sustainability

Review

High-Pressure Processing for Sustainable Food Supply

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Abstract: Sustainable food supply has gained considerable consumer concern due to the high percentage of spoilage microorganisms. Food industries need to expand advanced technologies that can maintain the nutritive content of foods, enhance the bio-availability of bioactive compounds, provide environmental and economic sustainability, and fulfill consumers' requirements of sensory characteristics. Heat treatment negatively affects food samples' nutritional and sensory properties as bioactives are sensitive to high-temperature processing. The need arises for non-thermal processes to reduce food losses, and sustainable developments in preservation, nutritional security, and food safety are crucial parameters for the upcoming era. Non-thermal processes have been successfully approved because they increase food quality, reduce water utilization, decrease emissions, improve energy efficiency, assure clean labeling, and utilize by-products from waste food. These processes include pulsed electric field (PEF), sonication, high-pressure processing (HPP), cold plasma, and pulsed light. This review describes the use of HPP in various processes for sustainable food processing. The influence of this technique on microbial, physicochemical, and nutritional properties of foods for sustainable food supply is discussed. This approach also emphasizes the limitations of this emerging technique. HPP has been successfully analyzed to meet the global requirements. A limited global food source must have a balanced approach to the raw content, water, energy, and nutrient content. HPP showed positive results in reducing microbial spoilage and, at the same time, retains the nutritional value. HPP technology meets the essential requirements for sustainable and clean labeled food production. It requires limited resources to produce nutritionally suitable foods for consumers' health.

Keywords: high-pressure processing; sustainable food; food quality; economic sustainability; waste minimization; water conservation

1. Introduction

Sustainability is a vital need of fulfilling the basic societal requirements by improving social, environmental, and economic systems [1]. With the world's increasing population, people mainly focus on healthy, nutritious, and safe foods [2]. For this reason, the main target of the United Nations 2030 programs is the implementation of the latest food production for the sustainability of food. Sustainability is a major feasible way to access the upcoming basic requirements for a safe, nutritious, and healthy diet [3]. Sustainable food processing demands the exclusive use of natural resources to minimize food waste [4]. Many foods, especially fruits, vegetables, and grains, are wasted during storage, transportation, and processing [5]. Nowadays, the food industry is forced to develop sustainable food systems [6]. Some limitations of conventional technologies that lead to the adaptation of non-thermal technologies are off-flavors due to chemical reactions, fluctuations in nutrients, and losses of food quality [7].

The food industry has adopted different effective non-thermal techniques such as a pulsed electric field [8] (PEF), ultra-sonication [9] (US), cold plasma [10], high-pressure processing [11] (HPP), and ultraviolet radiation. All of these techniques maintain the original food quality, overcome nutrient loss, and have a low energy consumption compared with conventional systems [12]. The effects on the flavor, viscosity, appearance, nutritional value, and practical function in inactivating pathogens and vegetative micro-organisms are reduced compared with many conventional therapies [13]. HPP technology is considered environmentally friendly and kills bacterial cells, yeasts, and molds without heat [14]. It lessens the need for chemical additives and increases bioavailability [15,16]. HPP is perceived as a replacement for thermal techniques because it improves food safety, increases shelf life, and preserves the sensorial, physiochemical, and nutritional content of food [17]. The basic goal of HPP of meat and meat items is to minimize the infectious and spoilage microbes and to extend the shelf life [18].

HPP is also called high hydrostatic pressure, ultra-HPP, pascalisation or cold pasteurization. In this technique, high pressure is applied to solid or liquid foods to enhance their safety, organoleptic attributes, and quality. Firstly, high-pressure treatment was applied in the late 1890s for the inactivation of microbes in dairy products, i.e., milk [19]. HPP works on the isostatic principle, which states that different media such as water or oil apply constant pressure to the sample. The combination of water with oil lubricates the equipment and reduces corrosion. Thus, it helps eliminate the microorganisms in food samples and is not affected by the size and shape of the food samples [20]. According to the isostatic principle, HPP does not depend on volume; therefore, pressure is transmitted instantly and constantly throughout a sample, and pressure gradients do not exist. HPP has been utilized in food sterilization and preservation processes to enhance the shelf life of food and maintain high quality by following Le Chatelier's and Pascal's principles for specific purposes [21]. Le Chatelier's Principle states that phenomena lead to a decrease in volume, such as state changes, chemical reactions, and alterations in molecular arrangement, enhanced by pressure. In contrast, volume increases by reduced pressure. HPP will perform an essential role as an alternative approach in food sterilization when the transmission medium is water [22].

It has been proven that HPP allows shelf-life extension [23], pathogen removal [24], and clean-label [25] convenience while providing natural and safe food to consumers. HPP has been utilized in different food categories such as vegetables, fruits, dairy, meat, sea foods [26], jams, fruit jellies, sauces, purees, juices [27], ready to eat meat, Deli Salads, Dips, Salsa markets [28], infants food, and the fish industry for different purposes. Table 1 describes the applications of HPP in different industries of food.

Table 1. Applications of HPP in the food industry.

Applications	Treatment Conditions	Food Sample		Treatment Effects	References
Meat processing	175–600 MPa, 3–5 min,	Meat, Meat Products, and Seafood		Showed minimal effect on nutrients and sensorial characters. Slowed down microbial growth and reduced the activity rate of spoilage bacteria.	[29–31]
Microbial reduction	300–600 MPa, 5–10 min	Meat, juices, milk products		Caused significant reductions in microbes in food items, i.e., about a 1.6–5-log reduction	[32–34]
Extraction	250–500 MPa, 5–15 min	Seeds, fruits, vegetables, plants, cereals	carbohydrates, bioactive compounds	Extraction yields were enhanced by HPP compared with the conventional method	[35–39]
Pretreatment	200–300 MPa, 2–6 min	Meat, fruits, vegetables		HPP as a pretreatment improved textural, nutritional, and sensorial attributes.	[40–43]
Seed treatment	200–400 MPa, 10–60 min 20–60 °C.	*Moringa oleifera* kernels, Basil, chia seeds		HPP enhanced the extraction of oil as well as the structure of seeds	[44–46]

MPa: megapascal, CFU: colony-forming unit.

HPP operated at 350 MPa for 4 min and combined with 0.05% allyl isothiocyanate (AITC), showed a 5-log reduction of *Salmonella* and at 350 MPa for 12 min with 0.075% AITC, showed more than 7-log inactivation of *Salmonella* in ground chicken meat [47]. HPP as a pretreatment maintained the color and texture of albacore steaks when operated at 200 MPa for 6 min [48]. Nunez-Mancilla et al. [49] studied the HPP impact on strawberries at 100–500 MPa for 10 min. The results clearly showed higher antioxidant activity and a total phenolic content at 400 MPa; HPP also retained the vitamin C content in strawberries. This review mainly focuses on describing HPP sustainability, advantages, and limitations. HPP is an efficient, non-thermal, and the most accepted technique by the consumer [50]. Furthermore, the continuous demand for healthy and safe foods has discovered HPP for mild food preservation without chemicals and preservatives.

The current study was done based on research articles found on 14 March 2021, using the internet database Web of Science (WoS). The authors discovered some of the most highly cited articles referencing the term "high-pressure processing". The search revealed papers that referred to "high-pressure processing" in their titles, abstracts, or author keywords. Furthermore, the authors established two criteria to limit the relevant research papers that were selected: either the most cited or the most current research.

2. Working Mechanism of HPP

HPP equipment mainly consists of the following components: a pressure vessel composed of high-tensile strength steel determined by the process's lethality, closures or plugs, a yoke/wire-wound steel frame, a pressure pump, and a control system [51] as demonstrated in Figure 1. The food sample is kept in a pressure chamber using water as a pressure-transfer medium after being filled and sealed in flexible pouches. Additional fluid may be injected into the pressure chamber to create pressure. Because of the isostatic principle, pressure is uniformly distributed across the whole product in the container, ensuring that all food parts are under equal pressure. Surprisingly, the product's size and shape have minimal impact on the HPP treatment.

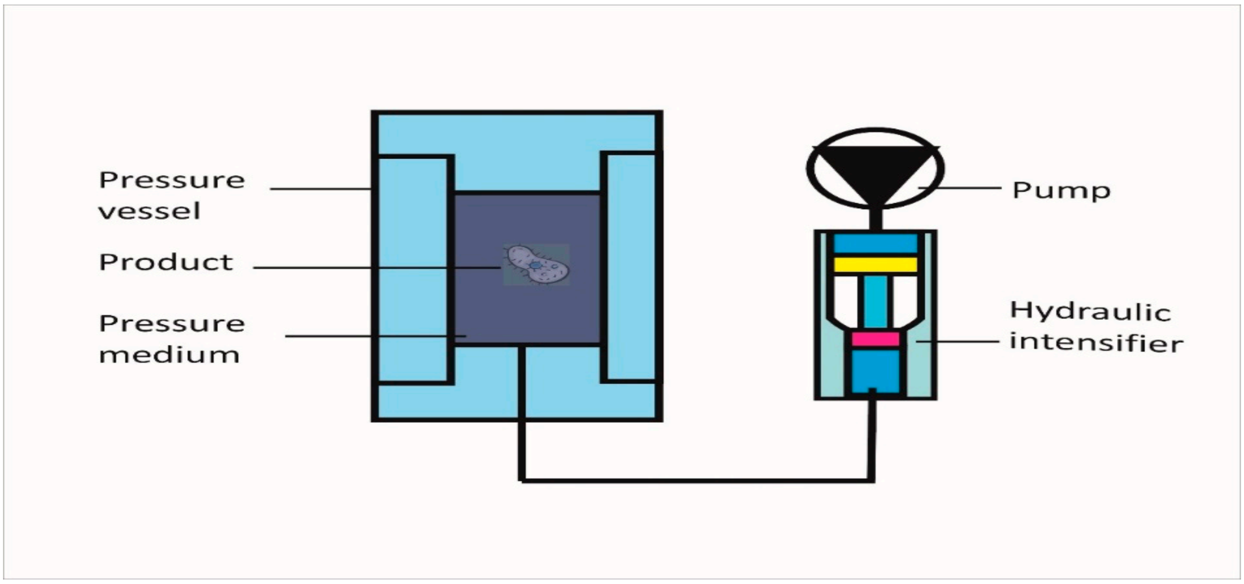

Figure 1. A standard batch HPP system.

A pressure vessel may also be used to create a pressure intensifier. The pressure vessel, which holds a packed food product and pressurization fluid, is intended to endure a certain pressure and temperature. The quantity of fluid that a pressure vessel can contain determines its size, varying from a few milliliters in research units to several hundred liters in commercial units [52].

Both batch and continuous HPP systems are utilized in food industries. Batch process systems are used for most solid food products; however, liquids and other pumpable goods have the option of being treated in a continuous system [53]. Semi-continuous process systems comprise two or more pressure vessels, a small pressure pump to fill the vessels, a high-pressure transmission pump, holding and sterile tanks, and controlling valves [54]. Pressure vessels contain a separating piston that moves freely to separate the product from the pressurizing fluid. Controlling valves prevent cross-contamination of the treated product with the upcoming untreated product [55]. At the start of the process, the pressure vessel using a low-pressure pump fills with the liquid product. When the food section is filled, the inlet valve is closed, and pressurizing fluid moves the free piston to compress the liquid. The vessel is depressurized after a suitable holding time, which will decompress the food and the piston returns to its original state. Finally, the processed liquid product is aseptically packed in sterilized containers [53]. Vessels are connected so that when one vessel discharges the product, the second system is pressurized, and the third is loaded with a food sample. Therefore, a continuous product is maintained. In a commercial-scale industry, three pressure vessels are used to provide a continuous product output. This production is generated by the operation of these three vessels simultaneously; one is loading, the second is compressing, and the last is discharging at any point in time [56].

Pressure, such as heat, is a fundamental thermodynamic variable. In a strict sense, the effects of temperature and pressure cannot be isolated during HPP. This is because each temperature has an associated pressure. Thermal effects result in volume and energy changes during pressure treatment. However, pressure mainly influences the product volume. The combined net impact may be synergistic, antagonistic, or additive [57]. Hence, the HPP process is characterized by three parameters: temperature (T), pressure (p), and exposure time (t) compared to heat preservation. Figure 2 shows the pressure, temperature, and time relationship in HPP.

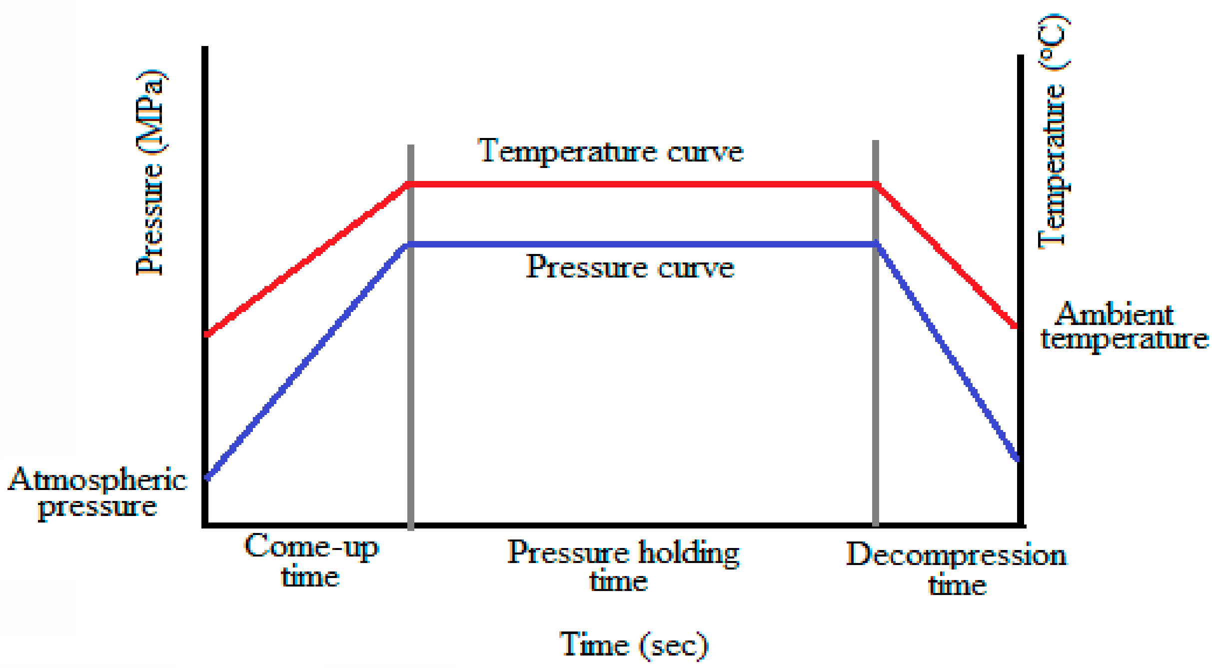

Figure 2. Presentation of temperature, pressure, and time in HPP.

The pressure is built up to a particular point until it reaches the desired pressure. The target pressure (pressure established as a standard for the product) is maintained for a specific time before being released. The pressure at which the sample food is held in the pressure vessel is termed the process pressure. The temperature at which the product obtains its process pressure is called the process temperature. The process temperature depends on the initial temperature, pressure transmitting fluid, and heat compression values. The time required to increase pressure from 0.1 MPa to the required process pressure is called the pressure come-up time [52]. However, the pump power (horsepower) and target process pressure increase or decrease the pressure come-up time. Strain gauges that function on the principle of a change in resistance under pressure strain (compression-decompression) and displacement transducers mounted on the external frame can be used to measure the pressure [58]. The pressure holding time is the time interval over which the product needs to be held under the process pressure. It is the period that occurs between the end of compression and the start of decompression.

In pulsed-HPP (*p*-HPP), pressure is applied with pulses to the sample with a total holding time [59]. The effectiveness of the *p*-HPP process has been reported to be more effective than an equivalent single pulse of equal time [60].

A pressure holding time of 3–10 min is used for economically viable commercial processes. After the pressurization, the temperature of the product is increased due to molecular arrangements. Therefore, a decompression period is needed to return the food sample from the process pressure to air pressure (0.1 MPa), and the product temperature is also reduced during depressurization [58]. HPP is applied at 400 to 600 MPa in most processes at ambient temperature. Most HPP processes operate at low temperatures, depending on the pressure of food processing. Depending on the product's composition, the water temperature of the product in the pressure chamber may increase by 3–6 °C for every 100 MPa increase in pressure. Table 2 shows the target pressure for different HPP applications in food.

Table 2. Target pressure for different food processing applications in HPP.

Applications	Target Pressure	Food Samples	References
Pasteurization	(300–600 MPa)	Meat, Milk, fruit juices, cereals	[61,62]
Sterilization	(500–900 MPa)	Fruits, macaroni, cheese	[63]
Extraction	(250–500 MPa)	Seeds, fruits	[35]
Pretreatment	(200–600 MPa)	Meat, vegetables	[40]

The target pressure must be varied for different food applications. For example, the target pressure for the extraction of xyloglucan from tamarind was 250–500 MPa [35]. Moreover, for pasteurization and sterilization, the target pressure was 300–600 MPa [64] and 500–900 MPa [63].

3. HPP Processing towards Sustainability

The Food and Agriculture Organization (FAO) and World Health Organization (WHO) reported on world food day 2019 the "Sustainable healthy diets–guiding principles" (FAO and WHO, 2019) and have described three pillars of sustainability: social, economic, and environmental. It was clearly defined that sustainable healthy diets are complete dietary patterns that improve an individual's health and wellbeing [65]. Furthermore, sustainable diets are accessible, feasible, safe, and nutritious and are mostly accepted by consumers and have less impact on the environment.

Food product quality and safety are the most crucial factors for society and industry [66]. HPP is an environmentally friendly technology, which provides sustainable food without compromising the safety or quality of products and improves the food sector economically [67]. Moreover, HPP is an all-natural process that assures clean labeling of food products. According to consumer demands, HPP allows natural food ingredients without the addition of chemicals and preservatives [68]. Table 3 demonstrates the HPP contributions towards sustainability in different food applications. The following part demonstrates each part of this contribution.

Table 3. HPP Contributions to sustainable food processing.

Contributions	Application	Treatment Conditions	Contributions Toward Sustainability	References
Food safety	Nutritional Improvement	200–600 MPa, 5–15 min	Improved nutritional value by HPP	[69]
	Food preservation	200–400 MPa, >2 min	More efficiently used for pasteurization of liquid foods and dehydration of solid foods	[70]
	Reduction of food contaminants	30 to 500 MPa, 30–50°C	Helped to decrease food contaminants and toxins.	[59]
	Solid food pretreatment	200 MPa, 0–6 min	Maintained texture and color	[48]
Environmental sustainability	Reduced food waste	300 MPa, 3 min.	Contribution to reducing food waste	[71]
Food packaging	Effects on food packaging	600 a, 60 min; 800 MPa, 10 min, 60 °C	Minimal effect on packaging material.	[72]
Economic sustainability	Profit attained	356 and 600 MPa, 30 min	Contributed to the recovery of valuable components from food	[73]
Water efficiency	Minimal water consumption		Not only energy saving but also water-saving technology	[74]
Energy efficiency	Minimal energy consumption	300–700 MPa	Utilised less energy than conventional techniques	[75]

Food security	Enhanced yield	200 and 500 MPa	HPP improved the food yield	[76]

HPP enhanced the extraction rate of bioactive compounds such as polyphenols, carotenoids, isothiocyanates, fatty acids, essential oils, and nutrients in food components [77,78]. For example, HPP enhanced the extraction of ferulic acid from *Angelica sinensis* [79] and the extraction of phenolic compounds from Chilean papaya (*Vasconcellea pubescens*) seeds [80]. Moreover, the extraction of astaxanthin carotenoid from shrimp shells was done efficiently by HPP at 200 MPa for 5 min [81]. Figure 3 illustrates the role of HPP in sustainable food production.

Figure 3. Contributions of HPP to sustainable food processing.

HPP was found to be capable of destroying vegetative as well as pathogenic bacteria and enzymes under certain circumstances; thus, it has been increasingly employed to compensate for the limitations of conventional thermal pasteurization and sterilization methods [82]. Microbes have a role in food spoilage and food losses. The inactivation of microbes helps to make food safe and extend the shelf life. HPP increases the product quality, sensory attributes, and shelf life and decreases microbial shelf life [64,83]. Woolf et al. [84] stated that the fragile sensory characteristics of avocado could be preserved with a long shelf life. HPP can also improve the product texture and structure [85].

3.1. Food Safety

Food safety has been a significant issue focused on since 1963 by the United Nations through an international forum. The FAO stated food safety as the "assurance that food will not cause harm to the consumer when it is prepared and/or eaten according to its intended use" [86]. According to another definition, food safety refers to food free from hazards [87]. Therefore, the number of interferences involving food safety can be diminished by assessing the possible hazards to forestall them and their adverse consequences.

Nowadays, HPP plays a role in reducing microbes, enhancing shelf life, preserving nutrients, and assuring the safety and quality of raw and processed food items [88]. For example, in the meat industry, HPP is helpful to increase the shelf life and safety of ready-to-eat meat products [89].

3.1.1. Food Preservation

Preservation of food reduces microbial growth. Survival and tendency to grow depend on the response of microbes. Spoilage and pathogenic microbes affect food quality and safety. The main requirement is the production of high-quality foods with high nutritional value. The latest preservation technologies were accepted based on their efficiency to reduce pathogenic and spoilage foodborne microorganisms [90]. HPP slows down the activation of microorganisms by controlling their reproduction and survival rate [91]. HPP reduced *L. monocytogenes* by about 0.91 log10 colony forming unit (cfu)/g at 600 MPa in different food items such as guacamole, cheese, fruit juices, meats, and seafood [92]. HPP has been proved as an effective food preservation technique to replace thermal techniques, especially in the meat industry. [93]:

i. Liquid Food Preservation:

According to Food and Drug Administration (FDA) terms, liquid food demands processes that show at least a 5-log reduction during preservation [6]. HPP successfully removes pathogenic and spoilage microorganisms in liquid foods [23]. In addition, a study on cactus juice was performed at 600 MPa, 15 °C for 10 min by HPP, and a 3-log reduction of yeast/mold was observed [94]. Table 4 explains the microbial load in some liquid foods after HPP treatment.

Table 4. Treatment of liquid foods by HPP.

Food Sample	Target Product	Treatment Conditions	Log Reduction	References
Coconut water	*Clostridium botulinum* type E and *Clostridium sporogenes*	550 MPa, 3 min, 10 °C	3.0 ± 0.1	[95]
Açaí juice	Bacteria	600 MPa, 3 min	5–6	[96]
Whole milk and skim milk	*Cronobacter sakazakii*	300 MPa, 400 MPa, 5.0 min	No detection	[97]
Cucumber juice	Yeast and mold, total aerobic bacteria	500 MPa 5 min	1.35–1.94	[98]
Beetroot and carrot juice	*E. coli*	300–500 MPa	No detection	[99]
Raw milk	Pathogens	600 MPa, 3 min	5	[100]
Acidic fruit juices	*Alicyclobacillus acidoterrestris*	600 MPa, 80 °C, 3 min	2.0–2.5	[101]
Wines	*Brettanomyces bruxellensis*	200 MPa, up to 3 min,	1.1–5.1	[102]

In 2013, orange juice was treated at 200–600 MPa, 20–60 °C by HPP. The result showed a 2-log reduction in *Alicyclobacillus acidoterrestris* [103]. Hiremath and Ramaswamy [104] concluded that applying 400 MPa for 10 min caused a 6-log inactivation of *E. coli* O157:H7 in mango juice using HPP. According to Huang et al. [105] *E. coli* O157:H7 showed 6-log CFU/g inactivation in frozen strawberry puree, under HPP conditions of 450 MPa for 2 min at 21 °C. Shahbaz [106] stated that applying HPP at 600 MPa and 25 °C for 1 min with 8.45 J/cm2 of TiO2-UV photocatalysis caused 7.1-log CFU/mL and 7.2-log CFU/mL reductions of *E. coli* and *Salmonella Typhimurium* in apple juice. Syed et al. [107] treated orange juice by HPP at 700 MPa for 5 min for complete inactivation of *S. aureus*. HPP successfully reduced the microbial content ($p \leq 0.05$) in Sabah Snake Grass juice at 400 and 500 MPa [11].

ii. Solid Food Preservation

HPP is a beneficial non-thermal process utilized to inactivate microbiota in certain foods. [108] HPP has been used for more than 100 years as a well-known pasteurization technique to make food products safe and contaminant-free [109]. HPP at 300–600 MPa effectively stopped the growth of decaying microbes in meat products [110].

HPP with antimicrobials increased the decontamination of foodborne pathogens and microbial safety of meat and meat products. [111] For example, parma ham treated with HPP showed a reduction of *L. monocytogenes* and was easily packaged and sold worldwide [112]. The same results were shown in the case of dry-cured ham by enhancing the shelf life of ham [113].

Water plays a major role in microorganism growth and enzymatic reactions in food [114] and therefore must be removed. HPP plays a role in food dehydration. For example, the combined effect of HPP and osmotic stress on the dehydration of ginger slices were studied [115]. At 600 MPa, the moisture content decreased, and the solid content increased.

HPP induced freezing and thawing, which formed ice crystals, resulting in a uniform crystal structure within the food matrices [116]. Thus, HPP preserves the structure and texture of solid food products through freezing. For example, peach and mango were treated at 200 MPa and −20 °C; high-pressure shift freezing of peach and mango with high supercooling formed uniform rapid ice crystals throughout the sample. As a result, large ice crystal formation and quality losses due to freezing cracking could be reduced [117].

HPP-assisted thawing caused less quality damage than traditional freezing techniques in meat by applying 100–200 MPa for 10 min [118]. According to another study, broccoli was treated at about 180–210 MPa pressure and −16 °C to −20 °C, which decreased the protein content and did not inactivate peroxidase and polyphenol oxidase enzymes. After one month, unpleasant changes in the flavor of broccoli occurred, but the texture remained the same. It destroyed the vacuole membrane and disorganized internal cells [119].

3.1.2. Effect of HPP on Food Contaminants

Food contaminants consist of environmental contaminants, food processing contaminants, unapproved adulterants, food additives, and migrants from packaging materials. [120] Environmental contaminants include impurities that are introduced by humans or naturally arise in water, air, or soil. Food processing contaminants contain unwanted components such as nitrosamines, chloropropanols, acrylamide, furanes, and polycyclic aromatic hydrocarbons (PAH) during baking, roasting, canning, heating, fermentation, or hydrolysis [121]. Moreover, chemical supplies found in food, animal feed, or antibiotic injections injected into poultry animals are examples of food contamination from chemicals [122]. HPP reduces the activity rate of pectin methylesterase (PME) isoenzymes. They mainly cause pectin degradation and cloud loss in most citrus juices. HPP showed less food quality loss, flavor retention, and eliminated spoilage microflora, i.e., yeasts, molds, and lactic acid bacteria, in citrus juice [123].

Over the last 10 years, HPP has become the most reliable and fastest decontamination technology, so many commercial large-scale units have been introduced in western countries [124]. Research has shown the combined effect of pressure and temperature (high-pressure thermal sterilization) in the inactivation of spores [125]. Therefore, high-pressure thermal sterilization (HPTS) was certified in 2015 and it reduces food processing contaminants (FPCs), e.g., furan [126], acrylamide, hydroxymethylfurfural (HMF), and 3-MCPD/-esters etc. HPP induced microbial inactivation and structural alterations in food components [127]. Therefore, it has been proved that it is a beneficial tool for the reduction of pesticides and mycotoxins. For example, studies showed that the common pesticide chlorpyrifos in fruits and vegetables, e.g., tomatoes and Brussel sprouts [128] was reduced under optimal conditions to 75 MPa, 5 °C, by HPP.

3.1.3. Reduction of Pesticides

Pesticides are helpful to eliminate pests, enhance shelf-life, and maintain quality. Specific laws enable their production, marketing, and usage [129]. About two million tons of pesticides are utilized every year worldwide. Sharma et al. [130] reported a serious risk by contaminating raw sources of food. The pesticide residue levels in food are controlled by law to lessen exposure to the consumer [131,132].

HPP has been utilized as a phytosanitary treatment for reducing insect pests in fresh or processed fruits and vegetables to enhance their shelf-life [133]. Moreover, HPP applied with pre-sterilized packaging reduced chemicals in liquid effluents [134].

3.1.4. Degradation of Toxins

Due to the increasing demand for safe food, it is essential to explore new innovative techniques for reducing pesticides and mycotoxins in food products [135]. Studies showed that most foods are contaminated by pesticides and mycotoxins [136]. The major sources of contamination are polluted raw materials [137] that are contaminated before coming into food factories [138]. Cereals utilized as staple food have a high risk of mycotoxins, such as aflatoxin and ochratoxin. HPP has a serious effect on mycotoxins and minimizes their toxicity in the environment [13]. Kalagatur et al. [61] found that when 550 MPa pressure was applied to maize grains at 45 °C for 20 min, the maximum reduction in ZEA and DON levels occurred. Another experiment was done to reduce two heat-resistant fungi, *Aliivibrio fischeri* and *Talaromyces macrospores*, in strawberry puree by combining pressure and heat [139].

HPP is an efficient technique utilized in the food sector to inactivate spore fungi and stop their growth. According to research, it was found that HPP (600 MPa) with US treatment (24 kHz/0.33 W/mL) at 75 °C for 30 min eliminated the ascospores of *Byssochlamys nivea* in strawberry puree [140]. In another study, the combination of HPP (600 MPa) and US (24 kHz/0.33 W/mL) at 75 °C helped to remove ascospores of *Neosartorya fischeri* and *B. nivea* in apple juice [62,141]. Moreover, the combination of HPP with ultrasound can enhance decontamination. A study by Huang et al. [142] concluded that 600–800 MPa pressure inactivated the mycotoxigenic fungus *A. flavus*. Tokusoglu, Alpas, and Bozoglu [143] proved that mold flora and the level of citrinin mycotoxin in black table olives were successfully reduced by HPP treatment.

3.2. Food Security

Food security is a multifaceted concept, and it can be achieved at the individual, household, national, regional, and global levels when all people consistently have physical and economic access to adequate, safe, and nutritious food to fulfill their intake needs and food choices for an active and healthy life. Food insecurity, malnutrition, and poverty are the most serious global challenges of the 21st century. Food insecurity is chronic. Xie et al. [144] showed an alarming food insecurity situation. The period from 2013 to 2019 was shown as an active period of food insecurity. According to one national nutrition survey, food insecurity has reached its highest level, it was 58% in 2005–2006 and about 72.8% in 2013, causing troubles in some regions.

3.2.1. Sustainable Nutrition Security

During 2014–2016, almost 795 million people worldwide were undernourished [145]. Therefore, there is a need for non-thermal techniques that preserve the nutrients and the quality of food products. Non-thermal preservation techniques result in minimal changes in flavors, nutrients, and vitamins due to low temperatures [146].

HPP generally causes no marked nutritional loss in foods compared with conventional thermal processes [147]. In addition, some studies showed no significant changes in carotenes immediately [148]. Some authors suggest that antioxidant activity increases by HPP [149], but others have come to the opposite conclusion [150]. Table 5 shows the effect of HPP on food nutrients in different food samples.

Table 5. HPP effects on food nutrients.

Food Nutrients	Food Sample	Treatment Conditions	Treatment Effects	Reference
Fatty acid	Caprine milk	200–500 MPa	No marked differences in the fatty acid profile, excluding an increase in branched-chain fatty acids.	[151]
Free amino acids	Serrano dry-cured ham	600 MPa, 6 min, 4 °C	No effect of HPP on total FAA levels	[152]
Protein	Milk	150–450 MPa, 15 min	The disintegration of casein micelles at >250 MPa; serum proteins were denatured.	[153]
Free amino acids	Chinese rice wine	400 MPa or 600 MPa 10 min	HPP increased the free amino acid content	[154]
Carotenoids	Cloudy carrot juice	300, 450, 600 MPa, 5 min, ≈22 °C	The highest carotenoid degradation (41%) occurred at 350 MPa, whereas the lowest (26%) occurred at 600 MPa.	[155]
Polyphenols	Kiwi berry	450, 550 or 650 MPa, 5 or 15 min	Caused a significant increase in the individual polyphenol content	[156]
Anthocyanins, non-anthocyanin phenolics, tocopherols	Acai juice	400, 450, 500 and 600 MPa, 5 min, 20 °C.	Efficient preservation technique for anthocyanins compared to thermal pasteurization (up to 40%)	[157]
Polyphenols, Enzymes	Carrot juice	450 and 600 MPa, 5 min, ≈ 22 °C	At 300 MPa, maximum inactivation of (PPO) enzymes (57%) was achieved, and at 600 MPa, about 31% inactivation of peroxidase (POD) enzymes was observed. Significant changes in the color parameters and the browning index were observed.	[77]
Anthocyanin, polyphenol oxidase, and β-glucosidase	Blueberry	300 MPa	HPP treatment resulted in better puree colour retention than the conventional treatment	[158]
Total phenolic compounds, vitamin C	Strawberry	100 and 500 MPa,10 min.	At 400 MPa, the maximum total phenolic content was obtained; preserved vitamin C content in strawberry.	[49]
Oxidoreductive enzymes	Mushroom	200–900 MPa, 5–45 °C, 1–15 min	HPP used in the experiments significantly ($p < 0.05$) decreased PPO and POD activities, with a greater decrease in the relative activity (RA) of the enzymes observed when the pressure was increased.	[159]
Carbohydrate hydrolysing enzymes	Lemon flavedo	400 MPa, 10 min	HPP-treated samples had high levels of carbohydrates Hydrolyzing enzyme inhibition	[160]
Polyphenol oxidase	Pawpaw	600 MPa, 4 °C, 76 s	HPP significantly decreased PPO activity. HPP was proved to be an effective technique for the longer shelf-life of fresh-packaged pawpaw pulp.	[161]

Additionally, it was considered that the HPP technique at 100, 200, and 400 MPa efficiently enhanced the functional properties of pine nut protein isolates with enhanced heat-induced gel strength [162]. Compared with conventional treatments, HPP enhanced nutrient retention [163] and reduced the effects on antioxidant activity [164]. As a result, HPP enhances the food shelf life and decreases nutritional losses [165].

HPP preserves the value of the vitamins in food; for example, it was observed that heat, light, pH, metals, and free radicals are prominent factors that affect vitamin E activity. In an anaerobic environment, tocopherols and trienols are stable to heat and alkaline conditions. A pressure of 400 to 600 MPa caused no marked reduction in the amount of tocopherol in milk [166]. However, HPP increased the concentration of phenolic compounds [167]. It was concluded that the polyphenol content of apple juice (600 MPa, 50 min) was 409.2 mg, which was 14% higher than that in thermal treatments. In addition, HPP application influences the stability of chlorophyll at a high temperature and low pressure. Medina-Meza et al. [168] showed high stability of chlorophyll at lower pressures from 400 to 650 MPa in spinach sauce.

HPP enhanced the solubility of myofibrillar protein at low pressure. Ziye et al. [169] stated that myofibrillar proteins are sensitive to high pressure. At 100–200 MPa, the quaternary structure dissociates, while above 200 MPa, tertiary structures are affected, and at 300–700 MPa, secondary structures are affected. HPP improves the gelation properties of myofibrillar proteins. Chan et al. [170] found that at low-pressure (≤ 200 MPa), the solubility of myofibrillar proteins improved; at a pressure higher than 300 MPa, the solubility of myofibrillar proteins decreased and large aggregates formed. Hence, it was proved that HPP successfully improved the texture of food products [171].

HPP plays a role in the tenderness of meat, which depends on myofibrillar and connective tissue. The mechanisms of meat tenderization that occur in the HPP of pre-rigour muscles and chill ageing of post-rigour muscles are different. HPP causes alterations in the muscle microstructure, sarcomere contraction, muscle fibre damages, and myofibril fragmentation, such as hydrolyzing the proteins in the muscle fibres, weakening the cell structure, releasing the ions, and activating calcium-activating enzymes [172]. HPP treatment (300 MPa, 20 min, 20 °C) reduced (34.78%) the sheer force of goose breast [173]. An HPP of almost 175 MPa decreased the sheer force of hot-boned beef and improved the eating quality. Thus, the moderate pressure treatment of pre-rigour meat seems to have potential since the meat was tender and looked normal [31]. According to Ma and Ledward [174], the tenderness of pre-rigour meat was significantly improved at about 100–150 MPa.

3.2.2. Food Yield

Limited agro-processing technologies have been a major concern, i.e., that many countries, especially developing ones, lack a nutritious food supply. HPP can tackle this issue. In earlier studies, it was observed that HPP had been used to increase oil yields. Jung and Mahfuz [76] reported that HPP treatment at 200 and 500 MPa enhanced the yield (3.20% and 1.30%) of soybean oil in the presence of aqueous enzymatic extraction (AEE) (protease enzyme). Moreover, when HPP was applied before AEE, a higher oil yield was obtained with ground kernels than with whole kernels at a similar pressure and time [44]. Table 6 illustrates the impact of HPP on food yield.

Table 6. HPP impact on food yield.

Components	Sources	Treatment Conditions	Yield	References
Polyphenols and anthocyanins	Blueberry pomace	500 MPa	A marked increase in the yield of polyphenols and anthocyanins was observed, about 70% and 40%, using HPP compared with the conventional heating method (53% and 32%)	[175]
Tomatoes		Below 100 MPa	A marked increase in the yield of tomatoes occurred, i.e., > 60%.	[176]
Astaxanthin	Shrimp Carapace	210 MPa	Increased the yield from 29.44% to 59.97% by HPP.	[177]
Cheese	Milk	250–600 MPa	A 15% increase in the yield of cheese was obtained	[178]

M. oleifera oil	*M. oleifera* (MO) kernels	50–250 MPa	Free oil (73% *w*/*w*) was recovered from ground-sieved kernels by using HPP compared with AEE alone.	[44]

In research, polyphenols and anthocyanins are extracted from blueberry pomace. The combined US, microwave, and HPP effect was compared with the conventional extraction method [175]. The recovery of polyphenols and anthocyanin increased by about 70% and 40% under HPP, while in the case of conventional treatment, the values were about 53% and 32% [179]. Other research was performed under HPP conditions of 470 MPa, 30 min, with a 55% ethanol solution to extract phenolic compounds from pomegranate (*Punica granatum*); again, the results showed a marked increase in the yields [73].

HPP treatment enhanced the extraction yields of carotenes from plant materials [180]. HPP at 200–600 MPa for 5 min increased the total carotenoid content [181]. Furthermore, HPP as a pretreatment [182] is highly feasible to enhance the recovery of valuable compounds by being implemented with the solvent [183].

3.3. Environmental Sustainability

Food product quality and safety is the main and most important factor for society and manufacturers and distributors [180]. Commercial food production systems have limitations, such as food losses and quality losses due to a high environmental impact [184]. HPP has less impact on the environment as it utilizes less energy and water and has lower CO2 emissions than conventional thermal processes [185]. Therefore, HPP treatment is considered environmentally friendly compared to conventional processing. HPP contributes to environmental sustainability by providing nutritious, safe, and healthy food with an acceptable shelf life in developed countries [186]. HPP has been proven more effective than MAP (modified atmosphere packaging) from an environmental and an economic perspective [187]. However, due to recent food loss and food waste, environmental sustainability may be threatened [187]. A study of thermal pasteurization of orange juice compared with HPP concluded that it is more environmentally friendly than thermal pasteurization [188].

3.3.1. Reduction of Food Waste

The FAO defined food waste as: "The decrease in quantity or quality of food. Thus, food waste is part of food loss and refers to discarding or alternative (non-food) use of food that is safe and nutritious for human consumption along the entire food supply chain, from primary production to the end household consumer-level" [189].

Recently, food waste elimination has gained more attention worldwide [190]. European countries have waste reduction plans to lessen their food waste by almost 30% and 50% by 2025 and 2030 (European Commission, 2018). Food loss and food waste affect food security in two ways. Economically, food loss and food waste reduction allow easy access to food by decreasing food prices. Some studies showed that higher food waste increases food prices [191]. Economic losses from food loss and food waste have no significant impact on the consumer lifestyle in developed countries but are a threat to human livelihood [191]. Although decreasing food waste and food loss contributes to improving food security, it has not been proven to have a clear role in dietary shifts and yield increases [192].

From food waste, different types of compounds such as phenolics and antioxidants are extracted; for example, fruits and vegetables usually contain sufficient bioactive compounds, which are mostly present in peels, seeds, and kernels [193]. It is necessary to rupture the cell wall to obtain natural extracts from the target product [194]. As an effective non-thermal technique, HPP is used for improving the extraction of natural extracts from food waste [195]. Many researchers have discussed the possibility of using HPP to lessen food waste in the food sector. Table 7 shows the valuable compounds extracted from food waste by HPP.

Table 7. Extraction of different valuable compounds from food waste.

Food Waste	Treatment Conditions	Recovered Compounds	References
Orange peel	300 and 500 MPa	Polyphenols	[71]
Tomato pulp	450 MPa	Lycopene, Flavonoids	[196]
Cape gooseberry pulp	300–500 MPa	Bioactive compounds	[197]
Grape pomace	200 MPa	Phenolic compounds	[198]
Pumpkin puree	600 MPa, 70 °C	Bioactive compounds	[199]

Pumpkin contains carotenoids that can be lost during harsh thermal treatments [200]. HPP can reduce carotenoid losses and natural color losses in pumpkins [199]. In addition, HPP tends to preserve carotenoid contents in vegetables such as pumpkin and other foods [201]. Pumpkin contains different valuable compounds that are extracted, e.g., polysaccharides, pectin proteins, fixed oils, and sterols [202]. HPP-assisted extraction more successfully extracted polyphenols from orange and lemon peels [71]. HPP operated at 200 MPa for 5–10 min to extract phenolic compounds from grape pomace improved the extraction rate up to 16 times compared with enzyme-assisted extraction [198].

Food pollutants indicate the presence of chemical or biological contaminants in natural food. The chemicals commonly related to food pollution are metals, chlorodane, pesticides, and agrochemicals [203]. The pollution load can be reduced by using electricity produced from a clean, renewable energy source. In addition, HPP reduces the usage of cooling systems, which saves 50% electricity consumption [204] and therefore also reduces pollutant emissions.

3.3.2. Effects on Food Packaging

To achieve the best pressure transfer within the food product, food prepared for HPP processing has no gas inclusions, no headspace in the package, and high moisture content. In addition, the type of material used to pack food products must also be appropriate. HPP technology is used in different packaging methods, e.g., whether the product is processed in a container or packaged after processing. The physical and mechanical properties of the packaging material affect the HPP capacity. Packaging materials should have a good pressure tolerance and sealing ability to prevent quality losses after the pressure is applied. The packaging materials must be flexible enough to transmit the pressure without structural damage. Due to pressurization, the food is compressed, and the package must allow this reversible deformation. HPP treatment does not apply to rigid materials such as metal and glass, as they will not withstand the treatment. The space should be less due to efficient utilization of packaging material, and it takes less time to reach the target pressure.

Different packaging materials such as soft polymeric bags, cans, trays, and bottles are commonly used for HPP food products. Vacuum packaging is mostly used for HPP products. HPP may lead to uneven processing. Packaging can reduce unnecessary physical pressure exerted on the external package by gases within the package [205]. Changes occur in the packaging properties of pressure-assisted thermally processed packaging materials used for extended storage time, but how these changes in packages affect product quality are not well understood [206].

In one study, the impact of HPP (680 MPa at 105 °C for 3 min and 680 MPa at 100 °C for 5 min) on polyethylene terephthalate (PET), ethylene-vinyl alcohol copolymer (EVOH), and Nylon6 was studied. There were no changes shown in the melting temperature and the enthalpy of fusion of the EVOH layer [207]. However, Ayvaz et al. [206] applied HPP (600 MPa, 110 °C, 10 min) to baby carrots in three different pouches (nylon, EVOH, ethylene-vinyl acetate (EVA)) and stored the pouches in the dark at suitable conditions (25 and 37 °C for four weeks). High-barrier packaging material, i.e., nnlon/EVOH/EVA, showed less impact.

Dhawan et al. [208] stated that pressure-assisted thermal sterilization (PATS) affected the polymer morphological properties and free volume distributions, which caused a reduction in the gas-barrier properties of polymer packaging materials and maintained the original properties of PATS-processed foods. Therefore, they investigated the effect of HPP at 680 MPa for 5 min at 100 °C on two multilayer EVOH films. HPP enhanced the oxygen and water vapor transmission rates in the two films.

Fleckenstein [209] experimented on several common single layer films (PE-HD, PE-LD, PP-BO, PA6-BO, and PET-BO) and multilayer (PS/PE, PPBO/ PE peel, and PET-BO/PE) films at 600 MPa at 80 °C/90 °C. The impact of HPP on the surface roughness of biaxial-oriented polymer films as single-layer films was studied. There were no changes shown in these films after treatment. HPP hardly affected the surface energy of any stretched, non-stretched, single, or laminated films.

Arfat et al. [210] determined the impact of HPP on polylactic acid (PLA) and polyethylene glycol (PEG) at 300 MPa at 23 °C for 10 min. HPP significantly increased the percentage crystallinity. HPP did not result in any marked alterations to the mechanical properties of the structure. In one study in 2013, the impact of HPP on the thermal and mechanical properties of low-density polyethene (LDPE) films was examined at 200–800 MPa for 5–10 min at 25 and 75 °C [211]. The storage modulus increased with increasing pressure intensity, and the tensile strength increased, but elongation decreased with increasing pressure treatment.

3.4. Economic Sustainability

Economic sustainability includes the efficient utilization of energy and water, with high profits through highly competitive food processing. This will be further explained in terms of HPP treatment.

3.4.1. Yield efficiency

Product yield is of substantial economic importance to food manufacturers, and HPP improves the yield of products, with effects depending on product type and treatment intensity [212]. HPP was successfully used in the treatment of oysters. HPP denatures the adductor muscle, which enables easy opening of the oyster shell without causing knife damage to the product, so it reduces labor costs and risks associated with hand-shucking [213]. Different food production systems involve the extraction of valuable components [214]. Generally, there are two essential parameters for the extraction of metabolites from cells: the solvent's diffusion into the cell and the mass transfer of metabolites into the bulk of the extraction medium [215]. Table 8 demonstrates that HPP was helpful to enhance production and profit margins. Nincevic et al. [216] observed that HPP enhanced pectin and polyphenol recovery from tomato peel waste by about 15% compared with conventional techniques.

Table 8. Extraction of valuable compounds using HPP.

Components	Sources	Treatment Conditions	Production	References
Pectin and polyphenols	Tomato peel waste	30 and 45 min	Enhanced pectin recovery by about 15 % compared with conventional extraction	[216]
Phenolic compounds	Watercress	3.1 min, 600 MPa	64.68 ± 2.97 mg/g yield recovered	[217]
Phosvitin	Egg yolk	400 and 600 MPa, 5 and 10 min	Phosvitin recovery was maximum at 600 MPa	[218]
Chitosan	Squid pen waste	500 MPa, 10 min	Maximum yield of 81.9%	[219]
Xyloglucan	Tamarind seed	250–500 MPa	Yields were about 51.6–53.0% higher than the conventional yield (46.4%)	[35]
Caffeine	Green tea leaves	500 MPa, 1 min	Maximum yields: 4.0 ± 0.22%	[220]
Lycopene	Tomato waste	700 MPa, 30 min	Maximum yield: 89.4 mg/kg	[221]
5-methyltetrahydro-folate	Egg yolk	400 MPa, 5 min	Maximum recovery: 93%	[222]

Phosvitin was successfully extracted from egg yolk at 400 and 600 MPa for 5 and 10 min by HPP [218]. According to Limsangouan et al. [35], the xyloglucan extraction rate was between 51.6% and 53% from tamarind seed using HPP at 250–500 MPa. Strati et al. [221] extracted lycopene from tomato waste using HPP; at 700 MPa for 30 min, the maximum increase in production, about 89.4 mg/g, was observed.

3.4.2. Water Efficiency

Limited water reserves force the government and water authorities to improve water utilization efficiency. The water consumption of every food industry varies. Some food industries, including meat, dairy, and fruit and vegetable processors utilize more water. Bakeries and grain producers, primarily involved in dry processes, are small water users [223]. There are always some benefits of higher water efficiency. For example, the Australian Government surveyed manufacturing groups and reported large savings in total water usage of up to 25, 30, and 60% using basic initiatives such as behavioral changes, water recycling (without conditioning treatment), and water use monitoring, respectively. HPP is used in food industries for energy saving and water saving purposes. It enhances reliability, decreases emissions, results in higher product quality, improves productivity [74], and has less influence on the environment.

3.4.3. Energy Efficiency

For the last 30 years, energy saving has been focused on automating production processes and increasing demand for food safety. The higher levels of hygiene consecutively established as goals subsequently lead to more significant consumption of cold and hot water and an increased number of cleaning cycles in production [204].

Non-thermal technologies utilize less energy than conventional technologies [224]. During HPP, momentary pressure of about 300–700 MPa is transmitted throughout the food products, reducing the processing time and, consequently, energy consumption [75]. Bull et al. [225] reported that HPP (600 MPa, 20 °C, 60 s) reduced microbes in 12 weeks and enhanced the shelf life compared to pasteurization (65 °C, 1 min; 85 °C, 25 s). Another study concluded that HPP (400 and 600 MPa for 5 min at 20°C) was a better alternative for apple processing than thermal pasteurization (75°C, 10 min) [226].

HPP requires less energy than chilling and freezing. The energy phase is changed during the HPP process; the heat of vaporization of water is nearly 30% lower than that at atmospheric pressure [227]. Due to water expansion during freezing, pressure increases can lead to lower freezing points [228]. Research indicated that HPP consumed less energy per kg of food than conventional thermal processes. During HPP, heat is conveyed to the foods through convection, conduction, or radiation, causing slow heat transfer rates and increased processing times. In HPP, there is no need for energy to generate heat, and isotactic pressure is applied by utilizing a specific amount of energy throughout the product. Therefore, it is considered that HPP reduces the total energy consumption in the food industry.

4. Limitations of HPP Processing

HPP is a feasible non-thermal technique that preserves food quality, preserves food safety, and increases the shelf life nutritional value but has some limitations in its introduction to the food sector.

The main disadvantage is that it is a costly process due to the high amount of power consumed [229]. Sampedro et al. [230] estimated that HPP was seven times more costly than conventional thermal processing. HPP has been utilizing for more than 100 years in the food sector, but it has limited use due to the high cost and requirement of skilled expertise [231].

In addition, HPP has limitations in killing spores; the combination of heat and HPP (PATS) would solve this problem [232]. Therefore, food with a higher acidic content is preferred for HPP compared with low acid food as it is less stable [233].

Moreover, in a modified HPP treatment method, the product is subjected to compression–decompression cycles with a fixed pressure holding time, but rapid compression and decompression increase the number of cycles in the vessel and subject the vessel material to significant stress and the risk of premature failure [60].

5. Conclusions

Consumers' demand for fresh and nutritional food has resulted in an increase in non-thermal processing techniques, which can retain authenticity and, at the same time, can ensure the safety of food. The combination of mild heat treatment with some of these non-thermal methods also delivered promising results. HPP used alone or in combination with other treatments stops microbial growth and improves macromolecules, increasing the chemical reactions and shelf life of food products. HPP responds to the demands of consumers for higher sensory and quality attributes, such as taste, extended storage, highly nutritious, healthy, and eco-friendly processing. HPP produces less waste than thermal processing. It also enhances energy efficiency and water efficiency in food products and causes no toxic gas emissions. HPP is a beneficial and sustainable technique for food production. However, despite the ability of HPP to reduce foodborne pathogens and enhance nutritional qualities and shelf life, the high fixed costs limit its use in food processing industries. Further research is required in terms of cost optimization and scalability of HPP to fulfill the needs of both the industry and the consumer.

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