynomial function of pressure, based on empirical models reviewed in previous works [46, 49, 122, 181]. A general equation (Eq. (5)) for estimation of the fluid temperature during the process has been suggested [122]:

$$T_p = T_{in} + \delta \times \Delta p + \xi \times \Delta p - \Sigma \text{heat loss} \tag{5}$$

where T_p is the fluid temperature during the process, T_{in} is the fluid inlet temperature, δ is the heat compression of the fluid, Δp the hydrostatic pressure, ξ homogenization heat, and heat loss that can be negligible if the system is well insulated (mostly relevant for laboratory-scale equipment) [122].

Effect on Bioactive Compounds and Properties of Food Matrices

(U)HPH has been suggested as a tool for improving the techno-functional properties of food and food components, investigated mainly in fruit juices. The utilization of (U)HPH in fruit juices processing is a promising example of a combination of the versatile applications of (U)HPH. The technology allows to achieve a reduction of microbial load, preservation of quality properties (such as the content of thermally sensitive compounds) of fresh products, and affect the physical properties, such as phase separation, in one single process. Each matrix reacts differently when subjected to (U)HPH processing and the effect on product properties cannot be easily predicted. Every fruit has a unique composition, and cell fragmentation exposes and releases internal and wall constituents (e.g., pectins and proteins), increasing the potential for particle-particle and particle-serum interactions. Also, the cell wall has its structure, and consequently different resistance to shear forces [104, 116]. Published data on fruit juices and juice concentrates showed that rheological properties were modified (e.g., decrease in apparent viscosity and thixotropic behavior changes) [104, 105, 173, 202, 213], decrease in sedimentation during storage [96, 156, 161, 173, 202], decrease in particle size with increasing homogenization pressure [7, 17, 22, 23, 96, 104, 105, 161, 173, 213], but reaching a critical size below which particles could not be further degraded regardless of the initial size [7, 161, 173]. While HPH was reported to induce a reduction in the thixotropic behavior of most fruit juices and juice concentrates [104, 213], an increase in this behavior was observed for tomato juices [96]. As further described, (U)HPH can reduce the consistency of many polysaccharide solutions, thus suggesting that such a technology could also be used to reduce the consistency of juice concentrates with low pulp content. From an engineering point of view, a lower consistency leads to lower friction during processing and distribution, thus minimizing energy requirements [104, 105]. Concentrated orange juice (COJ) is a common industrial raw material for the juice industry. As it is a concentrated product, its high consistency requires high amounts of energy for processing and handling. Leite et al. [104] evaluated the effect of HPH treatment on the rheological properties and flow behavior occurring in COJ. The apparent viscosity, the consistency index, and the mean particle diameter were reduced, while an increase in the flow behavior index was observed. Thus, the utilization of HPH presents an opportunity to minimize the energy required during COJ processing and distribution due to the reduction in the product's consistency.

The effect of (U)HPH on the preservation of some of the health-promoting and bioactive compounds such as vitamins, polyphenols, compared with the conventional heat treatments was previously reviewed [122, 210]. Recently, Sharabi et al. [167] investigated the possible improvement of milk nutritional quality during shelf life by testing the stability of ascorbic acid and riboflavin and antioxidant capacity in milk and model systems after HPH treatments. The results revealed reduced microbial load, almost unaffected concentration of ascorbic acid immediately after the treatment vs. rapid degradation during storage. The degradation rate of riboflavin, a light-sensitive molecule, was reduced by ~ 50%, depending on the homogenization pressure. The authors suggested that this outcome is an indirect effect of the (U)HPH on the degradation due to increased light scattering and absorbance of the wavelengths related to photo-oxidation of riboflavin. (U)HPH is known to disrupt plant matrices affecting both the functional properties of the products and the release of some bioactive compounds in the matrices. Juice beverage industry is facing several quality defects during storage, such as cloud loss, enzymatic browning, flavor changes, color loss, and deterioration of bioactive compounds [207]. Recent works have focused on these properties and the optional improvement by (U)HPH using different numbers of passes on some fruit beverages and nectars [85, 129, 156, 173, 180, 202, 207, 209]. Moscovici-Joubran et al. [129] studied the effect of different (U)HPH pressures and the number of cycles on the physicochemical, structural, and functional attributes of strawberry nectar. The study also tested the effect of a filtration step that partially removed large particles. As expected, the (U)HPH treatment reduced the particle size, but contrary to some previous publications on juices [96, 114, 156, 202], the stability against separation was also negatively affected, likely due to the destruction of a weak network. The total polyphenol concentration was not affected by the homogenization pressure itself but significantly enhanced with an increasing number of cycles at 200 MPa, whereas the color and the anthocyanins content were only slightly affected. Moscovici-Joubran et al. [129] demonstrated that the number of cycles has the potential of enhancing the extractable content of health-promoting compounds in processed matrices. The effect of (U)HPH on the antioxidant capacity of bioactive compounds was mainly investigated in food matrices, and specifically in fruit juices, and was reviewed before [81, 210]. In general, compared with the heat treatment, (U)HPH processing of juices was reported to better preserve antioxidant capacity [66, 85, 180, 191], total polyphenol content [66, 85, 180, 191], and bioactive compounds such as ascorbic acid [120, 167, 180, 191], carotenoids [66, 106, 180, 191], flavonoids [15, 191], and vitamins [19]. Toro-Funes et al. [184] investigated the effect of

(U)HPH and various inlet temperatures on soy drink bioactive compounds, phytosterols, isoflavones, and tocopherols. The total phytosterols and isoflavones content in soy drink increased with increasing pressures and temperatures. As the inlet temperature increased, the total tocopherols decreased while an increase in the pressure level increased their content. Liu et al. [113] investigated the impact of HPH and different inlet temperature on physical stability and carotenoid degradation kinetics of carrot beverage during storage. The use of lower inlet temperature combined with the HPH preserved the color during storage better than the same pressure level with higher inlet temperature. The physical stability of all the tested samples decreased during storage. Yet, the stability of the samples treated at a higher temperature and high pressure decreased more than samples treated with lower inlet temperature combined with the high pressure. The combination of high pressure and high inlet temperature also assisted in improving the preservation of carotenoids during storage when compared with the other tested treatments. A study carried out by Loira et al. [115] tested the application of (U)HPH to process grape must before fermentation. They demonstrated that (U)HPH processing led to an elimination of grape microflora allowing the reduction of the added sulfite levels needed for controlling oxidation and thus improving wine's aroma compared with sulfited wine.

Fernandez-Avila et al. [52] reviewed the potential and the current application of (U)HPH utilization for the production of nanostructures based on lipid, carbohydrates, protein, or protein-polysaccharide complexes loaded with biologically bioactive compounds such as vitamins and phenolic compounds. The bioaccessibility of bioactive compounds in model suspensions and food matrices as affected by HPH was reported in previous works and reviewed elsewhere [16, 27, 92, 122]. Some works published recently investigated the influence of HPH processing of food products on the bioaccessibility of some bioactive compounds such as carotenoids [110, 114, 201]. In general, HPH improved the bioaccessibility of total carotenoids [110, 201] and total polyphenols [201]. The addition of oil or emulsion before HPH treatment also enhanced the bioaccessibility of carotenoids without affecting the bioaccessibility of polyphenols [110, 201]. Liu et al. [110] studied the effects of HPH and the addition of oil on carotenoid bioaccessibility in carrot juice. They reported that the total carotenoids bioaccessibility was significantly higher when carrot juice was treated at pressures above 60 MPa and inlet temperature 70 °C. Liu et al. [114] studied the influence of HPH, number of cycles, and different inlet temperatures on the bioaccessibility of carotenoids in carrot juice, reporting that HPH increased the total carotenoids bioaccessibility. The physical stability was also improved while the effect of pressure level and number of cycles were more significant than inlet temperatures.

(U)HPH Effects on Polysaccharides

In the food industry, polysaccharides are extensively exploited to modify textural properties of fluids and semi-solid foods and used as stabilizers, thickeners, binders, suspending agents, emulsifiers, and gelling agents, depending on the functional properties of a given polymer [2, 133, 179]. When added to food, polysaccharides can modify hydration, solubility, rheological, and interfacial properties and can be used as texture enhancers [2, 70, 133, 179]. The rheological characteristics of food products are essential both for the process design and optimization (e.g., flow in pumps and pipelines) and for the final product itself as it affects product stability, quality prediction, sensory characteristics, and consequently consumer acceptance [146, 192]. Physicochemical properties, such as apparent viscosity, are associated with the polysaccharide molecular weight (Mw) distribution that can be affected by food processing [70]. Thus, many researchers have attempted to control polysaccharides molecular weight and make the distribution more uniform, mainly by the degradation of polysaccharides by enzymatic [87, 94, 97, 132], chemical [3, 41, 60, 67, 84, 93, 94, 151, 172], physical [1, 34, 38] methods, and also (U)HPH [70]. The latter showed a large effect on polysaccharides and their functionality. In (U)HPH processing, polysaccharides are subjected to the turbulent and shear forces [89]. Therefore, (U)HPH could influence the structure and the rheological properties of polysaccharides, which would thus influence their application in food systems [200]. The degree of physical change of polysaccharides during (U)HPH is influenced by processing parameters such as pressure and the number of homogenization cycles, and parameters related to the polysaccharide and the fluid such as solution pH and the polymer structure and concentration [89, 194]. Several studies explored the influence of (U)HPH on the rheological properties and the degradation of polysaccharides solutions. Studies investigating the influence of (U)HPH on polysaccharides and their techno-functional properties are summarized and presented in Table 1.

(U)HPH impacts on polysaccharides described in Table 1 indicate that the structure and conformation of polysaccharides (e.g., linear, branched) have a larger impact on the outcome of (U)HPH treatment than the polymer charge. Linear and stiff polysaccharides undergo depolymerization resulting in reduced polydispersity while globular-branched structures are less affected [194]. Also, pH has an impact on depolymerization, possibly reflecting the polymer conformation in solution during homogenization. At pH 6.3, (U)HPH induced conformational changes in pectins resulting in a more compact structure, while at pH 4.4, no conformational changes were noticed [170]. Besides, larger chitosan molecules were more susceptible to chain scission resulting in a narrower molecular weight distribution than that of original chitosan, indicating that large macromolecules were preferentially fragmented

Table 1 The effect of (ultra) high-pressure homogenization on the characteristics of polysaccharides

Polysaccharide ((U)HPH equipment)	Conditions	Main outcomes	Reference
Pectin (Avestin Emulsifex C5 homogenizer)	- 17, 124 MPa - Different pectin sources with different DE - pH = 5.8	- Reduction in the average M_w of high-methoxyl pectins - Only the viscosity of 70% DE was reduced	Corredig and Wicker [33]
Pectin (apple and citrus) (Stansted Fluid Power homogenizer)	- 0–300 MPa - Passes = 1–9 - pH = 4.4 and 6.3 - Apple pectin: more compact structure abundant in neutral sugars - Citrus pectin: relatively linear structure poor in neutral sugar side chains	- Pressure-dependent depolymerization - Depolymerization only occurred to pectins above a specific M_w threshold - Apple pectin was more resistant to the depolymerization - pH level has an effect on depolymerization and conformation in solution	Shpigelman et al. [170]
High-methoxyl pectin (Microfluidics Co. microfluidizer)	- 40–200 MPa - Passes = 0 and 5 - pH = 1.0–7.0	- Loss in viscosity - M_w and particle size decreased - Reducing sugars increased linearly with the decrease in average M_w	Chen et al. [25]
Pectin (citrus) (Panda Plus, GEA Niro Soavi homogenizer)	- 0–200 MPa - T_{in} = 10 °C - Suspension in distilled water - pH = 4.2	- Decrease in viscosity with Newtonian behavior	Augusto et al. [8]
Chitosan (Microfluidics Co. microfluidizer, model M-110 Y)	- 21–103 MPa - T_{in} = 25, 45, 50 °C - Suspension in 0.1 M acetic acid	- Fragmentation increased with pressure, turbulence intensity, exposure time, and decreased with polymer concentration - Negligible effect of inlet temperature - Larger molecules were more susceptible to chain scission	Kasaai et al. [86]
Sodium carboxymethylcellulose (Invensys APV homogenizer, APV 2000 apparatus)	- 0–200 MPa - Passes = 1–6 - 11 L h^{-1}	- Reduction in the molecular mass and the polydispersity - Depolymerization is dependent on pressure level and number of passes	Villay et al. [194]
Xanthan gum (BEE International, Nano Debee homogenizer)	- 40–300 MPa - Passes = 0–5	- Reduction in the M_w correlated with exponential viscosity decay - Depolymerization only above a pressure-dependent critical M_w.	Harte and Venegas [71]
Xanthan gum (Microfluidics Co. microfluidizer, model M-110)	- Passes = 0–20 - T_{in} = 23 °C - Suspension in distilled water	- Decrease in flow behavior, hydration rate, water uptake and M_w - Decrease in stabilizing and thickening properties	Lagoueyte and Paquin [98]
Alginate (BEE International, Nano Debee homogenizer)	- 40–300 MPa - Passes = 0–5	- Reduction in M_w correlated with exponential viscosity decay - Depolymerization only above a pressure-dependent critical M_w.	Harte and Venegas [71]
k-carrageenan (BEE International, Nano Debee homogenizer)	- 40–300 MPa - Passes = 0–5	- Reduction in the M_w correlated with exponential viscosity decay - Depolymerization only above a pressure-dependent critical M_w.	Harte and Venegas [71]
Methylcellulose (Stansted Fluid Power homogenizer)	- 20–350 MPa - Suspension in pure water	- Intrinsic viscosity decreased correlated to apparent changes in average M_w - Reduction in thickening properties	Floury et al. [58]
Maize starch (Niro Soavi homogenizer model NS1001L-PANDA 2 K)	- 60, 100, 140 MPa - Suspension in distilled water	- Induced gelation - Increase in gelatinization degree - Increase in granule size due to aggregation and loss of crystalline structure - Retrogradation not affected	Wang et al. [196]
Alkali-gelatinized high-amylose maize starch (ATS Engineering Inc. homogenizer, model AH100D)	- 25–125 MPa - T_{in} = 25 °C - 5–100 MPa, and 20–160 MPa	- Apparent viscosity decreased with pressure increase - More uniform microstructure - Decrease in the number of starch ghost particle above 100 MPa - Reduction in the retrogradation after storage - Decrease in viscosity	Wang et al. [197]

Table 1 (continued)

Polysaccharide ((U)HPH equipment)	Conditions	Main outcomes	Reference
β- glucan (HPVH, Gaulin laboratory homogenizer LAB60-10TBS, APV Gaulin GmbH)	- T_{out} = 40 °C and 15 °C	- Loss in shear thinning behavior - Reduction in molar mass - Fragmentation rate increased with concentration increase	Kivela et al. [89]
Wheat barn (Microfluidics Co. microfluidizer model M-110P)	- 159, 172 MPa - Suspension in distilled water	- Reduction in particle size - Increase in the particles' specific area - Reduction in the bulk density - Increase in the water and oil holding capacity, swelling capacity, and ion exchange capacity - Increase in material porosity - Optional modification to enhance physiological properties	Wang et al. [199]

[86]. Similar results were reported also for pectins [170]. For a specific homogenization pressure, the molecular weight reduction occurs until a critical molecular weight is achieved and no further reduction occurs if the homogenization pressure is kept constant or reduced [71]. These results also suggest that additional homogenization cycles at constant pressure would only reduce polysaccharide molecular weight polydispersity by depolymerizing remaining polysaccharide strands having a molecular weight above the critical molecular weight for the specific homogenization pressure. In the case of rheological properties of the polysaccharide containing system, the thickening properties of polymers were also reduced due to the (U)HPH treatment likely related to the reduction in molecular weight [58].

Effect on Proteins

Enzymes in food matrices and their activity are an important parameter influencing shelf life, characteristics of the product, and the fate of bioactive compounds. (U)HPH was previously reported to activate, inactivate, and in some cases, not to affect enzyme activity, and the data has been summarized in previous reviews [49, 122, 210]. Proteins in food are technologically valuable due to their diverse techno-functional properties such as solubility, swelling, water holding capacity, foaming, emulsifying, and gelling capacity [211]. The use of proteins as emulsifying and foaming agents is based on their amphiphilic characteristics, and their ability to migrate to the interface depends on the conformation and the flexibility of the molecule [65, 121, 147]. Research on processing technologies changing the functionality of polymers, including proteins, is growing, partially due to the opportunity to reduce the use of stabilizers and emulsifier agents. (U)HPH is one of the technologies capable of achieving physical protein modifications [70]. The effect of (U)HPH on the protein's secondary or tertiary structure is controversial. (U)HPH was reported as a useful tool for the disruption of protein quaternary structure [70]. Some studies suggest that (U)HPH up to 400 MPa has little impact on the secondary or tertiary structure when the solutions are immediately cooled after the homogenization [50, 64, 138–140] while others led to different findings [37, 203]. Various studies were conducted to understand the influence of (U)HPH on the techno-functional properties of proteins in suspension, such as foaming, solubility, and particle size distribution [26, 44, 109, 158, 205]. In this section, the focus will be mainly on the effect of (U)HPH on the techno-functional properties of plant-based proteins and more recent works dealing with proteins that possess poor water solubility. Protein unfolding can expose the inner hydrophobic regions increasing the potential for hydrophobic interactions between proteins, fat globules, and small particles finely distributed in the aqueous phase, creating a new oil-water interface that may favor the formation of particle aggregates [53, 150, 198]. (U)HPH impact on proteins, described in Table 2, indicate that (U)HPH has the potential to improve and modify techno-functional properties of proteins such solubility, emulsifying and foaming properties, particle size distributions, zeta potential, and rheological properties of proteins. Several works demonstrated that homogenization above a specific pressure might induce further unfolding of the protein and exposure of hydrophobic regions leading to protein aggregation and thus a reduction in some of the techno-functional properties [157, 158]. (U)HPH was also reported as a tool for enhancing proteins solubility [26, 168, 204, 205, 208].

Polysaccharides and Proteins Mixed Systems

Proteins and polysaccharides in the food matrix can improve physicochemical properties such as stability, rheological properties, and mouthfeel [48, 149, 160]. When these two ingredients are mixed in an aqueous phase, the interaction between them can result in segregation and/or association, depending on their concentration and net charge. If an electrostatic repulsive force occurs, phase separation of a protein and

Table 2 The effect of (ultra) high-pressure homogenization on proteins and polysaccharide-protein mixed systems

Compound/s ((U)HPH equipment)	Conditions	Main outcomes	Reference
Protein systems			
Soy protein isolate (Microfluidics Co. microfluidizer, model M-110P)	- 137, 207 MPa - Passes = 0–30 - Film-forming suspensions	- Reduction in particle size and narrower size distributions - Improved film mechanical properties and transparency combined with reduced water absorption - Shears-thinning behavior at 207 MPa	Song et al. [176]
Hazelnut protein (GEA Niro Soavi homogenizer, Panda PLUS 2000)	- 0–150 MPa	- Improvement in protein solubility, enhancement in emulsifying and foaming properties at pressures up to 100 MPa - Reduction in particle size at pressures up to 100 MPa - At pressures higher than 100 MPa, possible further unfolding of the protein might cause protein aggregation	Saricaoglu et al. [157]
Faba bean protein (BEE International, Nano Debee homogenizer)	- 103, 207 MPa - Passes = 6	- (U)HPH disrupted particles into more soluble aggregates and some level of protein unfolding - Increased particles' surface hydrophobicity - Improved foaming capacity and negative effect on the emulsifying properties	Yang et al. [205]
Chicken breast myofibrillar protein (BEE International, Mini DeBee homogenizer)	- 69, 103, 138 MPa - Passes = 2 - T_{in} = 4 °C	- Reduction in particles size - Higher absolute zeta potential, enhanced solubility, flowability, and stability with no observed protein degradation	Chen et al. [26]
Calm myofibrillar protein (Panda Plus 2000, GEA Niro Soavi)	- 40, 80, 120 MPa - Passes = 3 - T_{in} = 4 °C	- Reduction in particle size - Increase in absolute zeta potential, protein solubility, emulsifying, and foaming properties - Improved rheological properties - Changes in the secondary, tertiary, and quaternary structure - Reduction in shear stress, apparent viscosity, and viscosity coefficients - Increase in flow index	Shi et al. [168]
Mussel myofibrillar protein (GEA Niro Soavi homogenizer, Panda PLUS 2000)	- 20–100 MPa - Passes = 3 - T_{in} = 4 °C	- Reduction in particle size - Increase in absolute zeta potential, protein solubility, emulsifying, and foaming properties - Improved rheological properties - Changes in the secondary, tertiary, and quaternary structure	Yu et al. [208]
Oyster myofibrillar (GEA Niro Soavi homogenizer, Panda PLUS 2000)	- 0–120 MPa - Passes = 3 - T_{in} = 20 °C	- Decrease in shear stress, apparent viscosity, and the viscosity coefficients - Increase in flow index - Increased creaming stability - Increased absolute zeta potential and protein solubility - Reduction in particle size and turbidity	Wu et al. [204]
Deboned chicken meat proteins (GEA Niro Soavi homogenizer, Panda PLUS 2000)	- 0–150 MPa	- Reduction in particle size at pressures up to 100 MPa - At pressures higher than 100 MPa, possible further unfolding of the protein might cause protein aggregation - Increase in absolute zeta potential, protein solubility, emulsifying, and foaming properties - Improved rheological properties	Saricaogly et al. [158]
Lentil protein isolate (GEA Niro Soavi homogenizer, Panda PLUS 2000)	- 0–150 MPa	- Protein unfolding with increase in pressure - Decrease in particle size up to 100 MPa - Highest emulsifying activity and stability index at 50 and 100 MPa - Increase in foaming capacity stability up to 100 MPa - Suspensions with shear thinning behavior and weak gel-like behavior	Saricaoglus [155]
Polysaccharides and proteins mixed systems			
Casein and hydroxypropyl cellulose (Stansted Fluid Power homogenizer, model FPG 12500)	- 0–300 MPa - T_{in} = 20 °C - High and low Mw of hydroxypropyl cellulose	- Reduction of phase separation and viscosity - Smaller apparent particle size complexes during storage - Formation of aggregates consisted of nanoscale protein-polysaccharide complexes	Ye and Harte [206]
Soy protein isolate and hydroxypropyl methyl celluloses (Stansted Fluid Power homogenizer, model FPG 12500)	- 0–300 MPa	- Increase in foam overrun, especially for polysaccharides with higher Mw and treatment at 300 MPa, together with a decrease in the viscosity.	Martínez et al. [123]

Table 2 (continued)

Compound/s ((U)HPH equipment)	Conditions	Main outcomes	Reference
	- High and low Mw of hydroxypropyl methyl cellulose	- Suggesting formation of protein-polysaccharide aggregates. - Under those specific conditions, the Mw of the polysaccharide was an important factor in its interaction with soy protein isolate.	
Peanut protein isolate and chitosan (ATS Inc. homogenizer, model AH-100D)	- 600 bar - pH = 7	- Decrease in gel strength - Gels obtained with higher protein concentration were fragile	Jiao et al. [83]
Peanut protein isolate and xanthan gum (ATS Inc. homogenizer, model AH-100D)	- 600 bar - pH = 7	- Decrease in gel strength - Gels obtained with higher protein concentration were stronger - Heat did not affect solid-like structure	Jiao et al. [83]
Peanut protein isolate and guar gum (ATS Inc. homogenizer, model AH-100D)	- 600 bar - pH = 7	- Decrease in gel strength - Gel properties were scarcely affected by HPH treatment. - Gels obtained with higher protein concentration were tougher and highly stable	Jiao et al. [83]

polysaccharide-rich phases will occur. In the case of attractive electrostatic force, phase separation of protein and polysaccharide-rich phase and a solvent-rich phase will occur [149]. Some physical processes can induce changes in protein structure, altering the ability to interact, and among them is (U)HPH. (U)HPH impact on polysaccharides and proteins mixed systems is also described in Table 2. The impact of (U)HPH on the interaction between electrostatically charged polysaccharides and neutral polysaccharide and protein was demonstrated to effect the complexes [83]. Such studies may help to understand how (U)HPH can manipulate protein-polysaccharide interactions and open the way for further research on the formation of new functional polysaccharide-protein aggregates\complexes, and opportunities in the stabilization of hydrophobic proteins in an aqueous medium.

Improvement of Techno-Functionality of Complete Food Systems by (U)HPH

Many studies investigated the possibility of processing liquid food products by (U)HPH to reduce the microbial load, improve techno-functional and sensory properties, reduce fat content, and reduce the use of stabilizers [6, 28, 119, 122, 138, 139, 143, 166, 210]. The application of (U)HPH in dairy products, including for pasteurization and improvement of functional properties, has been comprehensively reviewed [9, 46, 49, 63, 122, 135, 166, 187, 210]. Recent works on bovine milk developed a method for monitoring and predicting the structural and functional changes in milk during (U)HPH at different inlet temperatures by monitoring the formation of Maillard compounds using face fluorescence spectroscopy [111, 112]. The influence of (U)HPH milk treatment on the properties of cheese has been previously reviewed [46, 135, 187, 210]. For dairy-based yogurt, several studies investigated the utilization of (U)HPH on skim and whole milk for the production of set or stirred yogurt and its influence on yogurt properties. They reported that (U)HPH treatment resulted in the reduction of particle size, the formation of finer dispersion, as well as the denaturation of whey proteins and dissociation of casein micelles. Thus, yogurt properties such as water holding capacity, firmness, syneresis, consistency, and water retention were improved [75, 102, 162, 164, 165]. The impact of HPH on techno-functional properties of some complete food systems is presented in Table 3. HPJ was studied and shown to change the physiochemical properties of skim milk, skim milk powder, and whole milk [76, 77, 185]. These findings may allow the future utilization of HPJ to manufacture novel functional ingredients to minimize/replace the addition of emulsifiers or stabilizers to food products. (U)HPH was also reported as a tool for changing during shelf life the physiochemical properties, texture, and sensorial properties of dairy products such as cream and yogurt [28, 148, 163].

The demand for plant-based protein beverages and yogurt substitutes as an alternative to milk and milk-based yogurt is increasing in recent years [82, 118]. Plant-based dispersions often suffer from techno-functional limitations such as poor aqueous solubility, off-flavor, color and physical instability [4, 39, 82]. Thus, recent works have focused on the utilization of (U)HPH as a preservation technology for such products and studied the outcome on techno-functional characteristics of plant-based drinks, e.g., particle size, physical stability, color, and volatile compounds. As expected, (U)HPH considerably reduced the microbial load and particle size and extended the product shelf life [31, 32, 35, 55, 56, 68, 69, 171], improved product color, usually luminosity, compared with the one observed for conventional heat treatment [32, 56], and improved physical stability, mainly against creaming, due to the particle size reduction [31, 55]. Also, (U)HPH processing resulted in a similar, or sometimes decreased the off-flavors when compared with conventional thermal treatments [32, 56]. (U)HPH was found to improve characteristics of yogurt alternative prepared

Table 3 The effect of (ultra) high-pressure homogenization on food system properties

Food system ((U)HPH units)	Conditions	Main outcomes	Reference
Whole milk (Flow Internationals Corp., Hyperjet 94i-S pump system)	- 125–500 MPa - T_{in} = 5 °C, 55 °C	- Decrease in fat content in supernatant fraction and corresponding increase in precipitate fraction - Increased viscosity and foaming properties with a bimodal particle size distribution at pressures 250 MPa and above - Limited foam stability at the pressure range of 375–500 MPa	Tran et al. [185]
Skim milk (Flow International Corp., Hyperjet 94i-S waterjet pump system)	- 100–500 MPa - T_{in} = 10 °C	- Increased in viscosity, foam expansion and foam volume stability indexes, and emulsion activity index at pressures of 300 MPa and above - A bimodal particle size distribution of milk treated at 400 and 500 MPa - Formation of uniform and non-uniform protein aggregates, larger than the casein micelles alone.	Hettiarachchi et al. [76]
Skim milk powder (Flow International Corp., Hyperjet 94i-S waterjet pump system)	- 100–500 MPa - T_{in} = 25–30 °C	- Higher apparent particle density and lower solubility at 500 MPa - No influence on physical and powder properties at 100 and 400 MPa - Higher foam expansion index and volume stability index at 400 and 500 MPa - Highest emulsion stability index at 500 MPa	Hettiarachchi et al. [77]
Skim milk powder (Avestin EmulsiFlex C-5)	- 41, 114, 186 MPa - Passes = 1–6 - T_{in} = 25 °C - Thermal treatment at 85 °C	- Changes in structure of casein micelles - Particle size reduction at 114 MPa and 186 MPa - Heating did not change significantly average particle size while combination between heat and HPH reduced the particle size	Sandra and Dalgleish [153]
Low-fat stirred yogurt (Microfluidics Corp. microfluidizer model M110-EH)	- 25–150 MPa	- HPH induced microstructural changes - Increase gel particle size, gel strength, and viscosity - Creation of low-fat yogurt with similar texture properties to full-fat yogurt	Ciron et al. [28]
Yogurt (Stansted Fluid Power Ltd. homogenizer, model FPG 11300)	- 200, 300 MPa - T_{in} = 30 °C, 40 °C - Single-stage homogenization	- Similar organic acids and volatile carbonyl compounds profile in yogurts from milk treated at 300 MPa and heat-treated milk - A different organic acids and volatile carbonyl compounds profile and a decrease in the *Lactobacilli* count in yogurts from milk treated at 200 MPa and both inlet temperatures - Lower levels of lactic acid in yogurts from milk treated at 300 MPa and both inlet temperatures	Serra et al. [163]
Cream (Stansted Fluid Power homogenizer)	- 300 MPa - T_{in} = 40 °C - 8 L h^{-1} - Single-stage homogenization	- Reduction in microbial load - Reduction in particle size - Reduced separation during storage for 29 days	Rodarte et al. [148]
Hazelnut beverage (GEA Niro Soavi, Panda PLUS 2000)	- 25–150 MPa - T_{in} = 15 °C	- Reduction in particle size with a monomodal particle size distribution - Improved microstructure and rheological properties - Reduction in consistency and friction loss, increase in flow behavior index - Higher values of G′ than G″ indicating that samples could be classified as a soft-gel network.	Gul et al. [69]
Tiger nuts beverage (Fluid Power Ltd. homogenizer, model DRG No. FPG11300)	- 200, 300 MPa - T_{in} = 40 °C	- Improved colloidal stability, mainly against creaming, due to reduction in particle size and new particle interactions - 200 MPa treatment enhanced lipid oxidative stability - Improved enzymatic stability - Shelf life microbiological stability was the highest at 300 MPa	Codina-Torrella et al. [31]
Tiger nut beverage (Fluid Power Ltd. homogenizer, model DRG No. FPG11300)	- 200, 300 MPa - T_{in} = 40 °C	- Improved microbiological shelf life by (U)HPH - No significant differences in aroma and taste attributes among all (U)HPH samples - Off-flavors were only identified in heat treatment samples - Greater luminosity and whiteness of samples homogenized at 300 MPa.	Codina-Torrella et al. [32]
Almond beverage (Stansted Fluid Power Ltd. homogenizer, model G12500)	- 200, 300 MPa - T_{in} = 55 °C, 75 °C - 200 MPa	- Improved colloidal stability, mainly against creaming, due to the reduction in particle size - Reduction of microbial load and at 300 MPa complete microorganisms' inactivation	Ferragut et al. [55]

Table 3 (continued)

Food system ((U)HPH units)	Conditions	Main outcomes	Reference
Almond beverage (Stansted Fluid Power Ltd. model FPG11300)	- T_{in} = 55 °C, 75 °C	- HPH induced the formation of aroma compounds indicative of lipid oxidation - Improved microbiological shelf life by HPH - Improved sedimentation during storage at 200 MPa and T_{in} = 75 °C - HPH increased lightness value	Ferragut et al. [56]
Soy beverage (Stansted Fluid Power Ltd. homogenizer, model FPG11300)	- 200, 300 MPa - T_{in} = 40 °C	- Observed protein aggregates at 300 MPa - Soy proteins were partially denatured at 200 MPa while at 300 MPa the observed denaturation was the same as the result of thermal treatment - Color differences between (U)HPH drink compared with the control and thermal treated drink	Cruz et al. [35]
Soy beverage (Power Ltd. homogenizer, model nG7900)	- 207, 276 MPa - T_{in} = 23–28 °C	- No difference in the sensory properties of soy drink treated with (U)HPH in comparison to commercial soy drink - Reduction in soy soybean solids particle size with no change during storage - (U)HPH caused a decrease in pH value	Sidhu and Singh [171]
Soy beverage (Stansted Fluid Power Ltd. homogenizer, model G12500)	- 200, 300 MPa - T_{in} = 55 °C, 75 °C	- Improved colloidal stability, mainly against creaming, due to the reduction in particle size - Reduction of microbial load and at 300 MPa complete microorganisms' inactivation	Ferragut et al. [55]
Soy beverage (Stansted Fluid Power Ltd. homogenizer, model FPG 11300)	- 300 MPa - T_{in} = 80 °C	- No microbiological growth during storage - High colloidal stability and decrease in hydroperoxide index during storage - No changes in the off-flavors volatile profile of soymilk compared with the thermal treatment	Poliseli-Scopel et al. [144]
Soy beverage and yogurt alternative (Stansted Fluid Power Ltd. homogenizer, model FPG11300)	- 200, 300 MPa - T_{in} = 40 °C, 50 °C	- Thermal treated soy beverage and (U)HPH treated samples exhibited different behavior to coagulation - Longer onset of gelation, and lower aggregation rate and gel network density - Greater firmness, higher water holding capacity	Cruz et al. [36]
Soy beverage and yogurt alternative (Stansted Fluid Power Ltd. homogenizer, model FPG11300)	- 200, 300 MPa - T_{in} = 50 °C	- Higher firmness and higher water holding capacity - Difference in yogurt alternative color during storage - More homogenous and compact network structure	Ferragut et al. [54]
Tofu (SPX Co. homogenizer, model APV 2000)	- 100, 150 MPa - Passes = 2–3 - Two concentrations of soy flour suspensions	- Reduction in particle size of soy flour - Improvement in syneresis and similar texture parameter compared with the control - Formation of a more continuous honeycomb-like structure	Liu et al. [108]

from the treated plant-based beverage, such as greater firmness, higher water holding capacity, and similar color compared with conventional heat treatment [36, 54].

Conclusion

(U)HPH is an emerging technology with potential applications in various areas of the food industry including pasteurization and sterilization, emulsion and suspension stabilization, and modification of the structure of whole matrices and specific biopolymers for the production of functional foods and novel ingredients. Major effects due to (U)HPH treatment are observed for polysaccharides, proteins, and their combination, leading to the formation of physically modified biopolymers with novel functionalities. The extent of these effects depends on a range of controllable processing parameters such as pressure, inlet temperature, valve design, solution pH, and others. To transform the current rich scientific data obtained from laboratory and pilot-scale work into commercial applications, the understanding of scaling up, energy consumption, and process cost estimation must improve. An additional possible driving force for the implementation of this technology could stem from a better understanding of (U)HPH effects on the bioaccessibility of bioactive compounds and the benefits of the modification of matrices and biopolymers when engineering the digestive fate of foods. From an engineering point of view, a more comprehensive understanding of the effect of valve type and geometry on the techno-functionality is also vital.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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