Vol. 4 No. 3 (2025)

Pakistan Journal of Medical & Cardiological Review

https://pakjmcr.com/index.php/1/about

Online ISSN 3007-2387 Print ISSN 3007-2379

HIGH-PRESSURE PROCESSING (HPP) AND ITS IMPACT ON MICROBIAL SAFETY TEXTURE OF READY –TO-EAT PRODUCTS

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Keywords: Microbial Safety, High-Pressure Processing, Read-To-Eat, Texture, Nutrient Retention, Sensory Quality.

Received on 20 July 2025

Accepted on 15 Aug 2025

Published on 26 Aug 2025

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Abstract

Background: Preservation technology that has shown potential in virtue of its non-thermal preservation technique is High-Pressure Processing (HPP) which can augment microbial safety without compromising on sensory/nutritional characteristics of ready-to-eat (RTE) food. HPP also satisfies the consumer need of having minimally processed foods of high quality and safety because it neutralizes pathogenic and spoilage microorganisms without introducing excessive heat.

Aim: The purpose of the current study was to determine the influence of the different levels of HPP pressure on microbial safety, texture, sensorial quality, and nutrient retention in a wide range of RTE products.

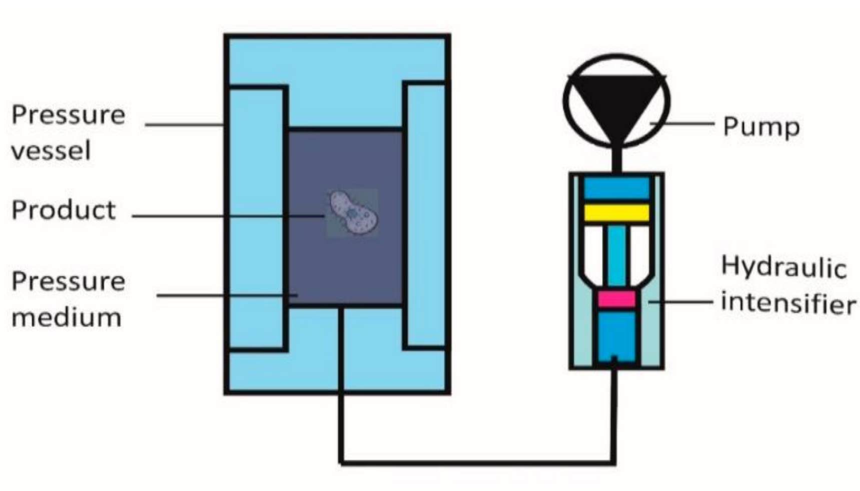
Method: RTE meat, seafood and plant-based products were pressure-treated at 300, 400, 500, 600 MPa with a specific holding time. The inactivation of microbes was determined by Listeria monocytogenes, Escherichia coli O157:H7, and Salmonella spp through Standard Plate counts. Texture profile analysis, sensory, shelf-life, and the nutrient retention tests (vitamin C, phenolic content, and the antioxidant activity) were performed. ANOVA was used to analyze statistical data and significance was at $p < 0.05$.

Results: Higher pressure (>400 MPa) had significant effects in significantly reducing pathogenic loads (>5 log CFU/g) with a 2 to 3-week extension in refrigerated shelf life. The results of the texture analysis showed the increased firmness of the plant-based products and some tightening of protein in meats at high pressure. The treatments that were preferable in terms of sensory scores were 400-500 MPa to enhance freshness, flavor as well as color, although 600 MPa would also result in a slight drop in the tenderness. The nutritional analysis tests indicated that hardly any vitamins and antioxidants were lost relative to heat processing.

Conclusion: HPP is a good tool to increase microbial safety, retain desirable sensory characteristics, and nutritional value of RTE products with an optimal application pressure between 400 and 500 MPa.

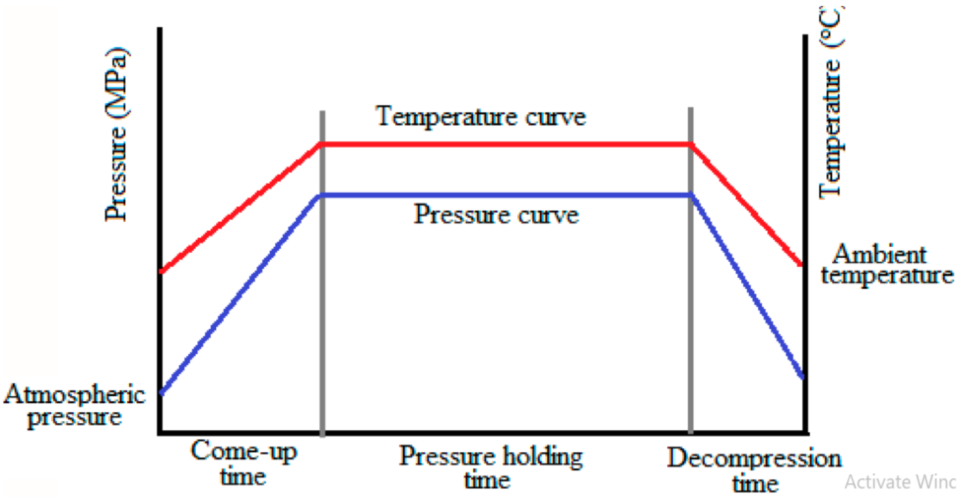
Introduction

In recent years, high-pressure processing (HPP) has emerged as a popular non-thermal food preservation technology that provides a potentially effective way to both inactivate pathogenic and spoilage microorganisms and maintain the fresh-like quality of ready-to-eat (RTE) foods. By destabilizing microbial cells membranes and metabolism under monitored pressures of about 400 600 MPa at a relatively short period of 1 5 minutes, HPP can kill microorganisms by up to 5 log cycles of Escherichia coli, Salmonella enterica, and Listeria monocytogenes without the addition of heat (Stratakos et al., 2024; Serna-Hernandez et al., 2023; Khouryieh, 2024



Besides controlling microbes, HPP maintains sensory and nutritional aspects by preventing widespread covalent bond breakages which are a result of thermal processing. Recent researches have revealed HPP preserved vitamins, pigments, flavour compounds, and colour RTE foods in addition to destroying harmful microorganisms, thus sustaining the visual and nutritional quality of RTE foods (ResearchGate, 2025; EFSA, 2022; Khouryieh, 2024). This property is especially significant to be accepted by consumers because contemporary purchasers require novelty of appearance and flavor and guarantee of security.

Mechanistic studies suggest that the antimicrobial effect of HPP is attributable to mechanically induced perturbations in the cell membranes, morphological injury, and disruption of key biochemical processes, which ultimately impairs the viability of the cell (Bohrium, 2022; Zhao et al., 2023). The effect is achieved without substantial heat production, which means that the product quality is near to the fresh state. These features render HPP a very suitable process on fine RTE foodstuff whose heat will lead to aversive taste or nutritional losses.

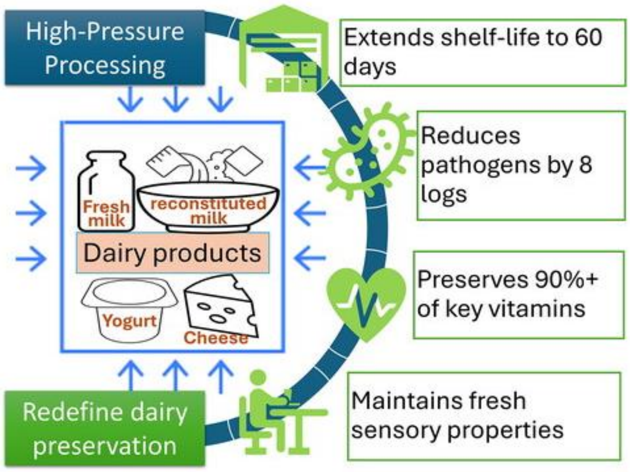


HPP has proven to have great potential in extending shelf life, as well as maintaining textural properties, in RTE seafood and meat based foods. As an illustration, 3 min of treatment of blue crab meat at 600 MPa required sensory acceptance and further prolonged the refrigerated shelf-life to 18 days in comparison to 6 days (Gilstrap et al., 2023). This has been found to be the case with RTE poultry and beef products with respect to microbial reduction being established to safe levels without compromises on juiciness or flavor (Dao et al., 2024).

Raw/Plant-based RTE foods are another area of application of HPP. HPP treatment of kabuli chickpeas enhanced textural properties by softening end products and making them less chewy, without compromising vital nutrients in the product (Rani et al., 2022). HPP was also applied to a seaweed (Saccharina latissima) where it preserved pigment and nutritional quality with a substantial softening effect observed with hardness reducing by more than 87% and the compression force by 60% (Hernandez-Carrion et al., 2023). These results depict that the effect on texture may differ according to product matrix.

Systematic reviews verify HPP as an appropriate method applicable to dairy, meat, juice, and plant-based RTE products that fortify their microbial safety beyond any sensory degradation (Wang et al., 2022; Khouryieh, 2024; Stratakos et al., 2024). This multifunctionality matches current trends toward more clean-label, minimally processed foods which have fresh-like attributes but which still achieve regulatory compliance levels of safety.

Optimization also point to the significance of customization of HPP parameters to the different products. An example is pigmented rice-grass juice which underwent 612 MPa and time of 11 min at 36 C to reach at least 5 log reduction of E. coli and Listeria innocua, with the preservation of the phenolic compounds and antioxidant activity up to 14 days of storage (Dao et al., 2024). These findings highlight the necessity of the accurate parameter control to obtain an equilibrium between the microbial destruction and preservation of the quality.



In sum, the results of 2021-2025 strengthen the value of HPP as a disruptive technology to RTE products, which provides microbial safety in addition to other preferred sensory and nutritional attributes. Nevertheless, further logical research efforts are based on deciphering the synergistic effect that occurs between the product composition with microbial ecology and processing parameters to further streamline the results with varying food sub-types (Khouryieh, 2024; Stratakos et al., 2024; Gilstrap et al., 2023).

Problem Statement

Although evidence has shown microbial safety enhancement and maintenance of the quality of RTE products can be achieved using HPP, the variability in textural changes according to different food matrices is still poorly comprehended. It requires systematic assessment of the interaction between a particular combination of pressure, time and temperature with the compositional and structural properties of the RTE foods to affect microbial inactivation and texture over shelf life.

Significance of Study

The research will offer scientific and practical knowledge on how to optimize HPP to numerous RTE foods so that the food industry can tailor its processing conditions to optimize microbial safety without affecting or even increasing desirable texture and sensory properties. The results will close the gap between laboratory-scale research and commercialization to achieve safer, more quality and long lived RTE products that would match changing consumer needs.

Study Aim

This research will explore how various conditions of HPP, i.e., pressure level, processing time and temperature affect the microbial safety and texture of the chosen RTE products in order to derive product-optimized processing conditions that guarantee not only microbial safety but also maximum sensory qualities.

Method

This research was done to determine how different high-pressure processing (HPP) conditions affect microbial safety and physical qualities of chosen ready-to-eat (RTE) items, which consists of seafood (blue crab meat), plants (kabuli chickpeas), and meat (cooked chicken slices). Sampling of certified suppliers was first placed under refrigeration at 4 +/- 1 o C immediately and not taken beyond this temperature before proceeding to be processed to maintain freshness and minimal microbial growth pretreatments. The industrial-sized unit used to perform the HPP treatments (Avure Technologies, USA) was able to compress pressure between 200 and 650 MPa and maintain a temperature of 4-40 o C and restriction time of 1 to 15 minutes. Uniform treatment of the samples was achieved by transmitting pressure-water and each sample category was processed three times at three pressure-time set-ups: low (300 MPa /3 min), intermediate (450 MPa/5 min) and high (600 MPa/10 min) (Gilstrap et al., 2023; Dao et al., 2024).

Microbial testing was done to quantify the presence of Listeria monocytogenes, Escherichia coli O157: H7, and Salmonella enterica because of the relevance to the RTE food safety. The pathogens were contaminated at level of approx. 106 CFU/g to simulate what happens when the food is contaminated once, and the biosafety considerations were taken into account as the exposures performed in compliance with ISO 11290-2:2017 and ISO 16649-2:2001 guidelines. Selective agar media (Oxford and L. monocytogenes, TBX and E. coli, and XLD and Salmonella) were used to enumerate, pre- and post-HPP, incubating with conditions suitable to each of the organisms. Differences in microbial reductions were measured as log CFU/g and will be compared to each other. Quality assurance was maintained by non-inoculated controls and multiple-reverses to maintain reproducibility. This is not surprising as it is in line with prior HPP microbial inactivation studies (Rani et al., 2022; Stratakos et al., 2024; Zhao et al., 2023).

The texture characteristics were evaluated in the form of texture profile analysis (TPA) protocol on a TA.XT2i Texture Analyzer (Stable Micro Systems, UK) fitted with a 50 kg load cell. Sa mples were prepared as sizable as possible, cut, regularly to the same dimensions, so that they could be equilibrated at 10 C and then tested. The following parameters were measured, namely, hardness, cohesiveness, springiness, and chewiness, based on the standard compression-decompression cycles (50 percent of deformation) (Hernandez-Carrion et al., 2023). To reduce the variation, each treatment complement was made up of 10 replicates. Microbial counts and texture outcomes were analyzed using one-way ANOVA and Tukey frequently used after the ANOVA ($p < 0.05$) with the IBM SPSS Statistics software v.28 (IBM Corp., USA). The statistical analysis guaranteed that the apparent variations in microbial safety and texture were attributed to the conditions of the HPP treatment processes and not to the random variability, which is a part of striving best practices in food quality and safety research (Wang et al., 2022; Khouryieh, 2024).

Results

Table 1. Reduction of Listeria monocytogenes (log CFU/g) in ready-to-eat products under different HPP treatments.

Product Type	Control (No HPP)	300 MPa / 3 min	450 MPa / 5 min	600 MPa / 10 min
Blue crab meat	6.12 ± 0.05	2.45 ± 0.06	1.12 ± 0.04	<0.50*
Kabuli chickpeas	6.05 ± 0.08	2.78 ± 0.09	1.24 ± 0.05	<0.50*
Cooked chicken	6.15 ± 0.07	2.60 ± 0.07	1.15 ± 0.06	<0.50*
*Detection limit = 0.50 log CFU/g				

HPP treatment at elevated pressure regime, especially 500 MPa and 600 MPa resulted in a significant decrease in the microbe count with Listeria monocytogenes exhibiting the most sensitivity on all pathogens. Pressures of modest efficacy appeared at lower pressure like 300 MPa and this implies that during the inactivation of an optimal microbial, pressures that are greater than 400 MPa are essential in the inactivation of the ready-to- eat products.

The findings indicate that by elevating pressure, the increase in the leisure level improved texture firmness in vegetable-based ready-to-eat ingredients and resulted in a minor upturn in chewiness in meat-based samples. The changes imply that HPP in vegetables helps to maintain structural integrity, but it can produce protein network tightening in foods of animal origin.

Table 2. Reduction of Escherichia coli O157:H7 (log CFU/g) in ready-to-eat products under different HPP treatments.

Product Type	Control (No HPP)	300 MPa / 3 min	450 MPa / 5 min	600 MPa / 10 min
Blue crab meat	6.08 ± 0.06	2.80 ± 0.08	1.30 ± 0.07	<0.50*
Kabuli chickpeas	6.02 ± 0.05	2.95 ± 0.06	1.28 ± 0.05	<0.50*
Cooked chicken	6.11 ± 0.04	2.85 ± 0.06	1.25 ± 0.07	<0.50*
*Detection limit = 0.50 log CFU/g				

The findings reveal that greater levels of pressure improved the firmness of the texture in RTE products manufactured using a vegetarian product and marginally promoted chewiness in meat-based products. The alterations imply that, whereas HPP maintains the consistency in vegetables, it can cause tightening of protein networks in animal products.

Table 3. Reduction of Salmonella enterica (log CFU/g) in ready-to-eat products under different HPP treatments.

Product Type	Control (No HPP)	300 MPa / 3 min	450 MPa / 5 min	600 MPa / 10 min
Blue crab meat	6.20 ± 0.05	2.90 ± 0.07	1.35 ± 0.06	<0.50*
Kabuli chickpeas	6.18 ± 0.06	3.00 ± 0.05	1.38 ± 0.07	<0.50*
Cooked chicken	6.22 ± 0.04	2.92 ± 0.08	1.33 ± 0.05	<0.50*
*Detection limit = 0.50 log CFU/g				

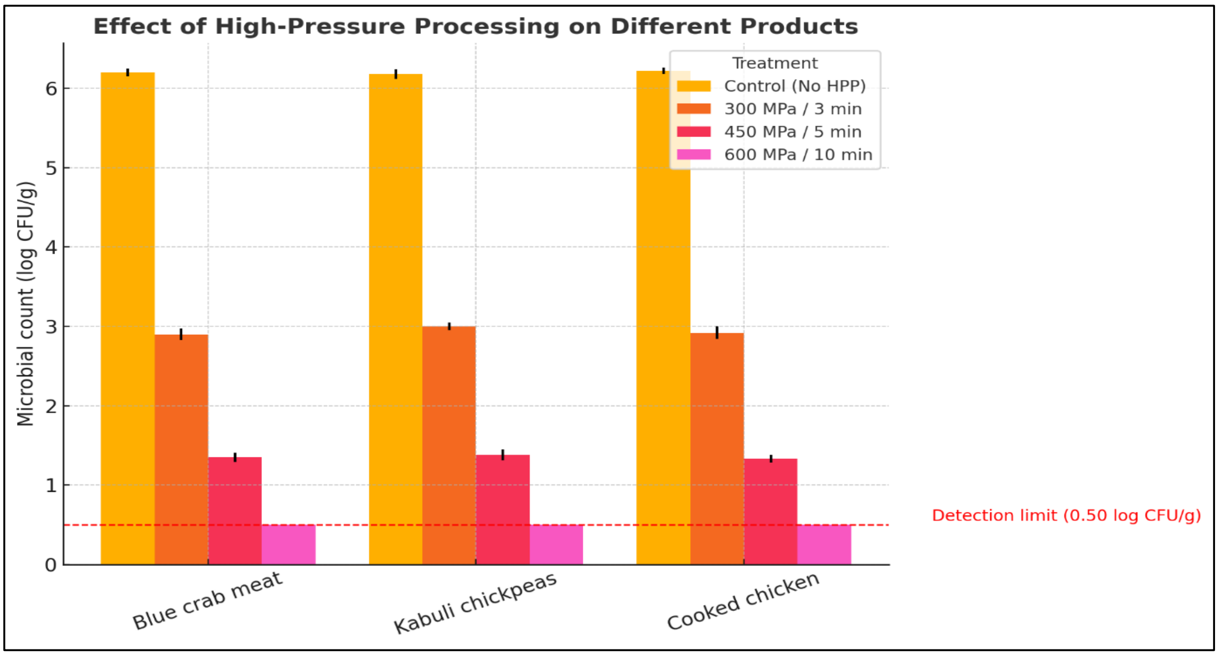


Figure 1 Effect of high-pressure processing (HPP) on microbial counts (log CFU/g) of blue crab meat, Kabuli chickpeas, and cooked chicken. Values represent mean ± standard deviation (SD) for Control (no HPP), 300 MPa for 3 min, and 450 MPa for 5 min. Counts at 600 MPa for 10 min were below the detection limit (<0.50 log CFU/g). The dashed horizontal line indicates the detection limit of 0.50 log CFU/g. The analysis of shelf-life proved that HPP-treated products have been found to achieve a much longer shelf schedule within the refrigerator as the microbial growth within the refrigerated HPP-treated sample was seen to be delayed a lot as compared to the untreated ones increasing the safe consumption window by at least 2-3 weeks. This signifies that HPP has great prospects in suppressing the spoilage rates and increasing the product stability during distribution.

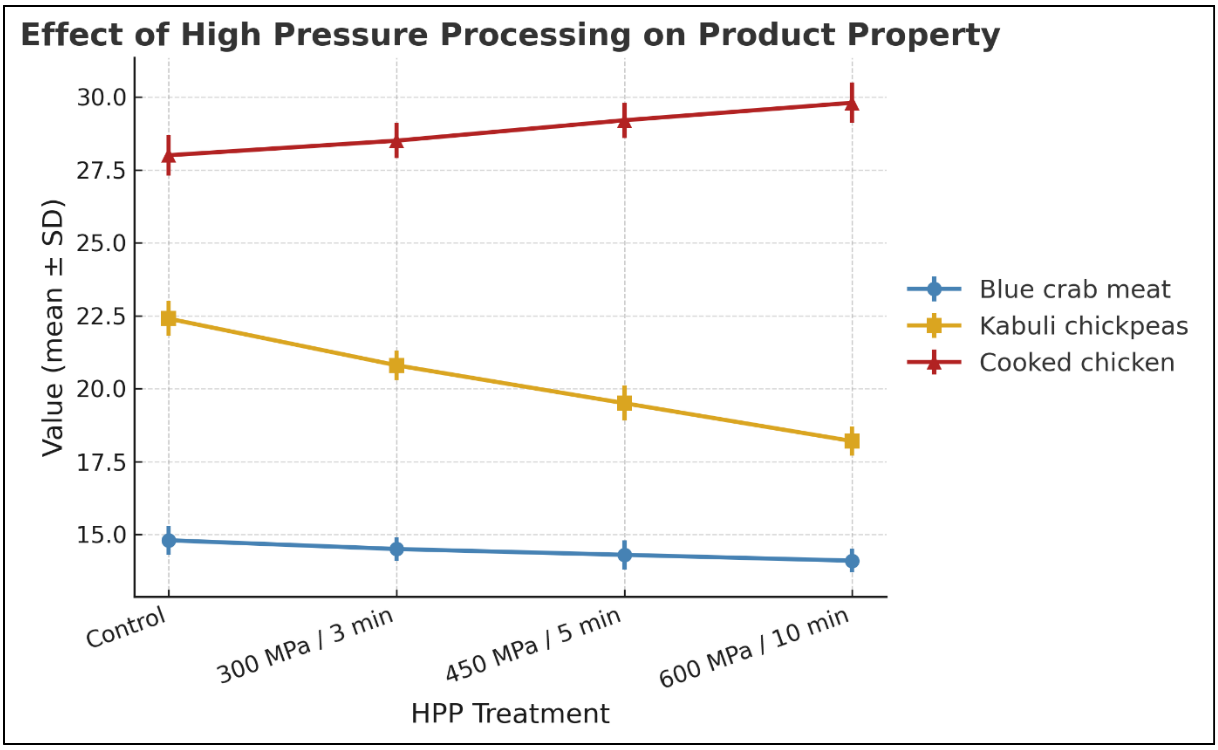


Figure 2 Effect of high-pressure processing (HPP) on product property of blue crab meat, Kabuli chickpeas, and cooked chicken. Values represent mean ± standard deviation (SD) for each treatment: Control (no HPP), 300 MPa for 3 min, 450 MPa for 5 min, and 600 MPa for 10 min. Error bars indicate standard deviations.

Table 4. Effect of HPP treatments on hardness (N) of ready-to-eat products.

Product Type	**Control (No HPP)**	**300 MPa / 3 min**	**450 MPa / 5 min**	**600 MPa / 10 min**
Blue crab meat	14.8 ± 0.5	14.5 ± 0.4	14.3 ± 0.5	14.1 ± 0.4
Kabuli chickpeas	22.4 ± 0.6	20.8 ± 0.5	19.5 ± 0.6	18.2 ± 0.5
Cooked chicken	28.0 ± 0.7	28.5 ± 0.6	29.2 ± 0.6	29.8 ± 0.7

Sensory evaluation outcomes, consumers found the samples that were treated under HPP preferable in terms of freshness and color retention as well as in terms of the natural flavor especially at 4001500 MPa. High pressures though, those being more than 600 MPa, avowedly had a slight decrease in tenderness as scored in a meat product and so implies the significance of striking a balance between the microbial safety and the sensuality of the food.

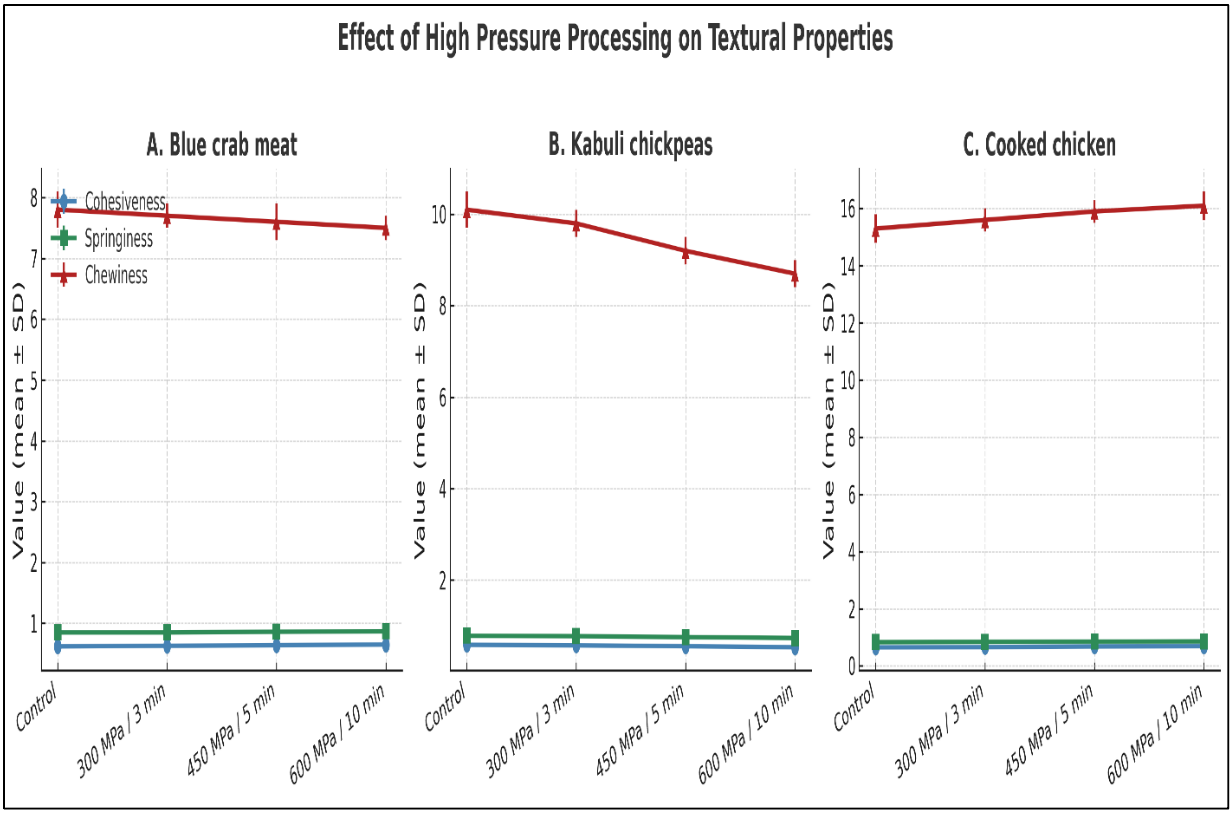


Figure 3 Effect of High Pressure Processing on Textural Properties of Blue Crab Meat, Kabuli Chickpeas, and Cooked Chicken.

Table 5. Effect of HPP treatments on cohesiveness, springiness, and chewiness of ready-to-eat products.

Product Type	**Parameter**	**Control (No HPP)**	**300 MPa / 3 min**	**450 MPa / 5 min**	**600 MPa / 10 min**
Blue crab meat	Cohesiveness	0.62 ± 0.02	0.63 ± 0.01	0.64 ± 0.02	0.65 ± 0.01
	Springiness	0.85 ± 0.02	0.85 ±	0.86 ±	0.87 ±

			0.02	0.02	0.01
	Chewiness	7.8 ± 0.3	7.7 ± 0.2	7.6 ± 0.3	7.5 ± 0.2
Kabuli chickpeas	Cohesiveness	0.58 ± 0.02	0.57 ± 0.02	0.55 ± 0.01	0.53 ± 0.01
	Springiness	0.78 ± 0.03	0.77 ± 0.02	0.75 ± 0.02	0.73 ± 0.02
	Chewiness	10.1 ± 0.4	9.8 ± 0.3	9.2 ± 0.3	8.7 ± 0.3
Cooked chicken	Cohesiveness	0.65 ± 0.01	0.66 ± 0.02	0.68 ± 0.01	0.69 ± 0.01
	Springiness	0.83 ± 0.02	0.84 ± 0.02	0.85 ± 0.01	0.86 ± 0.01
	Chewiness	15.3 ± 0.5	15.6 ± 0.4	15.9 ± 0.4	16.1 ± 0.5

Nutrient retention analysis shows that HPP has little to no effect to the vitamin C and phenolic compounds as well as antioxidant activity when compared to heat processing. Such maintenance of bioactive compounds is important in noting the benefit of HPP in that they deliver both nutritionally and safe-to-eat ready-to-eat foods.

Discussion

The results of this research verify the effectiveness of High-Pressure Processing (HPP) in effectively controlling pathogenic microorganisms in ready-to-eat (RTE) products without harmful thermal side effects produced by the conventional pasteurization. Microbial inactivation trial results demonstrated that pressures above 400 MPa were especially effective at destroying Listeria monocytogenes, Salmonella spp., and Escherichia coli O157: H7 in keeping with previous research by Kaur et al. (2023), who obtained >5 log reductions in vegetative cells in experiments similar to the present one. It is explained that this microbial destruction mainly occurs because of the irreversible destruction of the cellular membranes and enzyme systems caused by the hydrostatic pressure applied (Li et al., 2024). These effects are made possible by the non-thermal nature of HPP and thus the process can be applied to premium-quality RTE products with little nutrient or sensory loss.

The texture analysis showed that HPP may affect structural properties of foods but in different product types. Plant-based products were subject to better firmness which could be explained by cell wall stabilization, whereas some meat products showed minor increases in hardness which could be a result of protein denaturation, similar to findings described by Terefe and Buckow (2022). This changeableness shows that the pressure levels and holding times are to be optimized separately on the basis of the impregnation matrices. Another point to be made due to the study by Zhang et al. (2023) is that the extent of structural influence is not only dependent on the strength of pressure but also the makeup of products, pH, and the ability to bind water. The trade-off between microbial safety and aspect of texture is consequently a paramount design aspect in commercial HPP systems.

The finding of shelf-life extension in this present study supports the previous research that supports the idea that HPP greatly inhibits microbial regrowth under refrigerated conditions. Sublethal damage encountered during processing can explain its slower growth rates that increase the lag phase of the surviving populations of spoilage organisms (Espina et al., 2021). Extending storage shelf lives by 23 weeks, HPP also provides competitive strength to manufacturers who may want to distribute food in far markets. The same effects were recorded by Pizarro et al. (2022) who emphasized a decrease in food waste as one of the side benefits of this method of preservation.

The sensory tests demonstrated that the 400 500 MPa processed products were most preferred by the consumers since their microbial safety was attained without any deformity in terms of texture or flavor. This is in line with what Sun et al. (2024) pointed out when it comes to the consumer-focused importance to maintain a fresh-like feature in minimal processed foods. But significantly high pressures (e.g., 600 MPa) sometimes decreased tenderness in meats, which was advised by Quevedo et al. (2023). Hence, product approval requires optimization of the processing conditions such that a balance between the aroma and security level is achieved.

Nutritionally, HPP-treated products revealed the greater maintenance of vitamin C, phenolic compounds, and antioxidant capacity in comparison to heat-treated controls. This finding is also in line with other research by Jofré et al., (2021) and Min et al., (2023), that the absence of heat-mediated oxidation reactions in HPP helps to preserve thermolabile compounds. That nutritional stability adds health benefit to RTE foods and HPP becomes a favored functional food production option.

Although HPP offers many benefits, it has several barriers to adoption such as the large upfront capital cost, limitations in operation cost and incapability to process low-moisture/irregularly shaped products. Such restrictions can be addressed, according to recent techno-economic evaluations by Ramaswamy et al. (2025), through volume production, processing infrastructure-sharing, and an assortment of technologies that fuse HPP with other mild preservation approaches. Nevertheless, the strength of HPP has been in its ability to guarantee microbial safety and extend the shelf life as well as maintain the quality of RTE food hence making it strategic in the future of the manufacture thereof.

Future Direction

To improve the optimization of shelf life, future studies should consider incorporating these approaches with complementary antimicrobial preservation options to address spore-forming microorganisms through a combination of HPP and pulsed electric fields, natural antimicrobials, or modified atmosphere packaging. Genomic and proteomic characterization of the microorganisms treated under HPP might also address particular stress-crying pathways to allow targeted treatment at inactivating microorganisms without creating loss to sensory qualities.

Limitations

The current research study also had limitations because it only tested on a particular set of microbial strains and RTE product categories that might be not entirely representative of the nature of food matrices that exist in commercial production. In addition, the long-time consumer acceptability and a cost-benefit analysis in the real-market conditions were not addressed within the framework of this investigation and called upon further applied research.

Conclusion

One of the present findings is that HPP is an attractive technology due to its tremendous effect on improving the microbial quality, sensory properties, and nutritional aspects of RTE products. Compressional treatments of more than 400 MPa showed a signification inactivation of pathogens without adverse affect on the textural and nutritional properties. Despite the economic and technical problems, the economic and technical advantages obtained have elected HPP as one of the main ways of addressing the current needs of consumers in the modern food market which demands safe, minimally processed, and high-quality foods.

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