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Inactivation of microorganisms by high hydrostatic pressure: A literature review

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Abstract. The use of high hydrostatic pressure is intended to perform non-thermal inactivation of microorganisms in food products, to ensure their freshness and to prevent foodborne infections. These infections impact the healthcare system, the food industry, and consumers directly. This study aims to analyse the literature on the effectiveness of high hydrostatic pressure against pathogenic and opportunistic microorganisms transmitted through the consumption of contaminated food. Scientific publications for 2011-2023 were selected for the review. A total of 44 scientific publications were selected, the information from which was critically analysed, systematised and presented in the form of a literature review. The mechanisms of high hydrostatic pressure's effect on microbial cells are described. To illustrate the effectiveness of high hydrostatic pressure against microorganisms, data from selected publications regarding efficiency and treatment parameters are presented in tables. The inactivation of such clinically important microorganisms as *Bacillus cereus, Campylobacter jejuni, Clostridium perfringens, Escherichia coli, Listeria monocytogenes, Salmonella* spp., *Staphylococcus aureus* and *Toxoplasma gondii* in liquids and food has been demonstrated. High-pressure treatment has been shown to be a non-thermal food processing method, which distinguishes this method from traditional thermal processing methods such as boiling or pasteurization. One of the notable advantages of using high hydrostatic pressure is the non-thermal inactivation of various microorganisms, which preserves the nutritional and flavour properties of the processed product. It is also noted that food products can be processed in the final packaging, which reduces the risk of microbial contamination at the post-processing stages. The main disadvantages are the impossibility of complete inactivation of bacterial spores and the high cost of high-pressure processing equipment. Combining high-pressure treatment with other methods, such as heat treatment, can overcome the limitations of spore inactivation

Keywords: high pressure; pathogens; neutralization; non-thermal processing

INTRODUCTION

Gastrointestinal diseases account for a significant proportion of infections worldwide, and among them, diarrhoeal diseases are the second leading cause of global mortality. Food- and waterborne diseases cause the premature loss of millions of lives annually, most of which are among vulnerable groups such as children [1, 2]. According to S. Chuang *et al.* [3], these diseases not only have devastating health consequences, but also a significant economic impact in many sectors, including healthcare systems, tourism, food industry, and consumer welfare. While setting and enforcing regulatory standards and guidelines is a means of reducing food contamination by pathogens [4], the importance of effective food processing and preservation methods cannot be overstated. These methods have been used since ancient times and have a dual purpose: to contain the spread of pathogens responsible for foodborne infections, as well as to control microorganisms that cause spoilage and degrade food quality. The historical range of food processing and preservation methods includes heating, salting, freezing, drying, freeze-drying, fermentation, canning, and the use of antimicrobial agents. In addition, modern advances have added new processing methods, such as ionization radiation, pulsed electric fields, ohmic processing, ultraviolet light disinfection,

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and high-pressure processing (HPP) [5, 6]. Since the late 1990s, HPP has become a convincing and commercially feasible alternative for food processing [7]. This trend is driven by the growing consumer demand for food products that are not only microbiologically safe, but also retain their freshness and nutritional value [8].

Despite significant efforts to improve food safety, foodborne illness outbreaks associated with pathogenic bacteria reaching dangerous levels in food have been widely documented [9]. Bacteria can contaminate food at any stage during harvesting, processing, storage, and transportation, as well as during food preparation in restaurants or kitchens. According to the Centres for Disease Control and Prevention (USA), which is cited by M. Al-Mamun *et al.* [10], the pathogens that most often cause foodborne infections leading to hospitalization and death are *Salmonella* spp.*, Staphylococcus aureus, Listeria monocytogenes, Escherichia coli* (most often of the O157:H7 serotype), *Campylobacter* spp., *Clostridium perfringens,* and *Toxoplasma gondii*. These pathogens are pathogenic or opportunistic microorganisms that demonstrate the ability to persist or even multiply in various food substrates, making them an important foodborne hazard. This highlights the need to implement technological measures to effectively mitigate the food safety risks associated with these pathogens. Among the various methods, HPP treatment has been comprehensively studied in research aimed at neutralizing these infectious threats to improve food safety.

In the Ukrainian-language scientific literature up to 2023, high-pressure treatment is mentioned as one of the methods of improving food quality. In particular, T. Lozova [11] mentions ultra-high-pressure treatment to improve the quality and storage of bread. In the work of I. Bernyk *et al.* [12], high-pressure treatment is used to saturate meat raw materials with substances, including table salt. In this publication, high pressure is also mentioned as an alternative to heat treatment, but there are no microbiological data, the authors focus on the consistency and organoleptic properties of the product. The lack of Ukrainian scientific works and the positive results of world scientists on the inactivation of pathogens and microorganisms that cause food spoilage make this area of research interesting and promising. The purpose of this manuscript was to bring together data from various English-language scientific studies that both highlight the potential of HPP as a method of inactivating a wide range of microorganisms and reveal limitations to its use.

Google Scholar was used to search for literature sources. The literature was searched using a combination of keywords: "high-pressure processing", "high hydrostatic pressure", "inactivation", "log reduction", "bacteria", "fungi", "protozoa". The English-language literature sources for 2011-2023 were reviewed. Preference was given to articles describing high hydrostatic pressure treatment alone without the use of combined treatment with other non-thermal or thermal methods. Data on high-pressure treatment alone were selected from publications with several types of treatment or combined treatment. Articles with a focus on pathogenic and opportunistic microorganisms that cause disease were selected; articles on the inactivation of microorganisms that cause food spoilage were excluded. Book chapters, dissertations, and reports or abstracts from scientific conferences were not considered. Both open-access articles and articles from paid resources were reviewed. The data from the selected publications were systematised by the consistency of high-pressure processed foods and entered into the relevant tables.

EFFECT OF HIGH HYDROSTATIC PRESSURE ON PATHOGENS AND FEATURES OF ITS APPLICATION

HPP is a non-thermal treatment method that involves subjecting food products, beverages, or other materials to elevated pressure in the range of 100 to 1000 MPa, usually at room temperature or slightly higher [13]. This process is also known as ultra-high-pressure processing (UHP). HPP is known to inactivate various microorganisms, including bacteria, viruses, yeast, mould, as well as enzymes, while preserving the nutritional and taste properties of the processed product [1, 14, 15]. It is noted that HPP does not break covalent bonds, so changes in low-molecular-weight compounds such as vitamins, pigments, and flavourings are minimal [16].

The mechanism of microbial inactivation by HPP is not fully understood, but it is considered to be multifactorial. R. Levy *et al.* [6] mention that one influencing factor is the denaturation of proteins and enzymes, leading to the disruption of structures and functions of the affected by pressure cells. Hydrostatic effects induce mechanical stress on cellular structures, causing deformation and damage to cell membranes; the loss of membrane integrity contributes to cell death [17, 18]. Damage to bacterial cell membranes by high pressure induces intracellular oxidative stress [19, 20]. S. Ceuppens *et al.* [21] point out that another important factor is the impact on nucleic acids. Although they are much less sensitive to high-pressure effects compared to flexible lipid membranes, hydrogen bonds that maintain their spiral structure can be disrupted under high pressure [22]. Thus, pressure-induced structural changes in deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) molecules may interfere with DNA replication, transcription, and translation.

The mechanisms of impact of HPP are particularly effective against the vegetative cells of microorganisms, but processing without additional thermal treatment cannot completely inactivate bacterial spores, whose dense shells make them resistant to many processing methods [23, 24]. However, research by M.R. Sarker *et al.* [25] has shown that high pressure can trigger the germination of *Bacillus* spp. bacterial spores, making them susceptible to further treatments. J.H. Mok *et al.* [26] also indicated better processing efficiency with multiple pressurization-depressurization cycles compared to a single-cycle treatment of the same duration.

High-pressure processing is considered a non-thermal method for treating food products, despite the adiabatic temperature increase that occurs during pressure application to physical objects. For juices and other beverages, the temperature increase is 3°C for every 100 MPa at the initial product temperature of 25°C [13]. However, this temperature increase is temporary and local, lasting only during the pressure application period. When the pressure is released, the temperature also decreases and may even drop below the initial temperature if heat exchange occurs between the processed product and the elements of the high-pressure chamber. Additionally, as mentioned by M. de Alba *et al.* [15], processing can be carried out with additional cooling of the high-pressure chamber jacket. This distinguishes this method from traditional thermal processing methods, such as boiling or pasteurization, where the entire product is subjected to heating by external heat sources over an extended period, leading to a uniform temperature increase. Although the temperature increase caused by pressure does occur, it is not the primary means of achieving microbial inactivation. This processing method minimizes the impact of heat on sensitive nutrients, flavourings, and other desirable product properties that may be reduced or lost through prolonged exposure to elevated temperatures [15, 16]. Y. Zhou *et al.* [27] report that HPP can be performed in the final packaging, minimizing the risk of microbial contamination of the food product after processing. Inactivation of microorganisms slows down the spoilage of products, thereby extending their shelf life. T. Rode *et al.* [28] reported an increase in the shelf life of fresh fish processed with HPP at 200 and 500 MPa for 120 seconds. K. Aaby *et al.* [29] reported an extension of the shelf life of strawberry purée and juice when using 400-600 MPa for 1.5-3 minutes, and noted that HPP is better suited for products with a lower initial level of enzymes compared to thermal processing.

The practical application of HPP may be constrained by several factors that food industry companies need to consider. Among these factors is the cost of equipment: HPP requires specialised equipment capable of generating and withstanding high pressure. These devices are typically expensive to purchase and maintain. For small food product manufacturers or businesses with limited budgets, the cost of acquiring HPP equipment can be a significant barrier to implementing this technology [14]. Another factor is the potential change in product texture. Some food products may become softer or undergo other structural changes. For certain food products, such as fruits and vegetables, this change may be acceptable or even desirable. However, for others, especially those valued for their specific texture, such as certain cheeses or bakery products, these changes may be undesirable and limit the application of HPP [30]. High-pressure processing is typically conducted in a high-pressure chamber. To withstand the pressure, food products must be packaged in packaging made of robust and flexible materials [31]. As noted by H.W. Huang *et al.* [14], the packaging material used in HPP must have a compressibility of at least 15%, making only plastic packaging materials suitable for such processing. V.M.B. Balasubramaniam *et al.* [32] describe the penetration of propylene glycol into plastic packaging during combined HPP and thermal processing. The same authors report delamination of metal-plastic packaging with the penetration of propylene glycol between the aluminium and plastic layers. Therefore, companies using HPP need to invest not only in equipment but also in appropriate packaging materials.

Due to the direct impact on the structural elements of microbial cells, HPP offers many advantages in the processing of food products. Among them are extended shelf life and improved microbiological safety of food products. However, the practical application of HPP may be limited by a range of factors. Companies must weigh the benefits against financial expenses and potential texture changes to determine whether HPP is suitable for their specific products.

INACTIVATION OF PATHOGENS THAT CAN CAUSE FOOD INFECTIONS

Due to the mechanisms described above, HPP has been effectively applied for the inactivation of microorganisms that can contaminate food products and pose a danger to human health and life. Comparisons of pressure resistance among vegetative cells revealed that, among foodborne pathogens, strains of *Escherichia coli* O157:H7 were the most resistant. The United States Department of Agriculture (USDA) recognizes this strain as an indicator, and the HPP process achieving a 5-log inactivation of this strain is deemed sufficient to ensure the microbial safety of the product [14]. To illustrate the effectiveness of HPP treatment on bacterial suspensions and various liquid food products contaminated with different microorganisms, data from selected publications are compiled in Table 1.

Table 1. Inactivation of microorganisms in liquids and liquid food products by high hydrostatic pressure

Pathogen	Substrate	Pressure (MPa)	Initial temperature (°C)	Processing time (min)	Inactivation (log CFU/mL)	Reference
Bacillus cereus CECT 131 (vegetative cells)	Human milk	379 593,96	10	233 s*	4.62 6.93	[2]
A mixture of strains *Escherichia coli* (NCTC 11601, NCTC 11602, NCTC 11603, NCTC 9706, NCTC 9707)	Raw milk	400	18	1	0,85	[33]
				3	1.1**	
				5	2.2**	
		500		1	0.9**	
				3	1.9**	
				5	2.6**	
		600		1	3.6**	
				3	5.6	
				5	6.8	
Escherichia coli O157:H7 NCTC 12900	Suspension of bacteria in physiological solution	450	Not indicated	5	5.02	[34]

Table 1. Continued

Pathogen	Substrate	Pressure (MPa)	Initial temperature (°C)	Processing time (min)	Inactivation (log CFU/mL)	Reference
A mixture of strains *Listeria monocytogenes* (FMT 1750, NCTC 11994, NCTC 5214, NCTC 10888, NCTC 19118)	Raw milk	400	18	1	1.42	[33]
				3	1.5**	
				5	2.1**	
		500		1	1.6**	
				3	3.1**	
				5	5.48	
		600		1	3.2**	
				3	5.65	
				5	5.91	
A mixture of serovars *Salmonella (*ATCC numbers 13076, 8387, 6962, 9270, 14028)***	Orange juice	103	25	10	0.75	[35]
		241	25	2	0.53	
				4	0.69	
				8	1.44	
				10	1.88	
		380	25	2	2.76	
				4	5.56	
				8	>7	
				10	>7	
Staphylococcus aureus CECT 976	Human milk	379	10	233 s*	2.73	[2]
		593,96			5.81	
Staphylococcus aureus strains CTC 1008	Brain Heart Infusion culture	400	15	10	2.01	[36]
		600	15	10	7.96	
CTC 1019		900	Not indicated	5	>8	
		400	15	10	1.55	
		600	15	10	5.78	
CTC 1021		900	Not indicated	5	>8	
		400	15	10	1.82	
		600	15	10	7.32	
CECT 976		900	Not indicated	5	>8	
		400	15	10	1.81	
		600	15	10	7.79	
CECT 4466		900	Not indicated	5	>8	
		400	15	10	1.94	
		600	15	10	7.90	
		900	Not indicated	5	>8	

Notes: * – units of measurement according to the original publication; ** – data are presented in the form of a graph without specifying exact numbers, the numbers in the table are reproduced approximately; *** – description of the used microorganisms according to the original publication. Strain numbers correspond to *Salmonella enterica* subsp. *enterica* serovar Enteritidis ATCC 13076, *Salmonella enterica* subsp. *enterica* serovar Montevideo ATCC 8387, *Salmonella enterica* subsp. *enterica* serovar Newport ATCC 6962, *Salmonella enterica* subsp. *enterica* serovar Anatum ATCC 9270, *Salmonella enterica* subsp. *enterica* serovar Typhimurium ATCC 14028
Source: compiled by the author based on data collected during the literature review

When processing bacterial cultures of S. *aureus* with an initial concentration of approximately 9 log CFU/mL at a pressure of 400 MPa, A. Jofré *et al.* [36] demonstrated that, with inactivation of 1.55-2.01 log CFU/mL, a portion of microorganisms (up to 1.41 log CFU/mL) were subjected to sublethal damage and did not grow on a selective medium (tryptic soy agar with yeast extract and 10% NaCl). J. Kameník *et al.* [37], in the HPP inactivation of *E. coli* applied to tartare beefsteak, were able to recover sublethally damaged bacteria by inoculating samples into a liquid enrichment medium, regardless of the applied pressure (400 and 600 MPa for 5 minutes). To illustrate the effectiveness of HPP treatment on semi-solid and solid food products contaminated with different microorganisms, data from selected publications are compiled in Table 2.

Table 2. Inactivation of microorganisms in liquids and liquid food products by high hydrostatic pressure

Pathogen	Substrate	Pressure (MPa)	Initial temperature (°C)	Processing time (min)	Inactivation (log CFU/g)	Reference
Campylobacter jejuni	Ground chicken	200 300 400	4	5 10 15 5 10 15 5 10 15	0* 0* 0* 2.7 ≥6.87 ≥6.87 ≥6.87 ≥6.87 ≥6.87	[38]
A mixture of vegetative cells of strains *Clostridium perfringens* type F (KCCM12098, KCCM40946, KCCM40947, KCTC5101)	Emulsion-type pork sausage	500	4	4 cycles of 3 min	1. 9	[39]
A mixture of serovars *Escherichia coli* (O26:H11, O45:H2, O103:H2, O111:NM, O121:H19, O145)	Ground beef	250 350 450	5-7	5 15** 30** 5 15** 30** 5 15**	0.7 1.6 2.3 2.4 3.5 4.7 4.4 5.6	[40]
A mixture of serovars *Escherichia coli* (O91, O146, O153, O156)	Tatar beefsteak	400 600	3±1	5 min of processing + 168 h of storage at 4 °C	1.8 >4.7	[37]
A mixture of strains *Escherichia coli* O157:H7 (ATCC 43888, 43889, 43890, 45756, 11082)	Ground beef	250 350 450	5-7	5 15** 30** 5 15** 30** 5 15**	0.2 0.7 1.0 1.0 2.1 3.2 3.5 6.9	[40]
A mixture of strains *Listeria monocytogenes* (Scott A, 43256, 51742)	Melon purée	400 500	8 15 8 15	5 5	2.9 3.1 5.6 ≥7	[41]
A mixture of strains *Salmonella enterica* (*S.* Poona RM 2350, *S.* Newport H1275, *S.* Stanley H0558)	Melon purée	300 400 500	8 15 8 15 8 15	5 5 5	2.7 3.1 4.8 5.8 ≥7 ≥7	[41]
A mixture of strains *Salmonella Typhimurium* DT 104, *S.* Newport ATCC 6962, *S.* Enteritidis ATCC 13076, *S.* Senftenberg ATCC 8400, *S.* Kentucky FSIS 074	Ground chicken	250 350 450	4-6	15 15 10	0.5 1.7 >5	[9]
Toxoplasma gondii strain VEG	Raw ham cured ham	100-400 600 600	6±1	1 20 3-10 20	Infectious*** Non-infectious Infectious*** Non-infectious	[42]

Notes: * – treatment at 200 MPa did not show statistically significant inactivation; ** – treatment for 15 and 30 minutes consisted of repeated cycles of 5 minutes each; *** – ham samples were tested for infectivity by inoculation of mice with subsequent detection of cysts in their brains

Source: compiled by the author based on data collected during a literature review

The analysed studies indicated that the inactivation of the test strains is proportional to the hydrostatic pressure and treatment time, but it is important to note that the reaction of bacteria to high pressure can vary depending on the species, strain, and physiological state of the bacterial cells. In general, gram-negative bacteria are more sensitive to HPP treatment than gram-positive bacteria. This is due to differences in the structure of the cell wall of these types of bacteria. The outer membrane of gram-negative bacteria contains lipopolysaccharides that are sensitive to high pressure, whereas its absence and a thicker layer of peptidoglycan in the cell walls of gram-positive bacteria provide them with some resistance to damage caused by HPP. However, even within a species, the sensitivity of strains to HPP can vary. For example, Y. Liu *et al.* [19] showed that among 19 strains of *Campylobacter jejuni* inoculated into ground chicken that had been treated with HPP at 300 MPa and 30°C for 3 minutes, the inactivation data varied greatly. The sensitive strains were inactivated within about 3 log CFU/g, while the inactivation of the most resistant C. *jejuni* strain HCJ2316 was only 0.5 log CFU/g. Y. Zhou *et al.* [27] conducted a similar experiment with the laboratory strain of *Escherichia coli* JM109 and six strains of *E. coli* O157:H7 inoculated into ground beef. While high-pressure treatment at 400 MPa and 25°C for 15 minutes inactivated the laboratory strain completely (~8 log CFU/g), the inactivation of the pathogenic strains ranged from 1.57 log CFU/g (strain SEA13B88) to 3.49 log CFU/g (strain WM98A06026). These results emphasize why a single strain should not be used in studies evaluating the effectiveness of the HPP inactivation process.

S.H. Lee *et al.* [39] demonstrated that even with low microbial inactivation by HPP, there was a slowdown in the growth of vegetative cells of *Clostridium perfringens*. After HPP treatment at 500 MPa for 4 cycles of 3 minutes each, a bacterial concentration reduction of 1.9 log CFU/g was achieved. Following this treatment, the bacterial population did not increase for two weeks at 4°C.

Despite the positive results from experiments on the inactivation of various microorganisms by HPP, treated food products are not sterile and should be stored under refrigeration. Sublethally damaged bacterial cells, under appropriate conditions (availability of nutrients, temperature changes, product storage time), may recover and proliferate [43]. In contrast, some researchers have shown that sublethally damaged cells do not recover and die when storage conditions are maintained [44]. For instance, an experiment with a mixture of seven strains of Campylobacter jejuni inoculated in chicken liver demonstrated that HPP at 250 MPa and 4°C for 10 minutes resulted in a 1.3 log CFU inactivation. Storage at 4°C for 1 week led to an additional reduction in the *C. jejuni* population by 1.6 log CFU. Thus, the efficiency of HPP treatment against a wide range of foodborne pathogens has been demonstrated, and HPP technology can be combined with existing processing methods in the food industry to enhance their effects.

CONCLUSIONS

A review of English-language literature demonstrates the effectiveness and wide application of HPP for inactivating pathogenic microorganisms in liquid, semi-solid, solid food products, as well as physiological solutions. The collected data from scientific publications illustrate the potential of this food processing method as a standalone technique and suggest its prospective use in combination with other thermal or non-thermal processing methods. The broad spectrum of high hydrostatic pressure action makes this processing method versatile for controlling vegetative microbial contamination in various food products and beverages, consequently reducing cases of foodborne illnesses or other diseases transmitted through the consumption of contaminated products. Among the processed sources that compared the inactivation of gram-positive and gram-negative microorganisms, results indicated a higher sensitivity of gram-negative microorganisms to HPP treatment, explained by the unique structure of their cell walls containing more pressure-sensitive structures. Inactivation of both types of microorganisms was proportional to the magnitude of hydrostatic pressure and the processing time. In most reviewed sources, HPP was applied without combining it with other processing methods, but there are publications demonstrating its potential enhancement with other methods.

The introduction of high hydrostatic pressure processing technology will reduce the processing time of products, decrease heat-induced changes in products, while preserving natural vitamins, pigments, and flavourings highly valued by consumers. The reduction of microbial contamination, in addition to the improved safety of processed food products, will also extend their shelf life. One drawback of this method is its insufficient efficacy in inactivating bacterial spores, a limitation shared with other non-thermal processing methods and well-known in the scientific community. This limitation can be overcome by combining high hydrostatic pressure processing with other methods. Among other considerations, it is worth mentioning that high-pressure processing is not suitable for all products, but only for those with a homogeneous consistency, ensuring processing uniformity. Products with specific textures or porosity are not suitable for HPP treatment. To ensure quality processing for the packaging of such products, non-toxic flexible material with resistance to compression must be used.

Despite these drawbacks, high hydrostatic pressure processing is a promising technique for enhancing the safety and quality of food products. The results of the review indicate a convincing path for further necessary research and development that meets the evolving demands of both the food industry and consumers. A possible direction for future research is exploring the potential of combining HPP with other thermal and non-thermal methods to inactivate a broader range of pathogens, including spore-forming microorganisms.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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Інактивація мікроорганізмів високим гідростатичним тиском: огляд літератури

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Анотація. Використання високого гідростатичного тиску призначене для здійснення нетермічної інактивації мікроорганізмів у харчових продуктах, забезпечення збереження їх свіжості та запобігання харчовим інфекціям. Останні впливають на систему охорони здоров›я, харчову промисловість та, безпосередньо, на споживачів. Метою даної роботи було проведення аналізу літературних даних стосовно ефективності високого гідростатичного тиску проти патогенних та умовно патогенних мікроорганізмів, які передаються через вживання контамінованої їжі. Для огляду обиралися наукові публікації за 2011-2023 роки. Було обрано 44 наукових публікації, інформацію з яких було критично проаналізовано, систематизовано та оформлено у вигляді огляду літератури. Зазначені механізми впливу високого гідростатичного тиску на клітини мікроорганізмів. Для ілюстрації ефективності високого гідростатичного тиску проти мікроорганізмів дані з вибраних публікацій щодо ефективності та параметрів обробки зібрано у таблицях. Продемонстрована інактивація таких клінічно значимих мікроорганізмів як *Bacillus cereus, Campylobacter jejuni, Clostridium perfringens, Escherichia coli, Listeria monocytogenes, Salmonella* spp., *Staphylococcus aureus* та *Toxoplasma gondii* у рідинах та продуктах харчування. Показано, що обробка високим тиском є нетермічним методом обробки харчових продуктів, що відрізняє цей метод від традиційних термічних методів обробки, таких як кип'ятіння або пастеризація. Однією з помітних переваг застосування високого гідростатичного тиску є нетермічна інактивація різних мікроорганізмів, при якій зберігаються поживні та смакові властивості обробленого продукту. Також зазначається, що харчові продукти можуть оброблятися в кінцевій упаковці, що зменшує ризик їх мікробної контамінації на етапах після обробки. Основними недоліками є неможливість повної інактивації бактеріальних спор та велика вартість обладнання для обробки високим тиском. Поєднання обробки високим тиском із іншими методами, наприклад, термічною обробкою може вирішити обмеження стосовно інактивації спор

Ключові слова: високий тиск; збудники; знешкодження; нетермічна обробка