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Peran Pemrosesan Tekanan Tinggi dalam Menjaga Keamanan Mikrobiologis dan Cita Rasa Pangan Segar dan Olahan Minimal: Tinjauan Singkat

[The Role of High Pressure Processing in Maintaining Microbiological Safety and Flavor of Fresh and Minimally Processed Foods: A Mini Review]

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ABSTRACT

The microbiological safety of fresh food products is a crucial challenge in the food industry, mainly due to the high prevalence of pathogenic microorganisms such as Salmonella spp., Escherichia coli, and Listeria monocytogenes. At the same time, there is an increase in consumer demand for fresh products with optimal organoleptic and natural nutritional qualities. High-Pressure Processing (HPP), as a non-thermal processing technology, offers an innovative solution to these problems. This mini review aims to examined the basic principles of HPP, its effectiveness in inactivating microorganisms, and its impact on the sensory attributes of various fresh food products. Various studies show that HPP can significantly reduce the number of microbes while maintaining the organoleptic characteristics of fresh food products. Overall, HPP shows great potential as a future food processing technology that can bridge the need for safety and quality in fresh products.

Keywords: High-Pressure Processing, food products, fresh food

ABSTRAK

Keamanan mikrobiologis produk makanan segar merupakan tantangan krusial dalam industri makanan, terutama karena tingginya prevalensi mikroorganisme patogen seperti Salmonella spp., Escherichia coli, dan Listeria monocytogenes. Di sisi lain, terdapat peningkatan permintaan konsumen terhadap produk segar yang memiliki kualitas organoleptik dan nutrisi alami yang optimal. High Pressure Processing (HPP), sebagai teknologi pengolahan non-termal, menawarkan solusi inovatif untuk masalah-masalah ini. Tinjauan mini ini bertujuan untuk mengkaji prinsip dasar HPP, efektivitasnya dalam menonaktifkan mikroorganisme, dan dampaknya terhadap atribut sensorik berbagai produk makanan segar. Berbagai studi menunjukkan bahwa HPP dapat secara signifikan mengurangi jumlah mikroba sambil mempertahankan karakteristik organoleptik produk makanan segar. Secara keseluruhan, HPP menunjukkan potensi besar sebagai teknologi pengolahan makanan masa depan yang dapat menjembatani kebutuhan akan keamanan dan kualitas dalam produk segar.

Kata kunci: High-Pressure Processing, produk pangan, pangan segar

Introduction

In recent decades, healthy lifestyles have led to increased consumption of fresh food products and minimally processed foods (MPF). Badan Pengawas Obat dan Makanan Republik Indonesia (BPOM

RI, 2017) defines minimally processed foods as products that have undergone only limited post-harvest processing, such as washing, peeling, cutting, freezing, or blanching, without the addition of food additives, except for waxing purposes. Fresh fruit, pure juice, cut fruit, and ready-to-eat vegetables are some examples of products in this category. Although highly nutritious, fresh food products and MPF are very susceptible to microbiological contamination because they generally do not undergo adequate heating processes. Pathogens such as Salmonella spp, Campylobacter spp, Escherichia coli, and hepatitis A virus are often reported as the main causes of foodborne illness originating from the consumption of fresh produce (Mir et al., 2018; World Health Organisation, 2024). Contamination from these pathogens can harm bodily functions because it can cause food poisoning and shorten the shelf life of products.

Heat treatment technology is a popular choice because it is effective in reducing the number of microbes. However, its application has disadvantages in terms of maintaining the sensory properties of products, such as taste, colour, aroma, and texture, and even reducing the nutritional content of products. This has prompted the food industry to start shifting to the use of non-thermal or heat-free technologies. Various non-thermal technologies that have begun to be used in the industry include high-pressure processing, pulsed electric field, irradiation, and others. Many studies showed that the use of this technology has an impact on products that are not only microbiologically safe, but also maintain the nutrients and fresh characteristics of a product (Bhat et al., 2020; Juarez-Enriquez et al., 2015; Saikia et al., 2016).

Among various non-thermal technologies, High Pressure Processing (HPP) has gained attention and is already widely used commercially in the food industry (Patrignani & Lanciotti, 2016). The United States Food and Drug Administration (USFDA) dan the United States Department of Agriculture (USDA) have permitted the use of this technology in food processing systems (Dangal et al., 2023). This technology utilises high hydrostatic pressure (300–600 MPa) to inactivate pathogenic and spoilage microorganisms without the need for high temperatures. It is applied uniformly and directly to the product, which only alters non-covalent bonds (e.g., ionic, hydrogen, and hydrophobic bonds) in the product structure without damaging it (Silva et al., 2012; Toepfl et al., 2006)

Unlike thermal processing, which can reduce colour quality, texture, taste, and nutritional content, HPP can maintain flavour, colour, texture, and nutritional content so that products remain similar to their fresh state (Song et al., 2023). HPP can produce products that maintain the quality of phytochemical compounds and have a longer shelf life because it inactivates microbes and enzymes that cause browning (Zhang et al., 2017). Thus, HPP has great potential to ensure the safety of fresh food without compromising its sensory quality.

This article examines various fresh food products processed using HPP technology. The parameters assessed are the effectiveness of HPP in inactivating pathogenic microorganisms in fresh foods and the impact of HPP on maintaining the sensory quality of products, such as taste, colour, and texture. In addition, this article also discusses the basic principles of HPP in processing and the potential for developing HPP technology for the food industry in the future.

Methods

This study employed a systematic mini-review method with a structured approach to literature selection. Articles were retrieved from three reputable databases, namely Science Direct, Google Scholar, and MDPI, with publications ranging from 2015 to 2025. The main inclusion criteria were original research articles with the keywords high-pressure processing, fresh and minimally processed foods, microbiological analysis, and sensory evaluation. The articles discussed the application of High Pressure Processing in fresh and minimally processed food products (fruit, juice, and fish) and had to contain both microbiological and sensory test data. Through a multi-stage selection process based on methodological quality, relevance, and data completeness, from 72 initially identified articles, 16 articles were selected (see Table 1) and analysed in depth to compile this mini-review.

Discussion

Principle of HPP

High-pressure Processing is a method based on three main principles: Le Chatelier's principle, the isostatic principle, and the microscopic ordering principle (Ozaybi, 2024). Le Chatelier's principle states that when the pressure in a balanced system changes, the system will change its volume to restore balance (Rifna et al., 2019). Second, the isostatic principle, which is pressure applied quickly and evenly to all parts of the product, regardless of its size, shape, or composition (Balasubramaniam & Farkas, 2008). This prevents the product from being damaged or crushed during processing. Finally, the third principle, microscopic ordering, describes how, when the pressure of a sample is increased at a constant temperature, the molecules within it become more orderly (Chatterjee & Abraham, 2018).

To implement these principles, HPP instruments consist of several core components, including pressure tanks and covers, pressure generation systems, temperature control devices, and material processing systems (Kant & Mandal, 2017). These devices operate in five sequential stages. First, the tank chamber is filled with the transmission medium and product. Then, pressure is increased to the desired level and maintained at a stable level for a certain period of time. After that, the pressure is reduced again (decompression), and the processed product is removed from the tank (Sehrawat et al., 2021).

In practice, HPP relies on liquid transmission media, such as water, glycol-water solutions, silicone oil, sodium benzoate solutions, ethanol solutions, and castor oil (Balasubramaniam & Farkas, 2008). This liquid distributes pressure evenly across the entire surface of the packaged product. This is the weakness of HPP, which is not suitable for porous, dense, and low-moisture foods such as spices, dried fruits or powdered products, and products in very rigid packaging (such as glass and cans) because high pressure can damage their physical structure (Morales-de la Peña et al., 2019).

HPP technology not only reduces volume due to pressure, but also increases the average product temperature by 3°C per 100 MPa due to thermodynamics (Balasubramaniam & Farkas, 2008; Baldelli et al., 2024). However, this increase can still be controlled because there are now many commercial HPPs equipped with water jackets or cooling systems to maintain a stable temperature and avoid overheating (Balasubramaniam & Farkas, 2008).

The Effect of HPP on Microorganisms

One of the primary benefits of High-Pressure Processing (HPP) technology is its ability to extend the shelf life of food products significantly. This benefit is achieved through the effectiveness of HPP in inactivating harmful pathogens and spoilage microorganisms, which are the main causes of decay and health hazards. This inactivation process occurs through the application of high hydrostatic pressure (usually 300-600 MPa) evenly, which triggers cellular damage to these microorganisms. The mechanisms of damage include: (1) physical damage to the integrity of cell walls and membranes, causing leakage of intracellular components; (2) denaturation of proteins and inactivation of enzymes essential for cell metabolism; and (3) inhibition of protein synthesis due to disruption of ribosomal function (Nassar & Orlien, 2016; Woldemariam & Emire, 2019).

When sorted, the bactericidal effect of HPP begins with damage to the cytoplasmic membrane. The pressure applied increases the degree of phospholipid regularity, causing the membrane to thicken and lose its flexibility. The damage continues with the detachment and inactivation of membrane proteins, resulting in changes in permeability. Simultaneously, HPP triggers several intracellular disturbances, such as cytoplasmic acidification, oxidative stress, osmotic imbalance, and damage to cellular organelles such as ribosomes (do Rosário et al., 2017).

In terms of effectiveness, HPP is not uniformly effective at inactivating all types of microorganisms. Microorganisms such as vegetative cells, yeast, and fungi are sensitive and can be inactivated by HPP treatment at medium pressure (Muntean et al., 2016). On the other hand, some microbes show higher resistance, including Gram-positive bacteria such as Staphylococcus aureus and some strains of Listeria and Salmonella, especially in spore form (Woldemariam & Emire, 2019). To overcome this resistance, this type of bacteria generally requires higher pressure parameters or a combination with other treatments, such as heating, the use of antimicrobials, or other chemical, physical, or biological treatments (Roig-Sagués et al., 2015; Stratakos et al., 2016).

In addition to the type of microorganism, there are other factors that influence the effectiveness of HPP in inactivating microorganisms, namely process parameters and product characteristics. The main factors that influence the inactivation results include pressure level, treatment duration, process temperature, compression/decompression rate, and product properties such as pH, water activity, and chemical composition (Rifna et al., 2019). Regulatory agencies have established critical processing parameters for HPP treatment of food. These parameters include: target pressure, time interval to reach target pressure, decompression time, initial product temperature, initial pressure fluid temperature, product pH, and product water activity (Muntean et al., 2016). Therefore, careful optimisation of all process parameters and product characteristics is necessary to ensure the effectiveness of HPP in achieving microbial inactivation targets while maintaining the quality and safety of food products.

The Effect of HPP on the Sensory Properties of Products

High-pressure Processing (HPP) has a significant and generally positive impact on the sensory attributes of fresh products. Unlike thermal processing (TP), which often causes softening and undesirable colour changes, HPP works by applying high pressure that affects non-covalent bonds, such as hydrophobic and ionic bonds (Muntean et al., 2016). Because covalent bonds are not broken, very few chemical changes occur in HPP-processed foods. This means that low molecular weight flavour and nutrient components, such as vitamins, pigments, and flavour compounds, are relatively unaffected because the volume changes are minimal (Oey et al., 2008). This consistency is supported by several studies reporting that HPP is more effective at preserving the aroma and flavour of juice than TP because it has a limited effect on the covalent bonds of these compounds (Chang et al., 2017; Picouet et al., 2015). Treatment with specific combinations of pressure, time, and temperature can be used to achieve desired effects on the texture, colour, and taste of food.

In addition, HPP is highly effective in preserving the taste and nutritional value that is close to the characteristics of fresh products. Hu et al. (2020) shows that HPP has fewer negative effects on bitter taste and aroma perception, making juice products processed with HPP more preferred by consumers.

However, to maintain the quality of these processed products, cold storage is still necessary. Song et al. (2023) further found that cold storage was better at maintaining "fresh-like" attributes than room temperature storage, although sensory quality still declined during storage at any temperature. Their study also revealed that the interaction between treatment and storage conditions significantly affected appearance, while the interaction between storage time and temperature mainly affected appearance and aroma. Another key finding was that storage conditions had a greater influence on consumer preference than the type of treatment itself. Therefore, HPP provides the food industry with a unique method of preserving food that reduces nutrient loss and physicochemical quality while meeting public demand for food products that taste similar to freshly prepared ones (Vega-Gálvez et al., 2012).

Table 1. Summary of Fresh and Minimally Processed Products to Which HPP Technology is Applied

No	Products	HPP Parameters	Effects on Microbiology	Impact on Sensory	Reference
1	Coconut Water	600 MPa, 2 min, 4°C	HPP has been proven to reduce *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes* by up to 5-log.	In terms of aroma, flavour, and mouthfeel, the product is indistinguishable from fresh coconut water. However, there is a noticeable difference in appearance.	Punzalan et al., 2025
2	Jabuticaba (*Myrciaria cauliflora*) juice	200, 400, or 600 MPa for 5 min.	Juices processed with HPP-400 and HPP-600 showed low to undetectable levels of microorganisms (aerobic, coliform, psychrotrophic, yeast, and mould).	HPP treatment produces juice that is more palatable and less bitter than thermal processing.	Hu et al., 2020
3	Orange Juice	450 MPa for 3 min	Microbes are reduced to undetectable levels.	There were no significant differences in colour, citrus aroma, fermentation odour, citrus flavour, acidity level, and astringency between the orange juice samples tested.	Chu et al., 2025
4	Carrot Juice	600 MPa for 5 min	The total number of microbes remained below the threshold of 6.0 $\log_{10}$ CFU/mL even after storage for up to 21 days.	The resulting carrot juice retains its fresh taste and quality with improved sensory properties for up to 29 days in cold storage.	Picouet et al., 2015
5	Feijoa Puree	*E. coli*: 200, 300, and 400 MPa for 2, 4, and 6 min, 25 °C. *B. subtilis* and *S. cere-visiae:* 200, 250, and 300 MPa, 25 °C, for 2, 4, and 6 min Sensory: 600 MPa, 20 °C, for 5 min.	A reduction of 2.5-log was achieved at 400 MPa for 6 minutes. At 300 MPa, the log reduction was smaller, with values of 1.8-log after 4 minuter and 2.7-log after 6 minutes. However, at 300 MPa/6 minutes, the reduction reached 6.5 logs in all samples.	The treatment did not affect consumer acceptance, appearance, or colour of the product. However, it significantly affected the flavour and texture of the product.	Duong et al., 2015
6	Carambola Juice	600 MPa of pressure for 30, 60, 90, 120, 150, 180, 210, and 240 s at 10°C.	HPP reduces all microbes (aerobic, psychrotrophic, *E. coli* or coliform, yeast, and mold) in juice to undetectable levels (< 1.0 log CFU/mL).	Although both methods successfully enhanced the aroma, the HPP method showed significantly superior performance compared to the thermal method.	Huang et al., 2018
7	Cucumber Juice	HPP, 500 MPa/ 5 min	HPP is capable of suppressing microbial growth (aerobic bacteria, yeast, mould) to very low levels (<1 log) and maintaining microbiological stability during a 20-day storage period at refrigeration temperatures.	HPP juice is preferred overall over juice pasteurised using the HTST (high-temperature short-time) method.	Liu et al., 2016

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8	Peach–Strawberry Puree	HPP: 600 MPa, 20 °C, 10 min High Pressure-Mild Thermal Processing (HPMT): 600 MPa, 50 °C, 10 min	HPP achieved a 3-log reduction in aerobic bacteria, while HPMT reduced microbes to undetectable levels. The microbial stability of all samples became the same after 21 days of storage.	Compared to HPMT, HPP samples had the highest sensory quality (colour, appearance, aftertaste, flavour, aroma, and texture) and were the most preferred.	Bleoanca et al., 2021
9	Strawberry Purée	20 °C for 1.5 or 3 min at 400–600 MPa	Total aerobic bacteria (TAB) were at a level of 2.2–2.7 log CFU/g, with no yeast or mold detected.	HPP purée is more similar to fresh purée than to heat-treated purée, especially in terms of viscosity, freshness, and strawberry flavour.	Aaby et al., 2018)
	Strawberry Juice	400, 500, 600 MPa, 20°C, 1.5 or 3 min	TAB on day 0 was below 2.0 log cfu/g and did not undergo significant changes after processing. The juice shelf life reached a minimum of 49 days at a temperature of 6°C.	The sensory profile of strawberry juice shows significant differences between untreated juice (control) and juice processed using HPP after storage for 35 days.	
10	Sugarcane juice	523 MPa/50 °C/ 11 min	The number of aerobic mesophilic microbes, yeast, and mould did not show significant growth and remained below the detection limit (< 1.0 CFU/mL) during storage at 25 °C for up to 25 days.	No decline in sensory quality, unlike juices produced through thermal processing.	Pandraju & Rao, 2020
11	White grape juice	300 or 600 MPa for 3 min	HPP 600 MPa significantly suppressed microbial growth. After 20 days of storage at 4°C, the number of aerobic bacteria in the treated samples was much lower (1.2 log CFU/mL) than in the control samples, while coliforms, yeasts, and molds were not detected at all (<1.0 log CFU/mL).	Increased HPP pressure caused a slight decrease in acidity, aroma, and sweetness, but the values were still better than those of the heated samples. The thermal samples actually had a higher bitterness than the control and HPP samples.	Chang et al., 2017
12	Strawberry Puree	300 and 500 MPa for 1, 5 and 15 min at 0 and 50 °C	HPP at 500 MPa and 50°C for 15 minutes can extend the shelf life of the product to 12 weeks. During cold storage, the amount of mold and total microbes remains under control (not exceeding 20 and 140 cfu/g), and no yeast growth is detected.	The sensory superiority of HPP puree over pasteurized puree only lasts until the end of the fourth week of storage. After that period, the sensory quality of both products becomes equivalent or not significantly different.	Marszałek et al., 2017
13	Passion Fruit Purée	600 MPa for 5 min	No total number of aerobic bacteria, yeast, or mold was detected.	The HPP treatment successfully maintained the sensory quality of the puree the best, as reflected in the highest assessment score and its closest similarity to the fresh product (control).	Niu et al., 2022
14	Fresh Fish Fillets (*Salmo salar* and *Pleuronectes platessa*)	500 MPa for 2 min at a temperature of 4 °C	Effective in inhibiting the growth of microbes, including the *Enterobacteriaceae, Pseudomonas,* and mesophilic and psychotropic bacteria groups.	Statistically significant differences were found in the appearance and texture of the HPP samples compared to the controls. In contrast, the odor attribute did not show significant differences, indicating that HP treatment has a stabilizing effect on aroma.	Castrica et al., 2021
15	Concord Grape Puree	600 MPa, 3 min, 5 °C	HPP makes puree microbiologically stable for up to 4 months in the refrigerator, but HPP puree has less microbial growth and a longer shelf life.	Sensory test results prove that HPP puree is significantly superior to thermal puree. HPP puree not only better retains the freshness and consistency of fresh fruit, but also scores higher in overall preference,	Li & Padilla-Zakour, 2021

				product rating, and purchase interest.	
16	European Sea Bass Fillets	100, 200, 300, and 400 MPa; temperature: 3, 7, and 25 °C; processing time: 5 and 10 min	Treatment with 100–200 MPa for 10 minutes extends the shelf life of sea bass fillets to 10 days at 0°C. Higher pressures (300–400 MPa) can even extend it to 10–40 days, depending on the process temperature.	HPP >100 MPa makes the color of the fillet surface brighter, which is considered less attractive, but still acceptable at the beginning of storage. At the end of storage, it is the control and 100 MPa samples that show the most color change, while the >200 MPa samples remain stable. Temperature and processing time do not affect the sensory properties of the fillet.	Tsevdou et al., 2023

Potential for Technological Development

High-pressure Processing (HPP) technology has great potential to become a mainstay in food processing, especially in meeting modern consumer demand for convenient, safe, and natural products. One of its greatest potentials is its ability to extend shelf life without relying on additional food preservatives. The high pressure applied to the product not only inactivates pathogenic and spoilage microbes, but also produces a safe, fresh, and longer-lasting product (Huang et al., 2018). This is in line with the "clean label" trend, where consumers increasingly prefer products with minimal ingredients and free from synthetic chemical additives. With HPP, the industry can offer products that meet these criteria while ensuring safety and freshness, thereby opening up a vast new market.

On the other hand, the development and application of HPP are still limited by a number of challenges that must be overcome to reach a wider market. Although it is environmentally friendly because it operates at room temperature and does not produce chemical waste (in line with the principles of sustainability), the implementation of this technology is still hampered by economic and technical barriers (Balasubramaniam & Farkas (2008) states that the application of HPP is capital-intensive, both in terms of instrument costs and high power consumption during the process. Therefore, future research and innovation need to focus on developing more energy-efficient technologies, reducing investment costs, and optimising processes to make HPP more affordable and efficient for medium-scale food industries.

Conclusion

Based on the article review, it can be concluded that High Pressure Processing (HPP) is a very promising non-thermal processing technology for ensuring the microbiological safety of fresh food products without compromising their sensory and nutritional quality. This technology works by applying high hydrostatic pressure (300-600 MPa) evenly, which is capable of inactivating pathogenic and spoilage microorganisms by damaging cell membranes, denaturing proteins, and disrupting ribosomal function. The main advantage of HPP lies in its ability to preserve the taste, aroma, colour, texture, and nutritional content that are close to the characteristics of fresh products, as it only affects non-covalent bonds and does not significantly alter flavour compounds and vitamins. Although its effectiveness is influenced by the type of microbe, process parameters, and product characteristics, and it has limitations for porous and low-moisture products, the global adoption of HPP has increased rapidly and has been approved by food safety authorities. Thus, HPP addresses the industry's challenge of meeting consumer demand for safe, highly nutritious food products with sensory qualities similar to fresh products.

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