Contents list available http://www.kinnaird.edu.pk/

Journal of Natural and Applied Sciences Pakistan

Journal homepage: http://jnasp.kinnaird.edu.pk/

THE IMPACT OF HIGH-PRESSURE PROCESSING ON BIOACTIVE COMPOUNDS IN PLANT-BASED FUNCTIONAL FOODS

Shan muzamail[1]* , Aiman Asif[2], Muhammad Ali Nawaz[3], Muhammad Meelad Sultan[4], Saman Fatima[5], Aneeza Kokab[6], Sidra Rashid[7], Muhammad Mazahir[8]

[1*]Department of Nutrition, China medical university, Taichung, Taiwan

[2] Riphah international university Faisalabad

[3] Institute of Food and Nutrition Sciences (IFNS) PMAS Arid Agriculture University Rawalpindi

[4] National Institue of Food Science and Technology, University of Agriculture, Faisalabad

[5] Institute of Food Science & Technology University of Agriculture Faisalabad

[6]Department of chemistry, University of Okara

[7]PHRC, Ayub Agriculture Research Centre, Faisalabad

[8]Food Science Research Institute, NARC Islamabad

Article Info

*Corresponding Author

Email: emanrajpoot255@gmail.com

Keywords

Bioactive Compounds, High-Pressure Processing (HPP), Nutritional Quality, Plant-Based Foods, Sensory Attributes

Abstract

High-pressure processing (HPP) is a non-thermal process that subjects the food to high hydrostatic pressure for pathogens' destruction and shelf-life enhancement without compromising plant products' nutritional and sensory characteristics. The present paper reviews the factors that determine the bioactive compound stability/loss during HPP and the effects of this technology on nutritional value, shelf life, and consumer liking. HPP's effects on bioactive compounds include mechanical damage to the cellular structures and changes in intermolecular forces. These effects also increase the release and steadiness of such bioactive substances as polyphenols and carotenoids. Using the review context, this assessment explores the influence of processing parameters such as pressure, time, and temperature on the stability of the bioactive compounds. Interaction between HPP and other preservation processes which include mild heat or refrigeration storage can also enhance the quality of the products while at the same time extending their shelf life. It also includes their expansion to the commercial aspect and shows that HPP has been effective in use on food items including cold-pressed juices and plant-based soups. The regulatory part proves that HPP saves the basic parameters of food and contributes both to the effectiveness and safety of the process emphasizing the preservation of natural tastes and smells, consumers' acceptance is usually rather positive. Thus, future investigations should focus to the unknown effects of HPP on various bioactive compounds, their shelf-stability upon further storage, and the most effective processing parameters. Thus, promising trends that are connected with developments in the field of HPP and its additional application with the help of other innovative technologies in combination with contemporary packaging materials speak about the possibilities of further improvement of the functional profile and consumer attraction of plant-based functional food products. This review focuses on HPP effects on PB Foods and proposes possible research avenues to better enhance HPP in the food industry.

1. Introduction

Plant-based functional foods are a category of foods derived from plant sources that offer additional health benefits beyond basic nutrition. Unlike conventional foods that primarily provide essential macronutrients such as carbohydrates, proteins, and fats, functional foods are enriched with bioactive compounds—such as polyphenols, flavonoids, carotenoids, and dietary fiber—that contribute to specific physiological benefits. These properties include antioxidant activity, anti-inflammatory effects, regulation of blood pressure and cholesterol levels, modulation of the gut microbiota, and support for immune function. As a result, plant-based functional foods play a role in reducing the risk of chronic diseases such as cardiovascular disorders, diabetes, and certain cancers, while also contributing to improved overall health and quality of life (Alcorta *et al*., 2021). Such foods are usually enriched by various bioactive compounds including vitamins, minerals, phytochemicals, fibers and antioxidants responsible for functional characteristics of the foods. For instance, plant-based functional foods include fruits, vegetables, whole grains, nuts, seeds, and legumes—rich sources of vitamins, minerals, and phytochemicals essential for human health (Albuquerque *et al*., 2020). These natural foods become functional when they either inherently contain or are fortified with health-promoting bioactive compounds such as dietary fiber, antioxidants, phytosterols, and polyphenols. These components provide targeted physiological benefits, including improved digestion, enhanced immune response, reduced oxidative stress, cholesterol reduction, and better glycemic control. Over the past decades, the demand for such functional plant-based foods has increased significantly, driven by a growing awareness of their role in preventing chronic diseases like cardiovascular disease, diabetes, obesity, and certain cancers. Additionally, shifting consumer preferences toward natural, minimally processed foods free from synthetic additives and preservatives have further fueled the trend (Abe *et al*., 2023). In response, the food industry has expanded its offerings to include plant-based functional products such as fortified beverages, health bars, and dietary supplements that support specific health outcomes. Functional plant foods have a direct impact on the human body's health and are related to a decrease in inflammation, a healthy gut, better immunity and an overall reduction in chronic conditions like heart disease, diabetes, and some forms of cancer. These are believed to be attributed to the existence of bioactive compounds that elicit a protective impact on the body (Ashaolu *et al*., 2020). Growing global awareness of health and wellness, the demand for functional plant-based foods is steadily increasing, as consumers seek options that may help reduce the risk of chronic diseases. However, preserving the stability and activity of bioactive compounds during food processing remains a significant challenge for the food industry. This concern has led to the development and adoption of advanced food processing technologies designed to minimize nutrient degradation while ensuring food safety and shelf-life extension. Among these, high-pressure processing (HPP) has shown particular promise due to its non-thermal nature. In addition to HPP, other emerging technologies such as pulsed electric fields (PEF), ultrasound-assisted processing, cold plasma, and ultraviolet (UV) irradiation are also being explored for their ability to preserve thermosensitive phytochemicals and maintain the functional quality of plant-based foods (Kurek *et al*., 2022)Bioactive compounds are naturally occurring, non-nutritive constituents in foods—particularly in plant-based sources—that offer health benefits beyond basic nutrition. These include various classes of phytochemicals such as polyphenols, flavonoids, carotenoids, and certain vitamins, which are known to exhibit antioxidant, anti-inflammatory, and disease-preventive properties (Guan *et al*., 2021). Their preservation in food products is of great importance, especially in the development of functional foods aimed at promoting health and preventing chronic diseases. They are accountable for the processes that attribute these foods with 'health boost related' properties, necessary for the reduction of risks associated with ailments such as cardiovascular diseases, cancer, diabetes, and neurodegenerative disorders (Saini *et al*., 2020). The functions of antioxidants, anti-inflammatory, anti-carcinogenic and immune-modulatory activities of bioactive compounds have been defined and therefore are the core of all functional foods. For instance, polyphenols as those found in fruits, vegetables, whole-grain have been described to have antioxidant activity, they can mop free radicals and thus reduce oxidant stress in the body (Kamiloglu *et al*., 2022). Flavonoids which are presented in many plant-based foods are also classified as bioactive compounds due to their positive connection with the cardiovascular system and anticancer activity linked with the modulation of signaling of inflammation, and cell proliferation (Samtiya *et al*., 2021). Amongst the bioactive compounds; antioxidant vitamins such as vitamin C and E are utilized in skin health as well as the immune system and cellular recuperation mechanisms. Carotenoids, natural's pigments responsible for the colored appearance of fruits and vegetables such as carrots and tomatoes are associated with the eye and with macular degeneration decline (Pourzand *et al*., 2022). Phytochemicals of functional foods possess an astonishing capability of raising the living standards and anticipated life expectancy of the people. When these compounds are taken in as functional foods through the pathways of the defined diets, consumer may be able to lower their odds of contracting a chronic disease and hence boost up the general health status (Mittal *et al*., 2024). High-pressure processing (HPP) is one of the emerging non-thermal food preservation technologies, developed as an alternative to traditional thermal methods such as pasteurization and sterilization. Conventional heat-based processing often leads to the degradation of heat-sensitive (thermolabile) compounds, including many essential nutrients and bioactive components. In contrast, HPP operates without applying high temperatures, making it particularly advantageous for preserving thermosensitive substances in food products.Unlike thermal methods, HPP inactivates microorganisms and enzymes by subjecting food to extremely high pressures—typically ranging from 100 to 600 MPa—uniformly and instantaneously throughout the product, without altering its nutritional value or sensory properties (Rostamabadi *et al*., 2023). This method is based on Le Chatelier's principle, which favors reactions that reduce volume under pressure. When applied to food, this high pressure disrupts microbial cell membranes, induces protein coagulation, and damages enzyme structures, thereby extending shelf life while preserving the food's original quality (Amsasekar, 2022; D'Incecco *et al*., 2021).One of the most significant benefits of HPP is its ability to retain bioactive compounds—such as phenolics, vitamins, and flavonoids—that are typically destroyed by heat. These compounds are vital for the functional and health-promoting properties of plant-based foods. As a non-thermal technique, HPP prevents their degradation, thus preserving the functional integrity and nutritional profile of the final product (Sruthi *et al*., 2022). This makes HPP especially valuable in the processing of plant-based functional foods, where maintaining bioactive stability is essential.In addition to its advantages in preserving sensitive compounds, HPP is versatile in application. It is used for a wide variety of food products including fruit juices, smoothies, sauces, and ready-to-eat meals (Ding *et al*., 2023). Furthermore, it allows for in-package processing, reducing the risk of post-processing contamination and enhancing food safety (Kamboj *et al*., 2020). This review systematically explores the impact of High-Pressure Processing (HPP) on bioactive compounds in plant-based functional foods. As consumer demand grows for minimally processed foods with retained nutritional and functional qualities, HPP has gained attention as a non-thermal preservation method that enhances shelf life, ensures microbial safety, and potentially preserves sensitive bioactive compounds (Galanakis, 2021; Allai *et al*., 2023). The review focuses on the effects of HPP on key bioactives—phenolics, flavonoids, carotenoids, and vitamins—highlighting changes in their stability, bioavailability, and functionality across various plant food matrices (Banwo *et al*., 2021). It also compares HPP with conventional processing methods, evaluates influencing factors such as pressure, temperature, time, and food composition, and examines its synergy with other preservation techniques (Khaliq *et al*., 2021). Additionally, it assesses the nutritional, sensory, and consumer acceptance aspects of HPP-treated foods (Munekata *et al*., 2020), and identifies knowledge gaps for future research aimed at industrial-scale application of HPP in developing innovative, nutrient-rich plant-based products.

1.1 Bioactive Compounds in Plant-Based Functional Foods

Phytochemicals present in plant foods are thus receiving attention because of the associated health promoting effects. Such compounds present in plants play an important role in prosperity of human health by preventing diseases and contributing to total wellness (Banwo *et al*., 2021). This section will discuss what bioactive compound is, the types of bioactive compound, their source, and the health implication of bioactive compound in plant-based product; in addition, this section will discuss the different factors that influences the stability of the bioactive compound present in foods.

1.2 What are Bioactive Compounds and its Classification

Essential bioactive compounds as opposed to vitamins, and minerals are not component's that are vital for the normal survival of all human beings but play a role in preventing diseases (Mondal *et al*., 2021). These compounds can affect metabolism and provide beneficial actions; thus, they are an essential part of functional foods. The primary types of bioactive compounds in plant-based foods include:

Table 1. Major Classes of Bioactive Compounds in Plant-Based Functional Foods and Their Health Benefits

Bioactive Compound	**Examples**	**Health Benefits**	**Reference**
Phenolic Compounds	Flavonoids, phenolic acids, tannins	Antioxidant, anti-inflammatory, anticancer	Mutha *et al*., 2021
Carotenoids	Beta-carotene, lycopene, lutein	Antioxidant, vision support, reduced cancer risk	Starska, 2022
Glucosinolates	Found in broccoli, kale, Brussels sprouts	Cancer prevention, detoxification enzyme activation, apoptosis induction	Mitra *et al*., 2022
Vitamins	Vitamin C, Vitamin E	Antioxidant activity, immune system support	Szewczyk *et al*., 2021
Phytosterols	Plant sterols and stanols (e.g., β-sitosterol)	Cholesterol-lowering, cardiovascular health improvement	Rodríguez *et al*., 2020

1.3 Sources of Bioactive Compounds in Plant-Based Foods

Table 2. Key plant-based sources of bioactive compounds commonly found in functional foods. These sources are rich in phenolics, flavonoids, carotenoids, phytosterols, and omega-3 fatty acids, contributing to health-promoting properties (Din *et al*., 2023).

Food Group	**Examples**	**Major Bioactive Compounds**
Fruits	Berries, citrus fruits, apples, grapes	Phenolic compounds, flavonoids
Vegetables	Leafy greens, tomatoes, carrots, broccoli, Brussels sprouts	Carotenoids, glucosinolates, phenolic acids
Legumes	Beans, lentils, chickpeas	Polyphenols, phytosterols
Nuts & Seeds	Almonds, walnuts, flaxseeds, chia seeds	Phenolic compounds, phytosterols, omega-3 fatty acids
Whole Grains	Oats, barley, quinoa	Phenolic acids (e.g., avenanthramides), phytosterols (e.g., β-sitosterol)

1.4 Characteristics which influence Stability of Bioactive Compounds

Bioactive compounds that are mainly stored in plant-based foods are sensitive to a number of factors that exist before and after the foods have been harvested. These factors include:

1.4.1 Processing Methods

Some of the methods such as thermal processing, drying, freezing, and high-pressure processing, especially influence the stability of bioactive compounds. With these compounds some processes may even cause degradation while on the other hand processes such HPP may actually assist in preserving or even improving the stability (Barbosa *et al*., 2022).

1.4.2 Storage Conditions

Light, oxygen and temperature influences negatively affects the quality of the produce and reduces the shelf life and alters bioactive compounds such as vitamins and carotenoids (Darré *et al*., 2022).

1.4.3 PH and Water Activity

Its stability depends on the food matrix, including factors such as the pH and AW values of the food. For instance, there are the phenolic compounds which may be degraded when exposed to very low or very high pH levels (Cao *et al*., 2021).

1.4.4 Matrix Interactions

The bioactive compounds when come across other food matrix components like proteins, fats, and fibers it influences their stability and biological availability. These interactions may either prolong the life of the compounds, by preventing their degradation, or enhance the rate of their breakdown (Shahidi *et al*., 2022).

1.4.5 Agricultural Practices

It was also establish that factors such as soil characteristics and use of fertilizers together with the method of harvesting Bioactive compounds or phytochemicals within plant-based foods depend on the cultivation practices (Ramady *et al*., 2022).

2. High-Pressure Processing (HPP) Technology

High Pressure Processing (HPP) is one of the non thermal food preservation techniques that involves the application of pressure from 100-600 MPa in order to eliminate food spoilage microorganisms and other enzymes that can cause deterioration of foods. As with other traditional thermal technologies, HPP maintains the sensories and nutritional properties of food avoiding heat making it very effective in wholesome plant based functional foods (Khaliq *et al*., 2021).

2.1 The principles of high pressure processing

High-Pressure Processing (HPP) operates based on Le Chatelier's principle, which states that a system under stress will adjust to counteract the change. In HPP, high isostatic pressure is uniformly applied to inactivate microorganisms without damaging heat-sensitive components such as bioactive compounds (Iqbal *et al*., 2022). The food product is placed in a water-filled pressure vessel, where hydraulic force is applied uniformly regardless of the food's size or shape (Esin *et al*., 2021). Treatment duration typically ranges from a few seconds to several minutes, depending on the food type, ensuring effective microbial inactivation while preserving product quality.

2.2 Mechanism of Action

It is the process of altering the structure of the membrane and the protein in microorganisms and then inactivating them. The high pressure influences the several interactions in proteins and enzymes that are found in the microorganisms which are vital it their growth and survival. HPP does not disrupt covalent bonds as thermal processing does and so it does not compromise the activity of bioactive compounds, vitamins, phenolics, and flavonoids of plant-based foods (Amsasekar *et al*., 2022). Apart from the microbial inactivation, the HPP can induce changes in texture and structure of various food components as in the gelatinization of the starches and the denaturation of the proteins. But such changes are comparatively less than those brought about by heat treatment and hence the Nutritional and functional properties of plant based foods can be retained by using HPP (Nath *et al*., 2023).

2.3 Comparison of the Current Food Processing Techniques

HPP is unique from the conventional technologies of food processing as pasteurization and sterilization that kill the microbes using heat. It is a well-known fact that heat treatment of foods also with an effect of pasteurization reduces the concentration of heat-sensitive bioactive compounds and lowers nutritional and functional values of plant-based foods (Aganovic *et al*., 2021). On the other hand, HPP does not heat such compounds and consequently is a better technique for the processing of functional foods. Other non-thermal processing methods that have the goal of preserving the quality of food and at the same time making it safe include; PEF (pulsed electric fields) and UV (ultraviolet radiation). Still, HPP has a better ability to penetrate food matrices making sure that each part of the product is treated evenly. Also, HPP does not alter the colour, flavour and texture of the food as much as it is observed with UV and PEF due to which HPP is more suitable for retention of sensory characteristics of plant based functional foods (Yildiz *et al*., 2021).

Table: 3. Comparison of food processing techniques

Technique	Temperature	Pressure	Microbial Inactivation	Impact on Nutrients
Traditional Thermal Processing (Pasteurization, Sterilization)	High	Low	High	Low
High-Pressure Processing (HPP)	Low	High	High	High
Pulsed Electric Fields (PEF)	Low	Low	Medium	Medium
Ultraviolet Radiation (UV)	Low	Low	Low	Medium

3. Effect of HPP on bioactive compounds

High Pressure Processing (HPP) is a method of food preservation that has recently attracted interest because the food quality parameters such as nutritional and sensory properties are well preserved as well as the food safety. This section aims at reviewing the effects of HPP on different bioactive compounds in plant based functional foods with emphasis on; phenolic compounds, vitamins, flavonoids, carotenoids and antioxidant activity.

3.1 Effects on Phenolic Compounds

High-pressure processing (HPP) influences phenolic compounds variably, depending on the plant matrix and compound type. Generally, HPP enhances the release of phenolics such as gallic and caffeic acids by disrupting cell walls, thereby increasing their extractability and antioxidant potential (Fernández *et al*., 2020). However, certain phenolics, especially flavonoid glycosides, may degrade under prolonged pressure or combined heat treatment, potentially altering their bioavailability and antioxidant capacity (Navarro *et al*., 2022).

3.2 Effects on Vitamins

The stability of vitamins under HPP varies by vitamin type and processing conditions. Water-soluble vitamins, particularly vitamin C, show high retention under HPP, outperforming thermal treatments in preserving nutritional quality (Mieszczakowska *et al*., 2021). Conversely, fat-soluble vitamins like vitamins A and E are more sensitive, although their degradation is minimized due to the non-thermal nature of HPP.

3.3 Effects on Flavonoids

Flavonoids, known for antioxidant and anti-inflammatory benefits, respond to HPP based on their chemical structure and food matrix. HPP has been shown to increase concentrations of quercetin and rutin in certain juices by releasing bound flavonoids. It may also convert glycosides to aglycones, improving solubility and possibly enhancing antioxidant activity, depending on processing conditions (Dias *et al*., 2021; Ullah *et al*., 2022).

3.4 Effects on Carotenoids

Carotenoids such as lycopene, β-carotene, and lutein can become more bioaccessible following HPP due to cell structure disruption. For example, HPP enhances lycopene absorption in tomato-based products. However, carotenoids are prone to oxidation, necessitating oxygen-free environments during processing to preserve their integrity (Akram *et al*., 2021).

3.5 Effects on Antioxidant Activity

The impact of HPP on antioxidant activity is largely positive and is attributed to increased extraction efficiency and structural preservation of bioactive compounds like phenolics, flavonoids, and carotenoids. However, outcomes depend on the specific compounds and food matrix, as some foods may experience reduced activity if antioxidants degrade during processing (Saini *et al*., 2022).

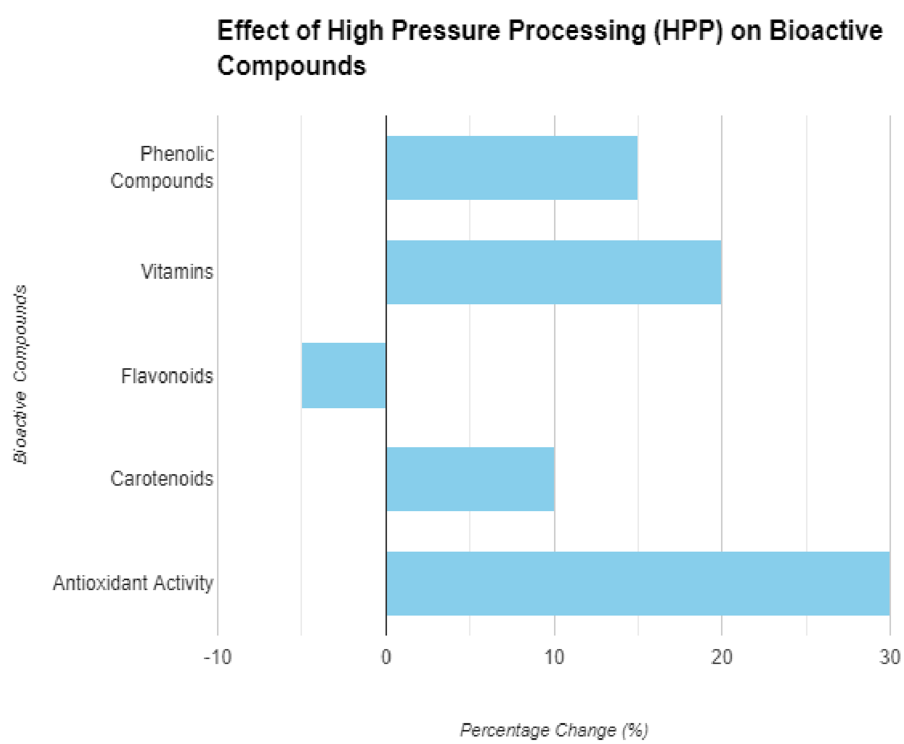

Figure: 1 Effect of HPP on Bioactive

Caption: The graph data indicates that HPP can have a positive impact on some bioactive compounds, while potentially having a negative impact on others.

4. Preservation or Loss Factors of Bioactive Compounds

4.1 Physical and Chemical Changes Induced by HPP

High-Pressure Processing (HPP) is a non-thermal technique that enhances food safety and shelf life while preserving nutritional value. It induces both physical and chemical changes in bioactive compounds. Physically, HPP disrupts cell structures, enhancing the release of phytochemicals such as polyphenols and carotenoids (Huang *et al*., 2020). Chemically, HPP influences molecular interactions, potentially modifying compound stability through protein denaturation and affecting oxidative reactions. These changes can lead to either degradation or stabilization depending on the processing conditions (Aganovic *et al*., 2021).

4.2 Factors Influencing Bioactive Compound Stability during HPP

Key factors affecting the stability of bioactive compounds during HPP include pressure level, processing time, temperature, and food matrix composition. Higher pressures and extended processing times can intensify matrix disruption, influencing compound retention. While HPP operates at low temperatures, even moderate heat can affect stability. The presence of lipids, carbohydrates, and proteins may protect or degrade bioactives through interactions that vary with processing conditions (Amsasekar *et al*., 2022).

4.3 Interaction of HPP with Other Preservation Techniques

HPP can be effectively combined with other preservation methods such as mild heat treatment, refrigeration, drying, or freezing. These hybrid approaches enhance microbial inactivation and improve the retention of sensitive bioactive compounds (Bhilegaonkar *et al*., 2023). For example, combining HPP with mild heat can improve both microbial safety and bioactive stability. Such integrated strategies optimize preservation while minimizing degradation during storage. Understanding these interactions is essential for improving bioactive retention and functional efficacy in plant-based foods (Jacobo *et al*., 2021).

.

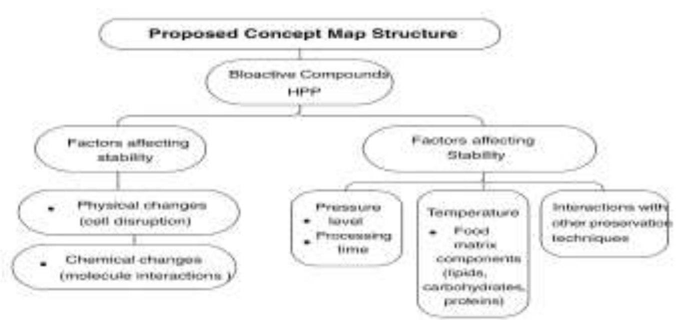

Figure: 2 Proposed concept map structure illustrating the relationship between high-pressure processing (HPP) and the stability of bioactive compounds, highlighting key factors such as physical and chemical changes, influencing parameters (pressure, temperature, time, food matrix), and synergistic effects with other preservation methods

5. Effects of HPP on Nutrient Content and Organoleptic Properties of Plant Foods

This section highlights the effects of HPP with regards to the nutritional quality and sensory properties as well as the consumer acceptance of products that have been subjected to HPP.

Table.2. Summary of the Effects of High-Pressure Processing (HPP) on Nutrient Content, Sensory Properties, and Consumer Acceptance of Plant-Based Foods

Category	Effect	Details
Nutritional Quality Post-HPP	Preservation of Nutrients	HPP preserves heat-sensitive nutrients like Vitamin C and E.
	Improved Nutrient Bioavailability	HPP permeabilizes cell walls, enhancing nutrient availability, especially antioxidants.
Sensory Characteristics Affected by HPP	Flavor Preservation	HPP retains the original taste of plant-based foods.
	Color Enhancement	HPP-treated fruits and vegetables display brilliant colors.
	Texture Retention	Texture is slightly lower than in heat-processed foods but is generally well-preserved.
	Mouthfeel Maintenance	Smoothness and mouthfeel of foods are maintained, important for shelf-life.
Consumer Acceptance	High Consumer Approval	Consumers prefer HPP-treated foods due to preserved nutrients, taste, and texture.
	Non-Thermal Process	HPP meets consumer demand for non-thermal food processing, enhancing nutritional value.
	Willingness to Pay	Consumers are willing to pay more for HPP products, associating them with better health and taste.
	Market Appreciation	Increased consumer knowledge of HPP benefits leads to higher product acceptance.

6. Uses of HPP in the Food Industry

High Pressure Processing (HPP) is now deemed as a revolutionary innovation in the food industry; and particularly it has taken a big leap in the field of plant functional foods. HPP involves application of very high hydraulic pressure which eliminates infectious agents and enhances the durability of the food with no negative effects on the nutritional value or taste (Jönsson *et al*., 2024). This method is particularly advantageous for plant- based functional foods containing sensitive bio active compounds to the conventional processing techniques.

6.1 Examples of Marketed Products Treated with High-Pressure Processing (HPP)

High-Pressure Processing (HPP) has emerged as a valuable technology in the commercialization of plant-based functional foods, enabling the preservation of bioactive compounds, flavor, and freshness without the use of heat or chemical preservatives. One of the most widely known applications is in cold-pressed juices, where brands like Suja Juice, Evolution Fresh, and Pressed Juicery utilize HPP to maintain nutritional integrity and extend product shelf life without compromising taste (Amsasekar *et al*., 2022). In addition to beverages, plant-based soups, sauces, and purees—such as those from Tio Gazpacho and Fawen undergo HPP to ensure microbial safety while preserving the fresh-like qualities of raw vegetables. These products highlight how HPP can support clean-label processing, appealing to health-conscious consumers. Furthermore, avocado-based spreads like Wholly Guacamole are treated with HPP to retain their creamy texture and natural color over extended storage periods. Similarly, plant-based dips such as Luvo's hummus and Lantana's lentil dips also benefit from HPP treatment, which helps stabilize the product without synthetic additives. In the category of functional shots and wellness beverages, brands such as Vital Farms and Natalie's Orchid Island Juice Company employ HPP for turmeric-ginger shots and antioxidant-rich fruit blends, enhancing safety while preserving sensitive compounds like curcumin and polyphenols. These examples collectively demonstrate that HPP is not only effective for preserving nutritional and sensory properties in plant-based products but is also commercially scalable and widely accepted in the marketplace.

6.2 Commercial applications of functional plant-based foods

As reported in commercial practices, HPP has been useful in improving the nutritious and safety value of the plant-based functional foods. It is used for retaining the essence of vitamins, antioxidants, polyphenols, and other stuffs that provide the health values of these foods. Cold pressed juices, plant based soups, ready to eat salads are some of the products which uses HPP to maintain nutritional value and shelf life and without using any chemical preservative. Using HPP, manufacturers may deliver the client base minimally processed foods, which will increase their shelf life and contain more nutrients (Ding *et al*., 2023).

7. Future Direction and Research Requirement

HPP technology is relatively new and its progression is quickly becoming dynamic and the trends that define its utilization in functional plant based foods promising. An emerging trend is combined utilization of HPP with other methods of food processing like pulsed electric fields and ultrasonic treatments to enhance the stability of bioactive compounds and ensure the safety and quality of the final product. Equipment design has also improved over the years more efforts has been directed on improving the capability and the size of the equipment which is essential for large scale industries. Furthermore, more attention is turning to the investigation of new pressure and temperature values, and using HPP integrated with new packaging materials to prolong shelf life, and nutrients stability (Pou *et al*., 2021). However, further studies on bioactive compounds in plant-based foods subjected to HPP are still limited: major research gaps. More precise research work is lacking regarding the different pathways through which HPP influences various classes of bioactive compounds; phenolic, flavonoids, vitamins etc. Thus, further studies should be conducted to determine the half-life of the above-compounded products after undergoing the HPP process as well as the pressure level and processing time that would have maximum efficiency of the compounds. There is also some lack of knowledge on how HPP influences the combination of other food processing techniques in terms of retention of bioactive compounds. Conquering these gaps will be vital for enhancing the further adjustment of HPP conditions for enhancing the potentialities of plant functional foods for human health and focus on developing new tendencies in the food industry.

Conclusion

A relatively new method of innovational change that has taken roots in the food industry especially with plant based functional foods is High- Pressure Processing abbreviated as HPP. Thus by HPP a high pressure is used to ax the pathogenic microorganisms that could potentially spoil the food product while still preserving the nutritional and sensory components of the food product. This non-thermal method is known to have little or no effect on bioactive compounds including the vitamins, antioxidants and polyphenols that are usually affected by the normal thermal treatments. These are some of the ways in which appealing to the consumers and the capability of the HPP to maintain integrity of the natural flavors, colour and texture of the plant-based foods serves the consumers in the best way possible. In addition, HPP maintains endorsement of minimally processed products which is an expanding class of products in view of the increased demand for fresh and healthy foods. HPP is predicted to be the source of further innovation as the technology develops with the improvements in equipment and its compatibility with other processing methods. If this applies continuously in the market it will not only enhance food safety and shelf life but will increase the acceptance and success of functional foods.

References

Abe-Inge, V., Aidoo, R., de la Fuente, M. M., & Kwofie, E. M. (2023). Plant-based dietary shift: Current trends, barriers, and carriers. Trends in Food Science & Technology, 104292.

Aganovic, K., Hertel, C., Vogel, R. F., Johne, R., Schlüter, O., Schwarzenbolz, U. ... & Heinz, V. (2021). Aspects of high hydrostatic pressure food processing: Perspectives on technology and food safety. Comprehensive Reviews in Food Science and Food Safety, 20(4), 3225-3266.

Akram, S., Mushtaq, M., & Waheed, A. (2021). β-Carotene: beyond provitamin A. In a centum of valuable plant bioactives (pp. 1-31). Academic Press.

Albuquerque, T. G., Nunes, M. A., Bessada, S. M., Costa, H. S., & Oliveira, M. B. P. (2020). Biologically active and health promoting food components of nuts, oilseeds, fruits, vegetables, cereals, and legumes. In Chemical analysis of food (pp. 609-656). Academic Press.

Alcorta, A., Porta, A., Tárrega, A., Alvarez, M. D., & Vaquero, M. P. (2021). Foods for plant-based diets: Challenges and innovations. Foods, 10(2), 293.

Allai, F. M., Azad, Z. A. A., Mir, N. A., & Gul, K. (2023). Recent advances in non-thermal processing technologies for enhancing shelf life and improving food safety. Applied Food Research, 3(1), 100258.

Amsasekar, A., Mor, R. S., Kishore, A., Singh, A., & Sid, S. (2022). Impact of high pressure processing on microbiological, nutritional and sensory properties of food: A review. Nutrition & Food Science, 52(6), 996-1017.

Ashaolu, T. J. (2020). Immune boosting functional foods and their mechanisms: A critical evaluation of probiotics and prebiotics.

Biomedicine & Pharmacotherapy, 130, 110625.

Banwo, K., Olojede, A. O., Adesulu-Dahunsi, A. T., Verma, D. K., Thakur, M., Tripathy, S., & Utama, G. L. (2021). Functional importance of bioactive compounds of foods with Potential Health Benefits: A review on recent trends. Food Bioscience, 43, 101320.

Barbosa-Cánovas, G. V., Donsì, F., Yildiz, S., Candoğan, K., Pokhrel, P. R., & Guadarrama-Lezama, A. Y. (2022). Nonthermal processing technologies for stabilization and enhancement of bioactive compounds in foods. Food Engineering Reviews, 1-37.

Bhilegaonkar, K. N., & Kolhe, R. P. (2023). Transfer of viruses implicated in human disease through food. In Present Knowledge in Food Safety (pp. 786-811). Academic Press.

Caiati, C., Stanca, A., & Lepera, M. E. (2023). Free radicals and obesity-related chronic inflammation contrasted by antioxidants: A new perspective in coronary artery disease. Metabolites, 13(6), 712.

Cao, H., Saroglu, O., Karadag, A., Diaconeasa, Z., Zoccatelli, G., Conte-Junior, C. A. ... & Xiao, J. (2021). Available technologies on improving the stability of polyphenols in food processing. Food Frontiers, 2(2), 109-139.

Darré, M., Vicente, A. R., Cisneros-Zevallos, L., & Artés-Hernández, F. (2022). Postharvest ultraviolet radiation in fruit and vegetables: Applications and factors modulating its efficacy on bioactive compounds and microbial growth. Foods, 11(5), 653.

Denoya, G. I., Xia, Q., & Xie, F. (2020). HPP of fruit and vegetable products: Impact on quality and applications. In Present and future of high pressure processing (pp. 273-293). Elsevier.

Dias, M. C., Pinto, D. C., & Silva, A. M. (2021). Plant flavonoids: Chemical characteristics and biological activity. Molecules, 26(17), 5377.

Din, S. R. U., Saeed, S., Khan, S. U., Kiani, F. A., Alsuhaibani, A. M., & Zhong, M. (2023). Bioactive compounds (BACs): A novel approach to treat and prevent cardiovascular diseases. Current Problems in Cardiology, 48(7), 101664.

D'Incecco, P., Limbo, S., Hogenboom, J. A., & Pellegrino, L. (2021). Novel technologies for extending the shelf life of drinking milk: Concepts, research trends and current applications. Lwt, 148, 111746.

Ding, Y., Ban, Q., Wu, Y., Sun, Y., Zhou, Z., Wang, Q. ... & Xiao, H. (2023). Effect of high hydrostatic pressure on the edible quality, health and safety attributes of plant-based foods represented by cereals and legumes: A review. Critical Reviews in Food Science and Nutrition, 63(20), 4636-4654.

El-Ramady, H., Hajdú, P., Törős, G., Badgar, K., Llanaj, X., Kiss, A. ... & Prokisch, J. (2022). Plant nutrition for human health: a pictorial review on plant bioactive compounds for sustainable agriculture. Sustainability, 14(14), 8329.

Esin, A. (2021). Fluid mechanics in food process engineering. In Engineering Principles of Unit Operations in Food Processing (pp. 167-247). Woodhead Publishing.

Fernández-Jalao, I., Balderas, C., Sánchez-Moreno, C., & De Ancos, B. (2020). Impact of an in vitro dynamic gastrointestinal digestion on phenolic compounds and antioxidant capacity of apple treated by high-pressure processing. Innovative Food Science & Emerging Technologies, 66, 102486.

Galanakis, C. M. (2021). Functionality of food components and emerging technologies. Foods, 10(1), 128.

Gandhi, G. R., Jothi, G., Mohana, T., Vasconcelos, A. B. S., Montalvão, M. M., Hariharan, G. ... & Gan, R. Y. (2021). Anti-inflammatory natural products as potential therapeutic agents of rheumatoid arthritis: A systematic review. Phytomedicine, 93, 153766.

Guan, R., Van Le, Q., Yang, H., Zhang, D., Gu, H., Yang, Y. ... & Peng, W. (2021). A review of dietary phytochemicals and their relation to oxidative stress and human diseases. Chemosphere, 271, 129499.

Huang, H. W., Hsu, C. P., & Wang, C. Y. (2020). Healthy expectations of high hydrostatic pressure treatment in food processing industry. *Journal of Food and Drug Analysis*, 28(1), 1-13.

Iqbal, A., Murtaza, A., Pinto, C. A., Saraiva, J. A., Liu, X., Zhu, Z. ... & Marszałek, K. (2022). High-pressure processing for food preservation. In Innovative and Emerging Technologies in the Bio-marine Food Sector (pp. 495-518). Academic Press.

Islam, S. U., Ahmed, M. B., Ahsan, H., & Lee, Y. S. (2021). Recent molecular mechanisms and beneficial effects of phytochemicals and plant-based whole foods in reducing LDL-C and preventing cardiovascular disease. Antioxidants, 10(5), 784.

Jacobo-Velázquez, D. A., Santana-Gálvez, J., & Cisneros-Zevallos, L. (2021). Designing next-generation functional food and beverages: Combining nonthermal processing technologies and postharvest abiotic stresses. Food Engineering Reviews, 13, 592-600.

Jönsson, M. (2024). Savouring the sea: Production and consumption of future seaweed foods.

Kamboj, S., Gupta, N., Bandral, J. D., Gandotra, G., & Anjum, N. (2020). Food safety and hygiene: A review. *International journal of chemical studies*, 8(2), 358-368.

Kamiloglu, S., Capanoglu, E., & Jafari, S. M. (2022). An overview of food bioactive compounds and their health-promoting. Retention of bioactives in food processing, 1.

Khalid, W., Maqbool, Z., & Arshad, M. S. (2022). Recent Advances and Innovation in Meat with Reference to Processing Technologies.

Khaliq, A., Chughtai, M. F. J., Mehmood, T., Ahsan, S., Liaqat, A., Nadeem, M. ... & Ali, A. (2021). High-pressure processing; principle, applications, impact, and future prospective. In Sustainable food processing and engineering challenges (pp. 75-108). Academic Press.

Khaliq, A., Chughtai, M. F. J., Mehmood, T., Ahsan, S., Liaqat, A., Nadeem, M. ... & Ali, A. (2021). High-pressure processing; principle, applications, impact, and future prospective. In Sustainable food processing and engineering challenges (pp. 75-108). Academic Press.

Kurek, M., Benaida-Debbache, N., Elez Garofulić, I., Galić, K., Avallone, S., Voilley, A., & Waché, Y. (2022). Antioxidants and bioactive compounds in food: Critical review of issues and prospects. Antioxidants, 11(4), 742.

Mieszczakowska-Frąc, M., Celejewska, K., & Płocharski, W. (2021). Impact of innovative technologies on the content of vitamin C and its bioavailability from processed fruit and vegetable products. Antioxidants, 10(1), 54.

Mitra, S., Emran, T. B., Chandran, D., Zidan, B. R. M., Das, R., Mamada, S. S. ... & Simal-Gandara, J. (2022). Cruciferous vegetables as a treasure of functional foods bioactive compounds: Targeting p53 family in gastrointestinal tract and associated cancers. Frontiers in Nutrition, 9, 951935.

Mittal, R. K., Mishra, R., Sharma, V., & Purohit, P. (2024). Bioactive Exploration in Functional Foods: Unlocking Nature's Treasures. Current Pharmaceutical Biotechnology, 25(11), 1419-1435.

Mondal, S., Soumya, N. P. P., Mini, S., & Sivan, S. K. (2021). Bioactive compounds in functional food and their role as therapeutics. Bioactive Compounds in Health and Disease-Online ISSN: 2574-0334; Print ISSN: 2769-2426, 4(3), 24-39.

Montemurro, M., Pontonio, E., Coda, R., & Rizzello, C. G. (2021). Plant-based alternatives to yogurt: State-of-the-art and perspectives of new biotechnological challenges. Foods, 10(2), 316.

Munekata, P. E., Domínguez, R., Budaraju, S., Roselló-Soto, E., Barba, F. J., Mallikarjunan, K., & Lorenzo, J. M. (2020). Effect of innovative food processing technologies on the physicochemical and nutritional properties and quality of non-dairy plant-based beverages. Foods, 9(3), 288.

Mutha, R. E., Tatiya, A. U., & Surana, S. J. (2021). Flavonoids as natural phenolic compounds and their role in therapeutics: An overview. *Future journal of pharmaceutical sciences*, 7, 1-13.

Nabi, B. G., Mukhtar, K., Arshad, R. N., Radicetti, E., Tedeschi, P., Shahbaz, M. U., ... & Aadil, R. M. (2021). High-pressure processing for sustainable food supply. Sustainability, 13(24), 13908.

Nath, K. G., Pandiselvam, R., & Sunil, C. K. (2023). High-pressure processing: Effect on textural properties of food-A review. *Journal of Food Engineering*, 351, 111521.

Navarro-Baez, J. E., Martínez, L. M., Welti-Chanes, J., Buitimea-Cantúa, G. V., & Escobedo-Avellaneda, Z. (2022). High hydrostatic pressure to increase the biosynthesis and extraction of phenolic compounds in food: A review. Molecules, 27(5), 1502.

Pou, K. J. (2021). Applications of high pressure technology in food processing. *International Journal of Food Studies*, 10(1).

Pourzand, C., Albieri-Borges, A., & Raczek, N. N. (2022). Shedding a new light on skin aging, iron-and redox-homeostasis and emerging natural antioxidants. Antioxidants, 11(3), 471.

Rodríguez, J. F., Dynarowicz-Latka, P., & Conde, J. M. (2020). How unsaturated fatty acids and plant stanols affect sterols plasma level and cellular membranes? Review on model studies involving the Langmuir monolayer technique. Chemistry and Physics of Lipids, 232, 104968.

Rostamabadi, H., Nowacka, M., Colussi, R., Frasson, S. F., Demirkesen, I., Mert, B., & Falsafi, S. R. (2023). Impact of emerging non-thermal processing treatments on major food macromolecules: Starch, protein, and lipid. Trends in Food Science & Technology, 104208.

Saini, R. K., Ranjit, A., Sharma, K., Prasad, P., Shang, X., Gowda, K. G. M., & Keum, Y. S. (2022). Bioactive compounds of citrus fruits: A review of composition and health benefits of carotenoids, flavonoids, limonoids, and terpenes. Antioxidants, 11(2), 239.

Saini, R. K., Rengasamy, K. R., Mahomoodally, F. M., & Keum, Y. S. (2020). Protective effects of lycopene in cancer, cardiovascular, and neurodegenerative diseases: An update on epidemiological and mechanistic perspectives. Pharmacological research, 155, 104730.

Samtiya, M., Aluko, R. E., Dhewa, T., & Moreno-Rojas, J. M. (2021). Potential health benefits of plant food-derived bioactive components: An overview. Foods, 10(4), 839.

Shahidi, F., & Pan, Y. (2022). Influence of food matrix and food processing on the chemical interaction and bioaccessibility of dietary phytochemicals: A review. Critical Reviews in Food Science and Nutrition, 62(23), 6421-6445.

Sruthi, N. U., Josna, K., Pandiselvam, R., Kothakota, A., Gavahian, M., & Khaneghah, A. M. (2022). Impacts of cold plasma treatment on physicochemical, functional, bioactive, textural, and sensory attributes of food: A comprehensive review. Food Chemistry, 368, 130809.

Starska-Kowarska, K. (2022). Dietary carotenoids in head and neck cancer—molecular and clinical implications. Nutrients, 14(3), 531.

Szewczyk, K., Chojnacka, A., & Górnicka, M. (2021). Tocopherols and tocotrienols—bioactive dietary compounds; what is certain, what is doubt? *International journal of molecular sciences*, 22(12), 6222.

Ullah, A., Munir, S., Badshah, S. L., Khan, N., Ghani, L., Poulson, B. G., & Jaremko, M. (2020). Important flavonoids and their role as a therapeutic agent. Molecules, 25(22), 5243.

Yildiz, S., Pokhrel, P. R., Unluturk, S., & Barbosa-Cánovas, G. V. (2021). Changes in quality characteristics of strawberry juice after equivalent high pressure, ultrasound, and pulsed electric fields processes. Food Engineering Reviews, 13, 601-612.