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REVIEW ARTICLE

Impact of High Pressure Processing on the Safety and Quality of Food Products: A Review

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Abstract: High pressure processing (HPP) has become a practical food processing technique that meets the preferences of consumers seeking lightly processed, convenient, and fresh-tasting food options. This paper reviewed the latest research on the impact HPP on the safety and quality of food products. The use of HPP has been showing favorable growth in the food industry primarily due to its potential to not only enhance the nutritional content and sensory attributes of food products but also to substantially extend their shelf-life and bolster safety standards. HPP is the most used among non-thermal food processing technologies. While its direct application to milk for consumption falls short of delivering consistent quality, it proves effective as a pretreatment step and in products using milk as a primary ingredient. In the context of meat production, HPP reduces microbial loads and extends shelf-life, yet concerns persist regarding its impact on product quality. The absence of in-depth studies regarding the attributes of carrots that support pathogen regeneration emphasizes the need for comprehensive research in this area, which could have far-reaching implications for similar fruit and vegetable products. This review underscores the need for a balanced assessment of HPP's effects on food safety and quality, offering insights that can guide the food industry in adopting this technology while ensuring consumer satisfaction and safety.

Keywords: High-pressure processing, nonthermal food processing technology, dairy products, meat products, fruit and vegetables, juice, safety and quality of food products.

1. INTRODUCTION

Traditional heat treatment techniques for sterilizing and preserving foods involve subjecting the foods to high temperatures to eliminate pathogens and spoilage microorganisms. However, these approaches often come at the cost of diminishing the overall quality of the food product, as it leads to the destruction of cells and essential nutrients [1]. This compromise in product quality has created a niche in the market for consumers who yearn for food that retains the freshness and nutritional value of its original state [1]. The dissatisfaction stemming from traditionally processed foods has spurred intensive research into alternative methods that can maintain stability and safety while circumventing the detrimental impacts associated with conventional techniques. Over time, numerous promising technologies such as high-pressure processing (HPP), pulsed electric field, ozone technology, cold plasma, irradiation, supercritical carbon dioxide, and ultrasound have emerged as potential candidates for achieving this objective. While some innovative methods, such as HPP, have gained traction in the commercial sector, many still require further investigation and refinement to meet the expectations of discerning consumers. Crucially, research should also delve into the perceived benefits and risks as perceived by consumers, as these factors wield significant influence over consumer acceptance [2]. Consumer opinions wield substantial power, capable of swaying the industrial adoption of these novel food preservation techniques. Therefore, understanding and addressing these factors are pivotal in shaping the future of food preservation technologies.

High pressure processing, also known as high-hydrostatic pressure processing (HHP) or ultra-high-pressure processing (UHP) is a non-thermal technique of food preservation that inactivates pathogenic and spoilage microorganisms. It achieves this in a nonthermal manner by applying elevated pressures, approximately 400-600 MPa, to prepackaged solid and liquid foods for a certain amount of time, usually 1.5 to 6 min [3]. As a nonthermal process, this has a high potential to avoid many undesired effects of traditional high-heat treatment processes. The advantages and limitations of HPP as a nonthermal technology are summarized in Table **1**. HPP emerged as a technology as early as the late nineteenth cen-

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Table 1. Summary of the key advantages and limitations of high pressure processing as nonthermal processing technology.

Advantages	Limitations
- Kills pathogenic and spoilage microorganisms	- Ineffective in inactivating bacterial spores
- Provides minimally processed foods and maintains the freshness of the original product	- Less effective on enzyme activity
- Retains the sensory properties and nutritional value of food products	- Ineffective in processing dry foods. Low moisture foods such as powdered products and dried fruit are not subjected to HPP due to the low microbial inactivation in food with moisture content below 40%
- Highly effective for foods with elevated moisture content	- Not suitable for foods that contain trapped air. Some foods such as marshmallows, bread, cakes, whole or fresh-cut fruit and vegetables, could be crushed by HPP
- Short processing times	- Undesirable changes in texture or color are possible
- Minimal energy consumption	- High equipment costs
- Provides uniform distribution throughout food	

tury, yet it did not appear in application in the food industry until the 1990s [4]. Over the past three decades, a multitude of attempts and implementations have been made in various segments of the food market, showcasing the versatility of this processing technique across different food categories such as fruits and vegetables, dairy products, and meat. Many of these applications have achieved notable success. Nonetheless, additional research and fine-tuning are still required to further advance its adoption.

The HPP equipment market is on a remarkable growth trajectory, driven by the increased demand for safe, high-quality, and minimally processed products across various industries. According to a report by Allied Market Research, the global HPP equipment market in 2020 exhibited a substantial valuation, with a total worth of $404.6 million. With a substantial annual growth rate of 11.2%, it is poised to reach a valuation of $1,238.3 million by 2030 [5], reflecting the pivotal role that HPP technology plays in shaping the future of manufacturing and ensuring the well-being of consumers worldwide. The average cost of HPP is estimated to be around US$0.05–0.5 per liter or kilogram, depending on processing conditions, and this cost range is noted to be lower than thermal processing costs [6]. A recent survey conducted by Khouryieh (2021) found that HPP emerged as the preeminent novel processing method within the food industry, boasting an impressive 35.6% dominance [7]. This finding underscores the growing significance of HPP as a technology of choice for food manufacturers, catering to the evolving needs and preferences of consumers in today's dynamic market landscape.

While nonthermal novel methods, such as high-pressure processing, have garnered significant attention due to their potential to enhance the nutritional value and sensory attributes of food products, extend shelf-life, and enhance safety, it is crucial to acknowledge that these techniques may exhibit certain limitations and deficiencies [1]. For instance, although HPP can enhance the microbiological safety of food [8, 9], it has the potential to alter the texture and flavor profiles of specific food items [10]. Hence, it is imperative to conduct a comprehensive assessment of the advantages and drawbacks associated with each nonthermal process to ascertain their holistic impact on food quality and safety. It also remains of paramount importance to meticulously scrutinize the ramifications of this pioneering technique on the quality and safety profiles of food items. Therefore, this review aimed to thoroughly assess the profound impact of innovative non-thermal HPP techniques on the realms of food quality and safety. This review was poised to scrutinize both the achievements and shortcomings of HPP technique in recent years, delving into an array of innovative approaches for its application across diverse food categories. Through an exhaustive analysis of recent literature, this review aims to serve as a guiding compass for forthcoming research endeavors of HPP.

2. BASIC PRINCIPLES AND PROCESS DESCRIPTION OF HPP

2.1. Principles

The three fundamental governing principles behind HPP are the isostatic principle, Le Chatelier's principle, and the microscopic ordering principle [11-13]. The isostatic principle posits that the uniform application of pressure acts equally in all directions. In HPP applications, pressure is instantaneously and homogeneously transmitted throughout a sample, regardless of the size and shape of the food. Le Chatelier's principle elucidates changes to equilibrium resulting from pressure application. It states that any phenomenon (such as phase transition, conformational change, or chemical reaction) under equilibrium conditions will undergo a reaction change accompanied by a decrease in volume when subjected to increased pressure, and vice versa. If pressure changes, the equilibrium shifts in a direction that tends to reduce the change in the corresponding volume. Consequently, pressure shifts the system towards the state of lowest volume. Finally, the principle of microscopic ordering describes the enhancement of the molecular ordering of material. At a constant temperature, increasing the pressure simultaneously increases the degree of ordering of the molecules of a substance.

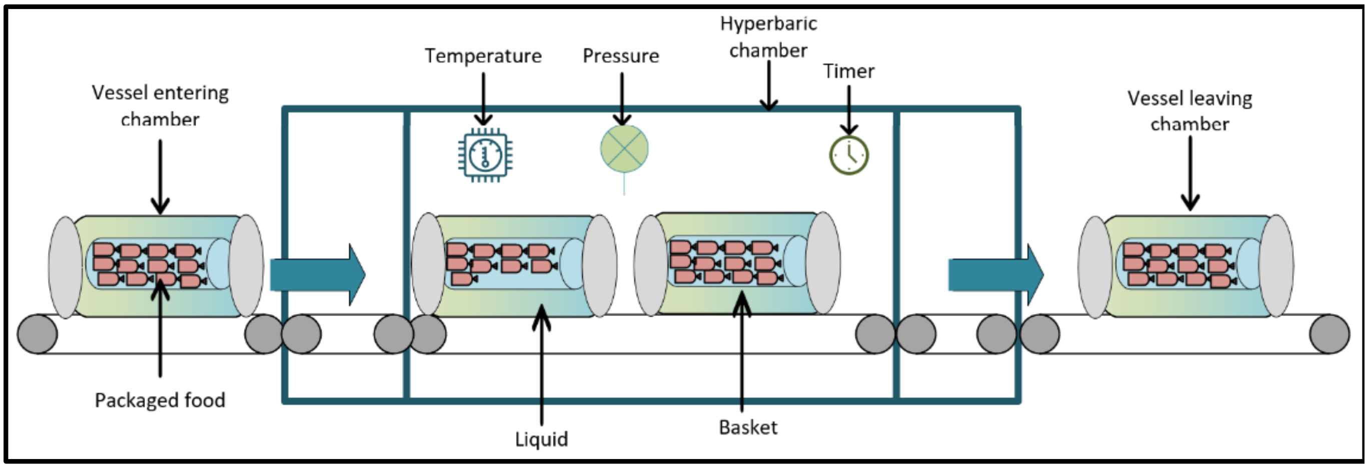

Fig. (1). Schematic representation of a high pressure processing (HPP) chamber.

2.2. Process of HPP

HPP generally utilizes pressures ranging from 100 to 800 MPa to kill various pathogenic and spoilage microorganisms to ensure food safety [12, 14]. During HPP, a food product is enclosed in an airtight, sealed, flexible container or package (Fig. **1**). Packages should be flexible containers since they can break if they cannot handle the high pressures produced within the HPP chamber. Packages typically used are plastic bottles or vacuum sealed packages. Following the packaging process, the product-contained package is then placed in a basket, which, in turn, is positioned within a hyperbaric vessel. This meticulous procedure ensures the product's integrity and safety during HPP. Once the vessel is situated in the chamber, pumps initiate the flow of a pressurized liquid, typically water or another hydraulic fluid, through the vessel. The water pressure can reach up to approximately 600 MPa in most commercial HPP equipment, but some equipment is capable of achieving up to 1,400 MPa [15]. However, the pressure applied usually leads to approximately 2–3˚C per 100 MPa rise in the temperature of water [16]. Upon achieving the desired pressure, the liquid flow is halted, maintaining the pressure for s short period of time, typically a few minutes. Then, the pressure is released, and the vessel is moved out of the chamber, allowing the extraction of individual packages. To ensure sustainability, the water or fluid used remains in the chamber, ready to be recycled and employed in subsequent batches.

3. EFFECT OF HPP ON THE SAFETY AND QUALITY PROPERTIES OF FRUITS, VEGETABLES, AND JUICES

Thermal treatments to preserve produce often led to unwanted changes in the makeup and consistency of the product [17]. In some applications, the desired end-sate may involve cooking or heating the material, meaning that traditional thermal processing is acceptable. However, many other applications prefer fruits and vegetables in as close to a state of freshness as possible. In a study of processing strawberry juice, HPP yielded the same microbial quality as thermal processing, indicating success in the safety of its application [17]. This study also found that the HPP treatment resulted in retained or enhanced quality attributes of strawberry juice compared to conventional thermal processing. It was demonstrated that HPP could develop a preferable product for consumers than strawberry juice processed using traditional methods. The application of HPP to strawberry juice and its puree was investigated [18, 19]. An effective reduction of total aerobic bacteria (TAB) and yeast and mold (Y&M), allowing for a shelf-life in cold storage for up to 49 d for both strawberry juice and puree was found [18]. HPP treatment effectively reduced surrogate compounds that represented norovirus and hepatitis A, leading causes of foodborne illness in the U.S., in strawberry juice and puree [18]. The HPP application to strawberry puree alone was investigated [20], focusing on its impact on quality attributes and shelf-life during cold storage compared to puree thermally processed. The study examined the samples in cold storage for twelve weeks. The results showed that HPP-treated puree had a shelf-life of six weeks, as there was a significant loss of vitamins at the end of the twelve weeks. After six weeks, the HPP-treated samples had higher levels of anthocyanins and polyphenols [20].

HPP applied to mulberry juice was found to effectively inactivate TAB and Y&M while the juice maintained better antioxidant properties and color properties compared to thermal treatment with a shelf-life of up to 28 d [21]. These results were identical in a similar study of carambola (starfruit) juice, where the initial concern was that there could be a more significant impact due to its unique microbial fermentation [22]. While HPP and thermal processing could extend the shelf life of cloudy hawthorn berry juice by up to 150 d in cold storage, HPP produced better results in maintaining the volatility of fruity aromas, color, antioxidant properties, and viscosity while reducing the time needed for processing [23]. The successful application of HPP to these many different fruit juices demonstrated not only the ability to reduce TAB and Y&M in many cases successfully but also HPP's ability to enhance many of the quality attributes of the fruit juices. These results demonstrate the vast potential for safely improving the quality of marketed products compared to traditional thermal processing.

Other studies determined the sensorial quality of HPP applications contrasted against thermal processing and found that HPP is the best application to retain fresh-like qualities

[24, 25]. HPP product was found to be the closest to fresh orange juice in viscosity, color, antioxidants, ascorbic acid, and sensory parameters [24]. An orange juice processed by HPP was found to have the closest to fresh-like sensory attributes [25]. This study also examined apple juice and found that the member panel split preference between HPP and thermal processing, where thermal processing resulted in aromas consisting of vanilla and apple while HPP resulted in aromas of kiwi and raspberry that were preferred [25]. This split in the results exhibits the probable need to have consumer panels conduct final testing on fruit and flavor combinations to determine which processes may be best for use in the final products.

HPP application to apple juice was proven more effective at retaining aroma-relevant volatiles than thermal treatment methods after processing and throughout a refrigerated storage period [26]. The effects of HPP applied to pineapple juice against thermal processing was investigated by [27]. The pineapple juice submitted to HPP retained more color, bioactive components, antioxidant activity, and volatile compounds over thermal processing, even though both methods impacted these characteristics. In a comparison between HPP and thermal treatment of apple puree, Rinaldi *et al.* [28] found that HPP showed less of a difference in viscosity and consistency, color, ascorbic acid, and total phenolic content. Further, the study used a consumer panel for sensory analysis and found that HPP obtained a favorable response compared to the thermally treated product [21]. Gold and green kiwifruit puree treated with HPP and thermal processing had no apparent impact between the two regarding sugars or organic acids, yet ultimately found HPP puree to more closely resemble the fresh control product after comparing color, vitamin C, and many volatile compounds [29]. Passionfruit puree treated with HPP retained its color better with a higher level of antioxidants while having a higher similarity in descriptive sensory profiles as the control sample versus the processes that used thermal methods to treat the puree [30].

Blueberries were successfully stored for at least 28 d following HPP treatment compared to freshly stored blueberries, which started to degrade after 7 d through their natural metabolism [31]. The blueberries processed at 600 MPa retained their moisture content and hardness better than the sample processed at 200 MPa. This study did not examine the microbial content for any of the samples. While other studies demonstrated the efficacy of HPP for achieving a reduction of pathogens, mainly when processed at higher pressures, this leaves microbial safety as a visual assumption through the lack of product breakdown or growth. Further, the study did not examine the impact of treatment on the nutritional composition of the blueberries after processing, which could lead manufacturers and consumers to be reluctant to adopt the process. However, this study successfully demonstrated that the blueberries retained their hardness and sensorial quality to the point that respondents could not determine the processed berries versus a control [31]. The success of HPP in this study demonstrates excellent strides in delivering desirable food products to consumers. It also reflects the potential for reducing a large amount of food wasted through spoilage.

Contaminated beetroot and carrot juice had HPP applied in a manner that created sublethal injuries to the pathogens to examine the survival rate and the potential for the pathogens to regenerate [32]. The study found that carrot juice submitted to HPP treatment supported the growth and regeneration of the sublethally injured *Listeria innocua*, while beetroot juice was considered safe. Further, the study determined a need to refrigerate these juices following treatment to prevent the regeneration of harmful pathogens. HPP applications to cauliflower demonstrated that it could be treated and stored for up to twenty-eight days with minimal impact on color and firmness [33]. This study found that the process did reduce the nutritional quality of the cauliflower, yet it only examined the nutritional value of one test sample for its entire study. The results of this research on cauliflower suggest a need for further analysis using a combination of methods to reach a more conclusive result, as there is likely a combination of treatments that can better store cauliflower while possibly preserving nutrients and sensory qualities [33]. The impact of HPP treatment on zucchini slices compared to thermal treatments was found to have a more significant effect on the color, causing it to be darker than other treatments [34]. Their examination concluded that a combination treatment of low pressures and short times with thermal variables might lead to the best results in the future.

In broccoli hummus, HPP outperformed microwave treatment after 28 d following treatment [35]. These results occurred following a study that looked at total phenolic content, total antioxidant content, and microbial analysis in addition to a sensory panel. HPP outperformed thermal treatment in all these areas. HPP applications in white wine found no influence on the sensory attributes of taste, odor, and overall quality, indicating the possibility that winemakers may no longer need to add sulfur dioxide to raw grapes and retain qualities similar to untreated wines [36]. In application to a multi-fruit smoothie, HPP enabled better sensory properties and higher nutritional quality compared to thermal treatment yet failed to eliminate enzyme activity that would likely limit shelf-life [37]. Further research on eliminating those specific enzymes without the undesirable side effects of thermal processing is necessary before the application can succeed.

Qualitative retention is essentially non-existent if the novel technology cannot ensure the safe consumption of the product across the entire industry. The critical dearth of research on pathogen inactivation and, consequently, the safe storage and extended shelf-life of vegetables underscores the urgent need for more investigation. The absence of in-depth studies concerning the attributes of carrots that support pathogen regeneration underlines the necessity for a comprehensive inquiry. Discovering the underlying cause of this phenomenon could have far-reaching implications for fruit and vegetable products with similar characteristics. Prior to implementing this technology on an industrial scale for widespread use in the vegetable industry, an extensive body of research is imperative. Nevertheless, the majority of available research strongly suggests that HPP significantly improves the qualitative attributes of produce and offers a practical solution to meet consumer demands for products that closely mimic freshness. Table **2** succinctly summarizes the results of the reviewed studies, highlighting a prevalence of successful outcomes rather than failures.

Table 2. HPP impact on the safety and quality of produce and juice products.

Food Product	Microbial Inactivation	Shelf-Life	Quality Impacts	References
Strawberry juice	equivalent to thermal	N/M	enhanced *vs.* thermal	[17]
Strawberry juice/ strawberry puree	effective reduction of TAB and Y&M	49 d in cold storage	reduced *vs.* control	[18]
Strawberry juice/ strawberry puree	effective reduction of Norovirus and Hepatitis A	N/M	N/M	[19]
Strawberry puree	N/M	six weeks in cold storage	enhanced *vs.* thermal	[20]
Mulberry juice	effective reduction of TAB and Y&M	refrigerated and ambient storage up to 28 d	enhanced *vs.* thermal	[21]
Carambola (starfruit) juice	effective reduction of TAB, E-Coli, and Y&M	40 d in cold storage	enhanced *vs.* thermal	[22]
Cloudy hawthorne berry juice	effective reduction of TAB and Y&M	150 d in cold storage	enhanced *vs.* thermal	[23]
Orange juice	N/M	N/M	enhanced *vs.* thermal	[24]
Orange juice	N/M	N/M	enhanced *vs.* thermal	[25]
Apple juice	N/M	N/M	split by consumer preference	[25]
Apple juice	N/M	N/M	enhanced *vs.* thermal	[26]
Pineapple juice	effective reduction of TAB and Y&M	21 d in cold storage	enhanced *vs.* thermal	[27]
Apple puree	N/M	N/M	enhanced *vs.* thermal	[28]
Gold & green kiwifruit	N/M	N/M	enhanced *vs.* thermal	[29]
Passionfruit puree	effective reduction of TAB and Y&M	N/M	enhanced *vs.* thermal	[30]
Blueberries	N/M	28 d in cold storage	better than control (lasted 7 days)	[31]
Beetroot juice	effective reduction of pathogenic bacteria	need for cold storage	N/M	[32]
Carrot juice	ineffective	N/M	N/M	[33]
Cauliflower	N/M	up to 28 d in cold storage	reduced nutritional quality	[34]
Zucchini slices	N/M	N/M	darker color	[35]
Broccoli hummus	N/M	N/M	enhanced *vs.* thermal	[36]
White wine	N/M	N/M	none *vs* control	[37]
Multi-fruit smoothie	N/M	Failed to eliminate spoilage enzyme	enhanced *vs* control	[38]

Abbreviation: N/M =Not mentioned.

4. EFFECT OF HPP ON THE SAFETY AND QUALITY PROPERTIES OF MILK AND DAIRY PRODUCTS

Milk is a prevalent dairy product. Although HPP was initially utilized in the milk industry, its industrial relevance in the dairy sector remains limited to this day, with only a few applications for dairy products, despite the existence of patents related to milk and dairy products. One plausible explanation for this scarcity of dairy product applications is the observed impact of HHP on various constituents of milk [38]. HPP demonstrated effective reduction of most undesirable enzymes from milk but only under the most intense treatments of the process [39]. While this study found the method capable of retaining much of the nutritional values lost during conventional thermal pasteurization, it also found that HPP can lead to reductions or damages in casein proteins that impact the milk quality. A study performed by

Wang and Moraru [40], where they investigated the impact of HPP on structural properties of milk protein content concerning pH and calcium content, found similar results. Their study found that pH levels and calcium significantly affect the structures created in milk protein content. Their analysis leads to potential applications of the technology for use in prepared foods where there would be a desire to retain milk's nutritional value and protein in shelf-stable products. However, a different study found that HPP applied at 600 MPa for three minutes significantly reduced many pathogens in raw milk and extended the shelf life by one week over that of traditionally pasteurized milk [41]. This study confirmed a theory that protein concentrations demonstrated an impact on whether larger or smaller particle sizes occurred following HPP treatment. This result was that a lower milk protein concentration of 2.5% resulted in progressively smaller particle sizes, while a higher protein concentration of 10% resulted in progressively larger particle sizes. In skim milk, HPP was effective in reducing the total bacteria count and could destroy *Escherichia coli* in HPP applications of 400MPa for 15 minutes and above [42]. In application to raw bovine milk, HPP did not reduce particle size but did increase viscosity, creaming, and lipase activity compared to raw milk, while thermal treatment resulted in a slight reduction of particle size and creaming [43]. The study found that a combination treatment using pressure and moderate temperatures provided the best results for quality attributes in milk. In a sensory analysis, 90% of the panelists could differentiate between HPP and thermally processed milk, and 61% preferred HPP-treated milk [44]. In this sensory analysis, the panelists evaluated color, milkiness, creaminess, mouthfeel, and aftertaste, where HPP scored higher in mouthfeel and aftertaste. In contrast, thermal treatment scored higher for color, milkiness, and creaminess. These results demonstrate that the process type could depend on the attributes the manufacturer may desire in an end product. The desire for specific features is especially true if the milk processed is not for direct consumption.

The application of HPP to bloomy rind cheeses did not retain the physical quality and characteristics of the cheese [45]. However, the application of HPP during the aging process was proven effective at reducing the effect of the pathogenic microbiological injected into the product for examination. These findings demonstrate the effectiveness of the safety of the HPP technique. However, the process needs refinement because creating a nonthermal technique capable of exerting substantial pressure without compromising the physical characteristics would enable safer and more efficient production, leading to better consumer satisfaction. Kapoor *et al.* [46] examined the impact of HPP application throughout different stages in the production of Indian cottage cheese (Paneer) made from bovine milk. The raw bovine milk was treated by HPP or thermal pasteurization before being processed into the cheese. After pasteurizing the milk, they were processed into two batches of cheese. Each of the two batches was then split into three parts and vacuum packaged where one was left alone, one treated with HPP, and one dipped in 2% lactic acid and then treated with HPP. HPP treatment of the milk before making the cheese did not significantly impact the shelf-life or microbiological quality. At the same time, HPP applied to the vacuum-packaged product extended the shelf-life to three weeks, and the samples dipped in lactic acid had their shelf-life extended throughout the four-week study. While it did raise the shelf-life to four weeks, the samples did have a higher hardness, more moisture expulsion, and a higher level of yellow color [46]. In yogurt containing probiotic bacteria, HPP applied during the final stages demonstrated no loss in viability throughout 28 d in refrigerated storage [47]. This testing examined results on the most baro-sensitive bacteria and indicated that HPP application would not eliminate other probiotic bacteria.

When used as a standalone process for milk intended for regular consumption, HPP often falls short of delivering a product of satisfactory quality. However, a higher rate of success is observed when HPP is employed as a pretreatment step before milk is incorporated into other products or in products manufactured using milk as a primary ingredient. On the other hand, HPP has found successful application in the preservation of dairy products like cheese, effectively inactivating pathogenic microorganisms. Table **3** succinctly encapsulates the outcomes, revealing that several products exhibit quality characteristics that are inferior to the control or traditional standards.

5. EFFECT OF HPP ON THE SAFETY AND QUALITY PROPERTIES OF MEAT AND MEAT PRODUCTS

As a naturally highly perishable food with a low shelf-life, meats present a potentially vast market for a successful method of extending that shelf-life. The meat industry has long embraced the use of HPP, specifically, in the Ready-to-Eat (RTE) meat products sector [48] Numerous studies have highlighted the effectiveness of HPP in enhancing the safety of both raw meat and meat products. A study of fresh chicken filets applied with HPP found that the process successfully reduced the spoiling and the pathogenic bacteria in the fillets [49]. While the study focused on the safety analysis through the removal of pathogens, they also submitted the treated chicken fillets to a sensory panel for feedback, using control to evaluate the product on color, smell, and taste with a scoring system that indicated acceptability. Unacceptable was characterized by products considered to be beyond shelf-life. The HPP-treated meat had a lighter color than the control in raw form. However, when cooked, the color appeared similar between the two. More importantly, the juiciness and coherence of the HPP-treated samples were rated higher better than the control by all sensory panel members. Radovčić *et al.* [50] conducted a similar study on chicken breast. However, this study used instrumentation to evaluate sensory details vice an evaluation panel. The results of this study also yielded an elimination of pathogenic bacteria, which increased in elimination as pressure and time increased. Treated chicken breast demonstrated a color change when compared to the control. These results are like previously reviewed studies. However, this study recorded machine-read measurements that translated to a lighter color. The cooking yield was unaffected by the treatment with HPP. Water-holding capacity measurements are a method to determine the moistness of the chicken breasts. There was increased moisture content for the chicken breasts treated under higher pressure. To assess the texture values of the

Table 3. HPP impact on the quality and safety of milk and dairy products.

Food Product	Microbial Inactivation	Shelf-Life	Quality Impacts	References
Milk	reduced undesirable enzymes	N/M	degraded casein proteins	[39]
Milk	N/M	N/M	degraded milk proteins	[40]
Milk	significant reduction in pathogens	extended by 1 week	degraded milk proteins	[41]
Skim milk	reduced bacterial count and destroyed E. coli	N/M	N/M	[42]
Raw bovine milk	N/M	N/M	reduced particle size and creaming	[43]
Raw bovine milk	N/M	N/M	enhanced *vs.* thermal	[44]
Bloomy rind cheese	effective reduction of pathogenic bacteria	N/M	unsatisfactory quality	[45]
Indian cottage cheese (Paneer)	effective reduction of TAB and Y&M	did not extend	none *vs* control	[46]
Probiotic yogurt	reduced pathogens while retaining probiotics	28 days in cold storage	no loss in viability	[47]

Abbreviation: N/M =Not mentioned.

samples, the researchers looked at hardness, chewiness, elasticity, and shear force. The application of low pressure had the effect of tenderizing the meat and lowering hardness and chewiness compared to the control. However, higher pressures gave higher hardness, chewiness, and shear force readings than the control sample. This result would indicate the need for further research.

Lee *et al*. [51] investigated the impacts of HPP applied at varying levels on raw blue marlin compared to a control sample. In appearance, blue marlin is a pinkish color, and the application of HPP caused it to lose this pigment and turn ever closer to white as the pressure applied increased. The meat's hardness, cohesiveness, and chewiness directly correlated to increased pressure for texture. The aerobic plate count, which represents the number of bacteria in the sample, saw a reduction in value as the pressure used increased. Included in this study was the examination of histamine values concerning HPP. Histamine values reached a significantly low value after 300 MPa of pressure were applied to represent a potential future use in preventing allergy poisoning related to fish consumption. A different research conducted on yellowfin tuna produced similar results [52]. HPP application to crab claw meat was a viable technique for preparing the meat to be sold as ready-to-eat or ready-to-cook as it presented no discolorations while also successfully inactivating bacteria within the samples [53]. In Asian hard clams, HPP was capable of 100% shucking and in the reduction of pathogenic bacteria, while there was an increase in the whiteness and hardness of the product [54]. Chorizo dry fermented sausage with HPP applied early in the fermentation process had a successful reduction of microbial loads and produced a product preferred over the standard treatment method by panelists [55]. Low-salt emulsified beef sausage treated with HPP before cooking, researched by Zhu *et al.* (2022), was effective from a microbiological and sensory perspective. For the quality analysis of this study, the researchers used machines to develop a texture profile analysis and a human member panel to evaluate the sensory properties. This study aimed to see if HPP could replace the high salt content of traditional methods. The treatment successfully reduced microbial pathogens for applied pressures above 100 MPa. A sensory panel assessed the meat based on appearance, flavor, and eating texture for sensory quality. The HPP treated with 200 MPa was rated highest and found acceptable by the panel with statistical results much like the control sample, which was processed using high salt content. This research indicates market potential where people must reduce sodium intake and illustrates a potential market for future applications.

The application of HPP in the realm of meat production has yielded diverse outcomes concerning product quality. In instances where measurement was conducted, it was observed that HPP effectively diminished microbial loads, rendering it a viable tool for extending the shelf-life of meat products. However, it is crucial to acknowledge that its influence on product quality remains a significant concern, potentially hampering consumer acceptance due to the prevailing consumer preference for fresher products. Table **4** briefly summarizes the various applications of HPP and underscores both areas where it enhances quality and instances where it impairs product quality.

CONCLUSION AND PROSPECTS

Based on the recently reviewed literature, it is evident that HPP has been showing great potential in enhancing the safety and quality of food products. This technology has been effective in inactivating spoilage and pathogenic bacteria without significantly impacting food quality or even enhancing it in some food cases. However, it should be noted that not all applications have been successful, with dairy products being the most challenging. The industrial adoption of this technology in the dairy sector remains limited with a few applications for dairy products having been developed so far, possibly due to the broad impact HHP has on various components of milk. When applied to milk intended for direct consumption, HPP may not consistently deliver a product of satisfactory quality. Yet, it finds more success when used as a pre-treatment step before milk is incorporated into other products or when milk is a primary ingredient. In meat products, the application of HPP has yielded diverse outcomes, with a notable reduction in microbial loads and extended shelf-life in products where

Table 4. HPP impact on the quality and safety of meat products.

Food Product	Microbial Inactivation	Shelf-Life	Quality Impacts	References
Chicken filets	effective reduction in spoilage and pathogenic bacteria	N/M	enhanced *vs* control	[49]
Chicken breast	effective reduction in pathogenic bacteria	N/M	lighter color, lower harness & chewiness	[50]
Raw blue marlin	effective reduction of TAB; histamines significantly reduced	N/M	increased hardness, cohesiveness, & chewiness	[51]
Yellowfin tuna	effective reduction of TAB; histamines significantly reduced	N/M	increased hardness, cohesiveness, & chewiness	[52]
Crab claw meat	effective inactivation of bacteria	N/M	no impacts	[53]
Asian hard clams	effective reduction in pathogenic bacteria	N/M	increased harness & whiteness	[54]
Chorizo (dry-fermented)	successfully reduced bacterial values	N/M	preferred over traditional	[55]
low-salt emulsified beef sausage	effective microbiological values	N/M	results similar to high-salt processed	[56]

Abbreviation: N/M =Not mentioned.

measurements were conducted. Nevertheless, concerns persist regarding its impact on product quality, which may influence consumer acceptance, given the prevailing preference for fresher meat products. The absence of comprehensive studies on the attributes of carrots supporting pathogen regeneration underscores the pressing need for extensive research in this domain. Understanding the underlying causes of this phenomenon holds significant potential implications for a wide range of fruit and vegetable products sharing similar characteristics. Before implementing HPP technology on an industrial scale within the vegetable industry, a robust body of research is imperative. However, existing research overwhelmingly indicates that HPP can substantially enhance the quality of produce, addressing the growing demand for products that closely resemble freshness and improved safety standards.

Although HPP shows great potential in enhancing food safety and prolonging shelf life, its impact on the overall quality of products cannot be overlooked. It is imperative to strike a delicate equilibrium between these advantages and the expectations of consumers. While HPP has proven to be a valuable nonthermal technology, it is not a one-size-fits-all solution. The application of this technology should be undertaken judiciously, taking into account the specific nature of each food product. Factors such as texture, flavor, and nutritional content must be scrutinized in the context of HPP, ensuring that these critical aspects are not compromised. A thorough assessment of product quality, both subjectively and objectively, should be an integral part of any HPP implementation strategy. Future investigations should delve deeper into the intricate dynamics between HPP, food quality, and consumer preferences. This research could encompass a spectrum of methodologies, ranging from sensory evaluations to analytical testing, enabling a comprehensive understanding of the multifaceted impact of HPP on food products to meet the ever-evolving expectations of discerning consumers.

CONSENT FOR PUBLICATION

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest financial or otherwise.

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REFERENCES

[1] Zhang ZH, Wang LH, Zeng XA, Han Z, Brennan CS. Non-thermal technologies and its current and future application in the food industry: A review. Int J Food Sci Technol 2019; 54(1): 1-13. http://dx.doi.org/10.1111/ijfs.13903

[2] Priyadarshini A, Rajauria G, O'Donnell CP, Tiwari BK. Emerging food processing technologies and factors impacting their industrial adoption. Crit Rev Food Sci Nutr 2019; 59(19): 3082-101. http://dx.doi.org/10.1080/10408398.2018.1483890 PMID: 29863891

[3] Koutsoumanis K, Ordóñez AA, Bolton D, *et al.* The efficacy and safety of high-pressure processing of food. EFSA J 2022; 20(3): e07128. http://dx.doi.org/10.2903/j.efsa.2022.7128 PMID: 35281651

[4] Balasubramaniam VM, Cánovas BGV, Lelieveld HLM. High Pressure Processing of Food: Principles, Technology and Applications. New York: Springer 2016. http://dx.doi.org/10.1007/978-1-4939-3234-4

[5] Allied Market Research. High pressure processing equipment market. https://www.alliedmarketresearch.com/press-release/high-pressure-processing-equipment-market.html

[6] Shankar R. High pressure processing- changes in quality characteristic of various food material processed under high pressure technology. Int J Innov Sci Res 2014; 3: 168-86.

[7] Khouryieh HA. Novel and emerging technologies used by the U.S. food processing industry. Innov Food Sci Emerg Technol 2021; 67: 102559.
http://dx.doi.org/10.1016/j.ifset.2020.102559

[8] Aganovic K, Hertel C, Vogel RF, *et al.* Aspects of high hydrostatic pressure food processing: Perspectives on technology and food safety. Compr Rev Food Sci Food Saf 2021; 20(4): 3225-66.
http://dx.doi.org/10.1111/1541-4337.12763 PMID: 34056857

[9] Jadhav HB, Annapure US, Deshmukh RR. Non-thermal technologies for food processing. Front Nutr 2021; 8: 657090.
http://dx.doi.org/10.3389/fnut.2021.657090 PMID: 34169087

[10] Abera G. Review on high-pressure processing of foods. Cogent Food Agric 2019; 5(1): 1568725.
http://dx.doi.org/10.1080/23311932.2019.1568725

[11] Sehrawat R, Kaur BP, Nema PK, Tewari S, Kumar L. Microbial inactivation by high pressure processing: Principle, mechanism and factors responsible. Food Sci Biotechnol 2021; 30(1): 19-35.
http://dx.doi.org/10.1007/s10068-020-00831-6 PMID: 33552614

[12] Balasubramaniam VMB, Monteagudo MSI, Gupta R. Principles and application of high pressure-based technologies in the food industry. Annu Rev Food Sci Technol 2015; 6(1): 435-62.
http://dx.doi.org/10.1146/annurev-food-022814-015539 PMID: 25747234

[13] Yordanov DG, Angelova GV. High pressure processing for foods preserving. Biotechnol Biotechnol Equip 2010; 24(3): 1940-5.
http://dx.doi.org/10.2478/V10133-010-0057-8

[14] Gomez B, Munekata PE, Barba FJ, Pinto CA, Saraiva JA, Lorenzo JM. Influence of high-pressure processing on the nutritional changes of treated foods. In: Knoerzer K, Muthukumarappan K, Eds. Innovative Food Processing Technologies. Elsevier 2021; pp. 74-86.
http://dx.doi.org/10.1016/B978-0-08-100596-5.22928-4

[15] Aguirre BD, Cánovas BGV. An Update on high hydrostatic pressure, from the laboratory to industrial applications. Food Eng Rev 2011; 3(1): 44-61.
http://dx.doi.org/10.1007/s12393-010-9030-4

[16] Balakrishna AK, Wazed MA, Farid M. A review on the effect of high pressure processing (hpp) on gelatinization and infusion of nutrients. Molecules 2020; 25(10): 2369.
http://dx.doi.org/10.3390/molecules25102369 PMID: 32443759

[17] Yildiz S, Pokhrel PR, Unluturk S, Cánovas BGV. Changes in quality characteristics of strawberry juice after equivalent high pressure, ultrasound, and pulsed electric fields processes. Food Eng Rev 2021; 13(3): 601-12.
http://dx.doi.org/10.1007/s12393-020-09250-z

[18] Aaby K, Grimsbo IH, Hovda MB, Rode TM. Effect of high pressure and thermal processing on shelf life and quality of strawberry purée and juice. Food Chem 2018; 260: 115-23.
http://dx.doi.org/10.1016/j.foodchem.2018.03.100 PMID: 29699651

[19] Pan H, Buenconsejo M, Reineke KF, Shieh YC. Effect of process temperature on virus inactivation during high hydrostatic pressure processing of contaminated fruit puree and juice. J Food Prot 2016; 79(9): 1517-26.
http://dx.doi.org/10.4315/0362-028X.JFP-16-004 PMID: 28221934

[20] Marszałek K, Woźniak Ł, Skąpska S, Mitek M. A comparative study of the quality of strawberry purée preserved by continuous microwave heating and conventional thermal pasteurization during long-term cold storage. Food Bioprocess Technol 2016; 9(7): 1100-12.
http://dx.doi.org/10.1007/s11947-016-1698-x

[21] Zou H, Lin T, Bi X, Zhao L, Wang Y, Liao X. Comparison of high hydrostatic pressure, high-pressure carbon dioxide and high-temperature short-time processing on quality of mulberry juice. Food Bioprocess Technol 2016; 9(2): 217-31.
http://dx.doi.org/10.1007/s11947-015-1606-9

[22] Huang HW, Chen BY, Wang CY. Comparison of high pressure and high temperature short time processing on quality of carambola juice during cold storage. J Food Sci Technol 2018; 55(5): 1716-25.
http://dx.doi.org/10.1007/s13197-018-3084-3 PMID: 29666524

[23] Lou X, Jin Y, Tian H, *et al.* High-pressure and thermal processing of cloudy hawthorn berry (Crataegus pinnatifida) juice: Impact on microbial shelf-life, enzyme activity and quality-related attributes. Food Chem 2022; 372: 131313.
http://dx.doi.org/10.1016/j.foodchem.2021.131313 PMID: 34655827

[24] Dhenge R, Langialonga P, Alinovi M, Lolli V, Aldini A, Rinaldi M. Evaluation of quality parameters of orange juice stabilized by two thermal treatments (helical heat exchanger and ohmic heating) and non-thermal (high-pressure processing). Food Control 2022; 141: 109150.
http://dx.doi.org/10.1016/j.foodcont.2022.109150

[25] Song Q, Rune CJB, Thybo AK, Clausen MP, Orlien V, Giacalone D. Sensory quality and consumer perception of high pressure processed orange juice and apple juice. Lebensm Wiss Technol 2023; 173: 114303.
http://dx.doi.org/10.1016/j.lwt.2022.114303

[26] Kebede B, Lee P, Leong S, *et al.* A chemometrics approach comparing volatile changes during the shelf life of apple juice processed by pulsed electric fields, high pressure and thermal pasteurization. Foods 2018; 7(10): 169.
http://dx.doi.org/10.3390/foods7100169 PMID: 30336618

[27] Wu W, Xiao G, Yu Y, *et al.* Effects of high pressure and thermal processing on quality properties and volatile compounds of pineapple fruit juice. Food Control 2021; 130: 108293.
http://dx.doi.org/10.1016/j.foodcont.2021.108293

[28] Rinaldi M, Langialonga P, Dhenge R, Aldini A, Chiavaro E. Quality traits of apple puree treated with conventional, ohmic heating and high-pressure processing. Eur Food Res Technol 2021; 247(7): 1679-88.
http://dx.doi.org/10.1007/s00217-021-03738-6

[29] Yi J, Kebede BT, Grauwet T, Loey VA, Hu X, Hendrickx M. Comparing the impact of high-pressure processing and thermal processing on quality of “hayward” and “jintao” kiwifruit purée: Untargeted headspace fingerprinting and targeted approaches. Food Bioprocess Technol 2016; 9(12): 2059-69.
http://dx.doi.org/10.1007/s11947-016-1783-1

[30] Niu H, Yuan L, Zhou H, *et al.* Comparison of the effects of high pressure processing, pasteurization and high temperature short time on the physicochemical attributes, nutritional quality, aroma profile and sensory characteristics of passion fruit purée. Foods 2022; 11(5): 632.
http://dx.doi.org/10.3390/foods11050632 PMID: 35267265

[31] Scheidt TB, Silva FVM. High pressure processing and storage of blueberries: Effect on fruit hardness. High Press Res 2018; 38(1): 80-9.
http://dx.doi.org/10.1080/08957959.2017.1402895

[32] Nasiłowska J, Sokołowska B, Broczek FM. Long-term storage of vegetable juices treated by high hydrostatic pressure: Assurance of the microbial safety. BioMed Res Int 2018; 2018: 1-12.
http://dx.doi.org/10.1155/2018/7389381 PMID: 30643817

[33] Kurek MA, Finnseth C, Skipnes D, Rode TM. Impact of high-pressure processing (hpp) on selected quality and nutritional parameters of cauliflower (*Brassica oleracea var. Botrytis*). Appl Sci 2022; 12(12): 6013.
http://dx.doi.org/10.3390/app12126013

[34] Paciulli M, Ganino T, Meza IGM, *et al.* High pressure and thermal processing on the quality of zucchini slices. Eur Food Res Technol 2021; 247(2): 475-84.
http://dx.doi.org/10.1007/s00217-020-03640-7

[35] Klug TV, Hernández MGB, Collado E, Artés F, Hernández AF. Effect of microwave and high-pressure processing on quality of an innovative broccoli hummus. Food Bioprocess Technol 2018; 11(8): 1464-77.
http://dx.doi.org/10.1007/s11947-018-2111-8

[36] Labarca BV, Wom PM, Habib G, *et al.* Oenological and quality characteristic on young white wines (*Sauvignon Blanc*): Effects of high hydrostatic pressure processing. J Food Qual 2017; 2017: 1-12.
http://dx.doi.org/10.1155/2017/8524073

[37] Picouet PA, Hurtado A, Jofré A, Bañon S, Ros JM, Guàrdia MD. Effects of thermal and high-pressure treatments on the microbiological, nutritional and sensory quality of a multi-fruit smoothie. Food Bioprocess Technol 2016; 9(7): 1219-32.

http://dx.doi.org/10.1007/s11947-016-1705-2

[38] Trujillo AJ, Ferragut V, Juan B, Sagues RAX, Guamis B. Processing of dairy products utilizing high pressure. High Pressure Processing of Food 2016; 553-90.

[39] Ahmad T, Butt MZ, Aadil RM, *et al.* Impact of nonthermal processing on different milk enzymes. Int J Dairy Technol 2019; 72(4): 481-95.
http://dx.doi.org/10.1111/1471-0307.12622

[40] Wang L, Moraru CI. High-pressure structuring of milk protein concentrate: Effect of pH and calcium. J Dairy Sci 2021; 104(4): 4074-83.
http://dx.doi.org/10.3168/jds.2020-19483 PMID: 33663855

[41] Stratakos AC, Inguglia ES, Linton M, *et al.* Effect of high pressure processing on the safety, shelf life and quality of raw milk. Innov Food Sci Emerg Technol 2019; 52: 325-33.
http://dx.doi.org/10.1016/j.ifset.2019.01.009

[42] Liepa M, Zagorska J, Galoburda R, Kostascuka S. Effect of high-pressure processing on microbial quality of skimmed milk. Proceed Latvia Acad Sci Section B Natural, Exact, and Appl Sci 2018; 72(2): 118-22.
http://dx.doi.org/10.2478/prolas-2018-0019

[43] Janahar JJ, Marciniak A, Balasubramaniam VM, Flores JR, Ting E. Effects of pressure, shear, temperature, and their interactions on selected milk quality attributes. J Dairy Sci 2021; 104(2): 1531-47.
http://dx.doi.org/10.3168/jds.2020-19081 PMID: 33309347

[44] Lim SH, Chin NL, Sulaiman A, Tay CH, Wong TH. Sensory analysis for cow milk product development using high pressure processing (HPP) in the dairy industry. Foods 2022; 11(9): 1233.
http://dx.doi.org/10.3390/foods11091233 PMID: 35563957

[45] Batty D, Goddik ML, Cusic WJG. Camembert-type cheese quality and safety implications in relation to the timing of high-pressure processing during aging. J Dairy Sci 2019; 102(10): 8721-33.
http://dx.doi.org/10.3168/jds.2018-16236 PMID: 31400901

[46] Kapoor S, Singh MP, Vatankhah H, Deshwal GK, Ramaswamy HS. Production and quality improvement of Indian cottage cheese (Paneer) using high pressure processing. Innov Food Sci Emerg Technol 2021; 72: 102746.
http://dx.doi.org/10.1016/j.ifset.2021.102746

[47] Tsevdou M, Rousi OM, Soukoulis C, Taoukis P. Impact of high-pressure process on probiotics: viability kinetics and evaluation of the quality characteristics of probiotic yoghurt. Foods 2020; 9(3): 360.
http://dx.doi.org/10.3390/foods9030360 PMID: 32204574

[48] Meloni D. High-Hydrostatic-Pressure (HHP) processing technology as a novel control method for listeria monocytogenes occurrence in mediterranean-style dry-fermented sausages. Foods 2019; 8(12): 672.
http://dx.doi.org/10.3390/foods8120672 PMID: 31842401

[49] Argyri AA, Papadopoulou OS, Sourri P, Chorianopoulos N, Tassou CC. Quality and safety of fresh chicken fillets after high pressure processing: Survival of indigenous brochothrix thermosphacta and inoculated listeria monocytogenes. Microorganisms 2019; 7(11): 520.
http://dx.doi.org/10.3390/microorganisms7110520 PMID: 31684053

[50] Radovčić N, Ježek D, Markov K, Frece J, Ćurić D, Medić H. The effect of high pressure treatment on the quality of chicken breast meat. Croatian J Food Technol Biotechnol Nutr 2020; 14(3–4): 76-81.

[51] Lee YC, Kung HF, Chen SL, *et al.* Effect of high-pressure treatment on blue marlin (*makaira nigricans*) quality during storage. J Aquat Food Prod Technol 2022; 31(3): 271-84.
http://dx.doi.org/10.1080/10498850.2022.2036886

[52] Tsai YH, Kung HF, Lin CS, *et al.* Impacts of high-pressure processing on quality and shelf-life of yellowfin tuna (Thunnus albacares) stored at 4°C and 15°C. Int J Food Prop 2022; 25(1): 237-51.
http://dx.doi.org/10.1080/10942912.2022.2029483

[53] Lian F, De Conto E, Grippo DV, *et al.* High-pressure processing for the production of added-value claw meat from edible crab (cancer pagurus). Foods 2021; 10(5): 955.
http://dx.doi.org/10.3390/foods10050955 PMID: 33925421

[54] Lin CS, Lee YC, Kung HF, *et al.* Inactivation of microbial loads and retardation of quality loss in Asian hard clam (Meretrix lusoria) using high-hydrostatic-pressure processing during refrigerated storage. Food Control 2022; 133: 108583.
http://dx.doi.org/10.1016/j.foodcont.2021.108583

[55] Dučić M, Barcenilla C, Cobo-Díaz JF, López M, Ordóñez AA, Prieto M. High pressure processing at the early stages of ripening enhances the safety and quality of dry fermented sausages elaborated with or without starter culture. Food Res Int 2023; 163: 112162.
http://dx.doi.org/10.1016/j.foodres.2022.112162 PMID: 36596111

[56] Zhu Y, Yan Y, Yu Z, Wu T, Bennett LE. Effects of high pressure processing on microbial, textural and sensory properties of low-salt emulsified beef sausage. Food Control 2022; 133: 108596.
http://dx.doi.org/10.1016/j.foodcont.2021.108596