

Microbiological and physical foundations of novel food preservation technologies using modern packaging

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Abstract

It is demonstrated that traditional thermal processing leads to the degradation of the nutritional composition of food products. The implementation of non-thermal methods (HPP, PEF, US) represents a key response to the global demand for minimally processed products. An analysis of the efficacy of high hydrostatic pressure (HPP) against microorganisms was conducted based on recent publications, demonstrating the inactivation of pathogens and spoilage-causing microorganisms. Factors influencing microbial inactivation via HPP—such as the composition of the suspension medium or food product, microbial species, cell growth phase, pH, and water activity (a_w)—are characterized, and the mechanisms by which HPP affects microbial cell morphology and cell membranes are described. Food products can be processed within their final packaging, thereby reducing the risk of microbial contamination during post-processing stages. State-of-the-art preservation methods, combined with modern active packaging, form the foundation of contemporary food production; they ensure high product quality and enable significant improvements in the environmental performance of manufacturing facilities. The primary remaining drawbacks are the inability to achieve complete inactivation of bacterial spores using HPP or other methods considered "cold" alternatives to thermal processing, as well as the high cost of high hydrostatic pressure processing equipment.

Keywords: non-thermal methods, HPP and PEF, environmental footprint, pathogen inactivation, active packaging.

Fundamentos microbiológicos e físicos de novas tecnologias de conservação de alimentos utilizando embalagens modernas

Resumo

Demonstra-se que o processamento térmico tradicional leva à degradação da composição nutricional dos alimentos. A implementação de métodos não térmicos (HPP, PEF e US) representa uma resposta essencial à crescente demanda mundial por produtos minimamente processados. Com base em publicações recentes, foi realizada uma análise da eficácia da alta pressão hidrostática (HPP) contra microrganismos, demonstrando sua capacidade de inativar patógenos e microrganismos responsáveis pela deterioração dos alimentos. São apresentados os fatores que influenciam a inativação microbiana por HPP, tais como a composição do meio de suspensão ou do alimento, a espécie microbiana, a fase de crescimento celular, o pH e a atividade de água (a_w), bem como os mecanismos pelos quais a HPP afeta a morfologia e as membranas celulares dos microrganismos. Os alimentos podem ser processados já em sua embalagem final, reduzindo, assim, o risco de contaminação microbiana durante as etapas posteriores ao processamento. Métodos modernos de conservação, aliados a embalagens ativas, constituem a base da produção contemporânea de alimentos, assegurando elevada qualidade dos produtos e permitindo melhorias significativas no desempenho ambiental das unidades de processamento. As

principais limitações ainda existentes são a incapacidade da HPP e de outros métodos considerados alternativas "a frio" ao processamento térmico de promover a completa inativação de esporos bacterianos, bem como o elevado custo dos equipamentos utilizados no processamento por alta pressão hidrostática.

Palavras-chave: métodos não térmicos, HPP e PEF, pegada ambiental, inativação de patógenos, embalagens ativas.

1. Introduction

The modern paradigm of the food industry is shifting toward "green" technologies that minimize thermal stress on raw materials. Traditional pasteurization and sterilization require significant energy input and often compromise the quality of the finished product. The use of non-thermal factors—such as high hydrostatic pressure and pulsed electric fields—combined with smart packaging enables the creation of a new production model that is both environmentally safe and economically viable. This work aims to systematize the physical principles underlying these methods and analyze their practical implementation worldwide.

1. Theoretical and Physical Basis of the Methods

1.1 The "Hurdle Technology" concept

The concept proposed by Leistner relies on the synergy of multiple factors. Instead of a single aggressive treatment, a combination of "mild" hurdles is employed: pH value, water activity, redox potential, and physical non-thermal factors. This disrupts microbial homeostasis, preventing adaptation to environmental conditions and thereby ensuring product stability at room temperature.

1.2 Physical mechanisms of non-thermal inactivation

- High Hydrostatic Pressure (HPP): The process is based on Pascal's principle (instantaneous pressure transmission) and Le Chatelier's principle. Pressures of 400–600 MPa induce protein denaturation and the crystallization of membrane lipids. This triggers a phase transition of the membranes from a liquid-crystalline to a solid state, causing irreversible damage to pathogen cells.
- Pulsed electric fields (PEF): Induce the phenomenon of electroporation. Under the influence of high voltage ($E > 20 \text{ kV/cm}$), nanopores form in the membranes. Mathematically, this is described by a critical transmembrane potential; when V exceeds 1 V , the membrane loses its barrier function.
- Ultrasonic cavitation: Generates microbubbles in the liquid; their collapse creates local "hot spots" (up to 5000 K) and shock waves that physically rupture bacterial cell walls.

2. Practical Application and Inactivation Efficacy

2.1 Industrial use cases

- HPP in retail: The Evolution Fresh brand (Starbucks) uses HPP for cold-pressed juices. This achieves a 45-day shelf life without compromising fresh fruit flavor. In the seafood sector, treating oysters at 300 MPa inactivates *Vibrio vulnificus* while keeping the product succulent (whereas thermal processing renders the meat "rubbery").
- PEF in processing: Industry giant McCain Foods employs PEF to treat potatoes before cutting. Electroporation makes potato tissue more pliable, reducing oil absorption during frying by 10% and minimizing cutting waste.

2.2 Bacterial load reduction metrics

To meet FDA food safety requirements, a process must achieve a 4–6 log reduction in pathogen levels. This requirement depends on the specific food product and the initial microbial load present before the primary microbial reduction stage—such as sterilization or pasteurization in conventional thermal processing. Research into identifying HPP treatment parameters capable of eliminating the viability of various microorganisms is of particular interest. Ensuring product safety through microbial inactivation is a key area of R & D for food

technologists (Huanget al., 2020).

High pressure induces conformational changes in cell membranes and cell morphology. It disrupts biochemical reactions and the genetic mechanisms of microorganisms, thereby reducing microbial counts. Various publications note that high-pressure treatment significantly impacts the cellular architecture and critical functions of microbial cells. Several studies describe the lethal effect of HPP on microbial populations, a phenomenon attributed to the simultaneous impact on cell membrane permeability, changes in cell morphology, and the disruption of biochemical reactions (Daher et al., 2017; Sehrawat et al., 2021).

Damage to less critical cellular compartments may not result in cell death; however, multiple, simultaneous effects on minor components or critical parameters do lead to cell death (Daryaei et al., 2016; Rendieles et al., 2011). As the authors note, the precise mechanism triggering cell death remains unknown, though it may be linked to simultaneous effects on proteins, ribosomes, and DNA (Guillou; Membré, 2019). The effect of the rate and mode of pressure increase on cell damage, particularly on *Escherichia coli* and *Staphylococcus aureus* (Yang et al., 2023) and shiga toxin-producing O157 *Escherichia coli* (Kameník et al., 2023), on *Toxoplasma gondii* infection from high-pressure-processed (HPP) raw and dried ham obtained from experimentally infected pigs (Garcia et al., 2020) is important.

To understand the impact of HPP on cell morphology, it is necessary to have a clear understanding of the structure and composition of the cell and its membrane. The bacterial cell wall is composed of peptidoglycans (consisting of *N*-acetylglucosamine and *N*-acetylmuramic acid, as well as three amino acids: D-glutamic acid, D-alanine, and meso-diaminopimelic acid). Unlike plant cells, bacterial cells lack a nuclear membrane, making their genetic material vulnerable to external factors such as temperature and pressure. Animal cells, however, lack a cell wall but possess a nuclear membrane. Although the plant tissues of various fruits and vegetables differ in their biological functions, they share a basic eukaryotic organization, consisting of a nucleus, cytoplasm surrounded by a membrane, a plasma lemma, and a cell wall (Gonzalez et al., 2010; Guillou; Membré, 2019).

2.3 Effect on the cell membrane

Increased pressure disrupts transport and respiration by altering cell membrane permeability, leading to intracellular nutrient deficiency and, ultimately, potential cell death (Kalagatur et al., 2018; Wang et al., 2013). Kalagatur et al. reported that HPP treatment damages the membrane, as evidenced by the penetration of PI, which stains dead *Fusarium graminearum* spores and emits bright red fluorescence. Increased PI uptake in *E. coli* at various pressures has also been reported by Klotz et al. (2010). Higher treatment pressures intensified the fluorescence, indicating greater inactivation of fungal spores at elevated pressures (at a constant temperature of 60 °C for 30 min) (Sehrawat et al., 2021).

It was also reported that incubating HPP-treated cells in a high-magnesium medium stabilized ribosomal structure; the conclusion was drawn that the loss of viable cells may be linked to the leaching of metal ions and intracellular solutes following cell damage. In addition to conformational changes in ribosomal structure, Yang et al. (2012) observed pressure-induced (500 MPa/30 min/25 °C) inactivation of *Salmonella*, *E. coli*, *Shigella*, and *S. aureus* in milk, attributed to morphological changes and the disruption of the peptidoglycan layer.

Pilavtepe-Çelik et al. (2013) reported that *E. coli* cells exhibited a smooth surface before pressurization; however, upon exposure to 200 MPa, the cells appeared larger, and further increasing the pressure to 250 MPa resulted in the formation of pits and indentations. In contrast, increasing the pressure to 200–250 MPa did not significantly affect the cell surface; however, higher pressures (300–400 MPa) resulted in a rough and cracked cell surface. Some morphological changes induced by high-pressure treatment of microorganisms are presented in (Table 1).

Table 1. Change in the morphology of microorganisms by high-pressure processing.

<i>Saccharomyces cerevisiae</i>	600/7/21	SEM	Perforations and release of the cell wall; scars on the surface of pressurized cells	Marx et al. (2011)
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<i>E. coli</i> ATCC25922; <i>S.aureus</i> ATCC2921	500/30/25	TEM	Cell membrane damage, cell wall rupture, and chromosome DNA degradation	Yang et al. (2012)
<i>Salmonella enterica</i> BCRC 12947	350/5/25	TEM, SEM	Cellular changes, which include irregular shape, expanded nucleoid regions, breakdown of the peptidoglycan layer, rupture of the cell wall, and partial disintegration and loss of the cell envelope	Wanget al. (2013)
<i>Vibrio parahaemolyticus</i> BCRC 10806	300/10/25	TEM, SEM	Bud scars on the surfaces of cells, pressure-induced cell envelope, and intracellular damage	Wanget al. (2013)
Fungal spores (<i>Fusarium</i> mycotoxins)	380/30/60	Fluorescence microscope	Damaged membrane integrity as observed by penetration of propidium iodide	Kalagatur et al. (2018)
Microbial cells from whey-lime beverage	500/10/25	FESEM	Leakage of cellular debris due to rupture of the cellular membrane induced by HPP	Bansalet al. (2019)
<i>Morganella morganii</i> , <i>Photobacterium phosphoreum</i>		SEM	HPP induced damage to the cellular membrane and cell wall	Lee et al. (2020)

Note: *SEM scanning electron microscopy, TEM transmission electron microscopy, FESEM field emission scanning electron microscopy. Source: Authors, 2026.

Maldonado et al. (Maldonado et al., 2016) examined cells after treatment with a fluorescent material to better understand the mechanism of inactivation by monitoring in situ inactivation of microorganisms during pressure increase, hold, and decrease. During pressure increase and pressure hold, membrane damage was observed with time, but was not observed during pressure decrease. When treated for longer times and at high pressure, a decrease in fluorescence was observed that was greater than expected. This could be due to ribosomal disruption, which could lead to further of binding during pressure application but to its release upon pressure release.

2.4 Impact on biochemical reactions

A variety of biochemical reactions are required to support life processes, performing different functions. These reactions are accompanied by a change in volume, and high-pressure treatment promotes reactions that lead to a decrease in the volume of the solution. In addition to the cell membrane, proteins and enzymes are also considered to be the main targets of high-pressure treatment for inactivation of microorganisms (Gautier et al., 2026). Key compounds such as ATP, present in cell membranes, are either denatured or detached from the membrane under the influence of high-pressure treatment.

The application of high-pressure treatment also leads to denaturation of functional proteins, which reduces proton transport, resulting in a decrease in intracellular pH (Huang et al. 2014). In addition, denaturation and unfolding of proteins lead to their aggregation inside microorganisms, and this process is irreversible at elevated pressure by Kalagatur et al. (2018).

Some of the irreversible changes at elevated pressure observed due to the association of hydrophobic molecules or volume reduction may include the dissociation of oligomeric proteins into their subunits, conformational changes of the active site (Serment-Moreno et al., 2014), protein biosynthesis and a decrease in the number of ribosomes due to damage to protein structures when treated with a pressure of 60 MPa, as well as irreversible denaturation of proteins at pressures above 300 MPa have been reported previously.

This was explained by the dissociation of mainly uncharged ribosomes, i.e., without tRNA or mRNA, which is accompanied by a decrease in the volume of the solution, as found in *in vitro* experiments (Simonin et al., 2011). Responses of yeasts to pressure. In addition, during high-pressure treatment, the uptake of amino acids by microorganisms is reduced, resulting in their inability to synthesize protein, which ultimately affects the metabolic processes of microorganisms. It has been reported that protein synthesis and gene expression are affected by pressures in the range of 30–50 MPa, and the nuclear membrane of yeast is affected at pressures of approximately 100 MPa. (Bravim et al., 2012; Fernandes et al., 2001; Ludikhuyze et al., 2001; Rendueles et al., 2011; Sehrawat et al., 2021).

Pressures of about 400–600 MPa effectively cause damage/changes to the cytoplasm and mitochondria. The effect of pressure on the structural (reversible or irreversible changes) and functional properties of proteins and enzymes depends largely on the type of protein, as well as on the operating parameters (Agregán et al., 2021). The reduction in volume, intracellular pH, protein aggregation, and inactivation of key enzymes of microorganisms lead to cell death.

2.5 Effects on genetic machinery

The functionality of genetic material depends on its enzymes, and pressure disrupts the activity of enzymes. Inactivation of enzymatic activity reduces the synthesis of ribosomes, which are necessary for the replication and transcription of genetic material. This leads to condensation of genetic material, as reported in the case of *Listeria monocytogenes*, *Salmonella typhimurium*, and *Lactobacillus plantarum* (Bansal et al., 2019), affecting the functionality of nuclear material. Inactivation of intracellular enzymes and the ability of acyl-tRNA amino acids to bind to mRNA and ribosomes are sensitive to pressure.

Moreover, even small changes in amino acids can cause a change in protein shape. Covalent and hydrogen bonds are least affected by pressure compared to electrostatic, hydrophobic, and ionic interactions. Since hydrogen bonds are involved in the formation of the helical structure of DNA, nucleic acids are relatively resistant to high pressure. However, at elevated pressure, when an endonuclease comes into contact with DNA, it cleaves it and leads to DNA condensation (Gautier et al., 2026; Maldonado et al., 2016).

Epifluorescence microscopy has revealed conformational changes in cytosolic proteins as well as in the nucleoids of *E. coli* K-12TG1 (Gautier et al., 2026; Maldonado et al., 2016). Eliminating or transferring regulatory genes associated with pressure resistance affects the strain's tolerance to pressure; namely, a pressure of 50–100 MPa is sufficient to inhibit the replication and transcription of the genetic material of microorganisms. Damage to the outer membrane is repairable after decompression, whereas repair of damage to the cytoplasmic membrane is difficult because RNA and protein synthesis require energy. Therefore, it can be concluded that the effect of HPP is multi-purpose, which leads to a significant decrease in the number of viable microorganisms.

2.6 Effect of HHP on bacterial spores

Inactivation of bacterial spores under the action of VHD remains a difficult task due to the resistance of spores to the treatment limits allowed by existing industrial VHD installations (for example, ~650 MPa and 50 °C). Several studies have shown that high pressure can modulate the mechanism of bacterial spore germination, making them susceptible to subsequent treatments for inactivation (Huang et al., 2014).

Unfortunately, germination under the influence of high pressure is a unique phenomenon for spores of the genus *Bacillus*, but not for *Clostridium* (Agregán et al., 2021; Serment-Moreno et al., 2014). Alternative strategies for the inactivation of bacterial spores at commercially available levels of pressure and temperature include stimulation of the germination stage by including known germinating substances in the food product to increase the lethality of IOP treatment for bacterial spores (Chuan et al., 2021).

2.7 Factors affecting the inactivation of microorganisms by HPP

The food matrix plays a significant role in protecting microorganisms during exposure to high pressure. In addition to the processing parameters (pressure, time, and temperature), the response of microorganisms to high pressure also depends on the composition of the suspension medium or food product, the type of microorganism, the phase of cell growth, pH, and water activity (Gautier et al., 2026; Guillou; Membré, 2019). A 2024 risk assessment (Loeffler et al., 2024) published in the *Journal Microbial Risk Analysis* showed that although direct consumption of hot plant-based dishes (from cereals/lentils) is safe, prolonged storage (96–120 hours) or cooling

at room temperature poses a high risk of contamination with *Bacillus cereus* (up to 5.85 log CFU g⁻¹) in lentils), especially for French consumers who practice large-batch cooking.

2.8 Food composition

The food matrix is a complex structure consisting of several components in different proportions and can have a significant impact on the protection of microorganisms from pressure. After all, cells that have been stressed by increased pressure can recover in the presence of the food matrix. Microorganisms in buffers and microbiological media are more sensitive to pressure compared to food, as indicated by studies by many scientists (Lyu et al., 2023; Mok et al., 2022; Moussa et al., 2007).

Histamine-producing bacteria (*Morganella morganii* and *Photobacterium phosphoreum*) were found to be more resistant to pressure in tuna meat-based mash compared to phosphate buffer, as indicated by the lower D value of the bacteria in the case of phosphate buffer (Lee et al., 2020). This means that data obtained in studies using buffers or synthetic media cannot be applied to food, since higher pressure processing may be required to achieve the same degree of reduction.

2.9 pH

The pH of the suspension medium during high-pressure processing (HPP) can affect the inactivation of microorganisms. The synergistic effect of pressure and pH increases the destruction of microorganisms and damage to cell membranes, and damaged cells are unable to recover during further storage. Pressure leads to a decrease in pH due to an increase in the number of hydrogen ions resulting from the ionization of water molecules. Therefore, a deviation from neutral pH towards low pH increases the susceptibility to inactivation of microorganisms (Pang et al., 2022).

Studies have shown that vegetative cells are very sensitive to pressure treatment at low pH (Daruaei et al., 2016). A significant reduction in the killing efficiency of eight bacterial strains when the pH of cell suspensions was changed (from 6.5 to 5.5 and to 4.5) and treated with HPP at 345 MPa for 5 min at 25–35 °C. It was found that the number of *S. aureus* decreased rapidly with increasing pH. These results may be due to the interaction of pH and food matrix, and it was concluded that the reduction was quite sensitive to low and high pH, soy protein, and sucrose. In some of the above studies, it was reported that bacteria are sensitive to the influence of environmental pH.

2.10 Water activity (a_w)

Low water activity provides a protective effect for microorganisms in suspension in food products, and it was demonstrated that vegetative cells are sensitive to increased pressure at high a_w (Daryaei et al., 2016). As reported by Pilavtepe-Çelik et al. (2013), rod-shaped bacteria (*E. coli*) show greater resistance than slender rod-shaped bacteria (*Pseudomonas aeruginosa*), while cocci (*S. aureus*) show the highest resistance. The different levels of pressure resistance can be explained by significant differences in structure. Inactivation of spores requires high pressure combined with moderate temperatures due to their high resistance compared to vegetative microorganisms (Rocha-Pimenta et al., 2020; Wu et al., 202). Non-proteolytic type B spores (spore-forming pathogens) are very insensitive to HPP (Daryaei et al., 2016), either because they can contain dipicolinic acid, or this may be due to the thickness and structure of the bacterial spore shell.

A two-step treatment is more effective for the inactivation of spores. In the first step, HPP treatment is performed at low pressure to germinate the spores. In the second step, high-pressure treatment is used to inactivate the spores. Pressure and heat also act synergistically to inactivate spores without germination. When high pressure is applied at elevated temperatures, corticolytic enzymes present in bacterial spores are inactivated directly, thus avoiding the spore germ ination step (Landfeld et al., 2011). The inactivation of bacterial spores by HPP has been extensively studied in comparison to the inactivation of fungal spores (Kalagatur et al., 2018).

High-pressure treatment changes spoilage characteristics and shelf life of Pacific oysters (*Crassostrea gigas*) during refrigerated storage. Journal of Ocean University of China (Cao et al., 2017). Kerry et al. (2006) reported that HPP can reverse the spoilage process of oysters observed during refrigerated storage. In both fresh, spoiled and spoiled oyster samples treated with HPP, a dominance of different microorganisms at the phylum, class, order, family, and genus levels was observed.

2.11 Modeling the kinetics of microbial inactivation

The reduction in microbial numbers during pulsed pressure increases is due to the occurrence of cavitation in the cell due to the rapid increase and decrease in pressure during high-pressure processing (HPP), which leads to physical changes in the cell wall and, ultimately, to loss of cell integrity and cell death (Lee et al., 2020). According to studies, the magnitude of the depressurization has a greater effect on the cell wall than the pressure increase. Increasing the pressure increase time gives microorganisms additional time to be exposed to the stress that occurs during the pressure increase, which increases the degree of inactivation.

In addition to pressure treatment, the rate of bacterial cell inactivation increases at elevated temperatures, which may be due to thermal damage, which in turn enhances the destruction caused by pressure exposure (Chakraborty et al., 2015; Serment-Moreno et al., 2014). Some results of studies that have examined the separate effect of a single pulsed increase in pressure, regardless of the duration of pressure exposure, are summarized in Table 2.

Table 2. Probability of effect (PE) values for different microorganisms in food samples.

Sample	Microorganisms	Treatment conditions (MPa/°C)	CUT/DCT in (min/min)	Maximum PE values at the highest treatment (log values)	Reference
Mango juice	<i>E. coli</i> (O157:H7);	250–550/20–23	1–3/< 20 s	3.5	Hiremath & Ramaswamy (2012)
	<i>L. monocytogenes</i> (Scott A)			0.12	
Black tiger shrimp	<i>E. coli</i> ATCC 11775	300–600/27	1.5/< 10 s	2.17	Pavuluri & Kaur (2014)
Mango pulp	Natural microflora; <i>Aerobic mesophiles</i> ; Yeast & mold; Coliforms; Lactic acid bacteria; Psychrotrophs	100–600/30	0.30–1.62/< 10 s	1.62; 2.70; 4.24; 5.23; 4.59; 2.88	Kaushik et al. (2015)
Black tiger shrimp	<i>Aerobic mesophiles</i> ; Psychrotrophs; <i>E. coli</i> , <i>S. aureus</i>	300–600/27	0.35–1.5/< 10 s	1.32; 1.37; 1.72; 1.40	Kaur & Rao (2017)

Note: Source: Authors, 2026.

Inactivation of microorganisms in various food products is given in (Table 3).

Table 3. Efficiency of inactivation of microorganisms.

Product	Processing method	Pathogen	Reduction level (log10)	Reference
Apple juice	PEF (35 kV/cm)	<i>E. coli</i>	5.5 – 6.0	Evrendilek et al. (2000)
Guacamole	Guacamole HPP (600 MPa)	<i>Listeria monocytogenes</i>	5.0+	Wiśniewski et al. (2024)

Milk	Ultrasound + Heat	<i>S. aureus</i>	4.5 – 5.0	Z. Herceg et al. (2012)
Beef	Cold plasma	<i>Salmonella typhimurium</i>	4.2	Yadav & Roopesh (2022)

Source: Authors, 2026.

3. Environmental Aspect and Energy Saving

According to research by Pereira & Vicente (2010) in traditional pasteurization systems (thermal processing of products), energy is consumed to heat water and packaging, whereas PEF directs energy specifically toward membrane disruption (Table 4).

Table 4. Comparison of energy consumption for processing 1000 L of product.

Processing method	Energy consumption (kWh)	Water consumption (L)	Environmental footprint (CO ₂)	Reference
Pasteurization (HTST)	85 – 120	2000 – 3500	High	Tomasula et al. (2014)
High Pressure (HPP)	18 – 30	150 – 250	Low	Li & Padilla-Zakour (2021)
Pulsed electric fields (PEF)	6 – 18	10 – 50	Minimal	Landiet al. (2025)

Source: Authors, 2026.

4. Modern Packaging and Regulatory Requirements

The effectiveness of preservation depends directly on the quality of the packaging. Kerry & Malley (2014) define active packaging as a system that interacts with the product via oxygen absorbers. In the EU, these materials are regulated by Regulation (EC) No 1935/2004 (Regulation, 2004), while in Ukraine, they are governed by DSTU 8302:2015 (DSTU, 2016), both of which establish strict rules regarding packaging inertness under high pressure.

Traditional preservation methods—pasteurization and sterilization—have long dominated the food industry. However, intensive heat treatment inevitably degrades vitamins, organoleptic properties, and the natural structure of products (Jay et al., 2014).

Modern consumers are driving the demand for the "Clean Label" concept: products should be minimally processed and free from artificial preservatives, yet possess a long shelf life and remain completely safe. This compromise is made possible by innovative technologies operating at the intersection of microbiology, physics, and advanced materials science (Jay et al., 2014; Pilavtepe-Çelik, 2012).

4.1 Microbiological foundations: a paradigm shift

Traditional preservation methods destroy microbiota through protein denaturation caused by high temperatures. New technologies operate in a subtler and targeted manner, minimizing thermal damage to the product itself (Wiśniewski et al., 2024; Yadav; Roopesh, 2022).

Mechanisms of microorganism inactivation:

- Disruption of cell membranes: High-intensity physical fields increase the permeability of the lipid bilayer, causing critical leakage of intracellular contents (lysis) (Jay et al., 2014; Pilavtepe-Çelik et al., 2012).
- Enzyme inactivation: Targeted alteration of the conformation of enzymes responsible for microbial metabolism and replication occurs without breaking the covalent bonds of small molecules (such as vitamins and aromatic compounds)(Tomasula et al., 2014).

- Oxidative stress: Generation of free radicals that cause targeted damage to pathogen DNA and RNA, rendering them unable to reproduce (Lee et al., 2020).

4.2 Physical foundations of innovative technologies

Modern physical preservation methods are often referred to as "gentle" or "non-thermal" (non-thermal processing) (Pilavtepe-Çelik, 2012). Pascalization, or High Hydrostatic Pressure (HPP). The product, in its final packaging, is placed in a chamber where it is subjected to pressures ranging from 300 to 600 MPa:

- Physical principle: According to Le Chatelier's principle, pressure accelerates processes that lead to a reduction in volume. Hydrogen and hydrophobic bonds within macromolecules are disrupted (Soni et al., 2016).
- Microbiological effect: Vegetative cells of bacteria, molds, and yeasts are destroyed due to membrane deformation and the inhibition of ATPase activity. At the same time, the covalent bonds of biomolecules—such as those affecting taste, color, and vitamin content—remain intact (Soni et al., 2016).

4.3 Pulsed Electric Fields (PEF)

Primarily used for liquid and flowable products (juices, milk, purées). The product passes between electrodes that deliver short-duration (microsecond) high-voltage pulses (20–40 kV/cm) (Ali; Ibrahim, 2026; Pyatkovskyy, 2023):

- Physical principle: The phenomenon of electroporation. Exposure to an electric field generates a potential across the cell membrane, leading to the formation of transmembrane micropores (Ali; Ibrahim, 2026).
- Microbiological effect: If the potential exceeds a critical threshold (approximately 1 V), electroporation becomes irreversible, resulting in the immediate death of the microorganism (Pyatkovskyy, 2023).

4.4 Low-temperature (cold) plasma

An innovative method for the surface sterilization of products and packaging. A gas (air, nitrogen, or helium) is ionized by an electric discharge at room temperature (Hiremath; Ramaswamy, 2011):

- Physical principle: Generation of a flux of ultraviolet radiation and reactive oxygen/nitrogen species (Kaur; Rao, 2017).
- Microbiological effect: Instantaneous destruction of biofilms and surface sterilization through bombardment with charged particles and radicals that disrupt bacterial cell walls (Kaur; Rao, 2017).

4.5 Synergy with modern packaging types

Physics-microbiological methods do not operate in isolation; they require the right "casing." Modern packaging acts not merely as a barrier but as an active participant in the preservation process (Berdejo et al., 2023; Pereira; Vicente, 2010).

4.5.1 A. Retort pouches

Multilayer flexible laminates (polymer films + aluminum foil) capable of withstanding harsh sterilization conditions (up to 135 °C) and high pressure (HPP) (Pereira; Vicente, 2010):

- Advantage: Due to the pouch's flat shape, heating (or pressure penetration) occurs significantly faster than in a rigid metal can. This reduces the duration of exposure, thereby preserving the product's texture (Pereira; Vicente, 2010).

4.5.2 B. Active packaging

Systems that alter conditions within the packaged product to extend its freshness (DSTU, 2016; Jay et al., 2014):

- Oxygen scavengers: Reduce O₂ levels to below 0.01%, preventing the proliferation of aerobic microorganisms and lipid oxidation (Knorr et al., 2011).
- Antimicrobial films: Polymers incorporating natural antibiotics (nisin), essential oils (thymol, carvacrol), or silver nanoparticles into their matrix. These agents slowly diffuse to the product surface, inhibiting pathogen growth during storage (Berdejo et al., 2023; Pereira; Vicente, 2010).

4.5.3 C. Smart and bio-based packaging

- Time-temperature indicators (TTI) and freshness indicators: Sensors integrated into the packaging change color in response to the accumulation of bacterial metabolites (e.g., volatile amines in fish) or temperature fluctuations (Knorr et al., 2011; Realini; Marco, 2014).
- Biopolymers (PLA, PHA): Derived from renewable resources, these are modified using physical methods (e.g., plasma treatment) to impart hydrophobic and gas-barrier properties comparable to those of petroleum-based plastics (Balasubramaniam et al., 2015; Heinz et al., 2001; Toepfl et al., 2014).

4.6 Hurdle technology

A major trend in the modern food industry is the "hurdle" concept. Instead of relying on a single drastic physical treatment (such as extreme heat), a combination of several mild factors (hurdles) is used; while no single factor is sufficient to eliminate the entire microflora on its own, their synergistic effect ensures a complete result (Aslam et al., 2025; Misra et al., 2019).

Example of a synergistic hurdle combination: Low-level High-Pressure Processing (HPP) + mild heating (up to 45 °C) + antimicrobial active packaging with Modified Atmosphere Packaging (MAP) (Kerry et al., 2006; Leistner, 2000; Marsh et al., 2007; Suppakul et al., 2003). Result: Microorganisms overcome the first barrier (membrane weakening) but perish at the second and third, while the product retains the organoleptic properties of a fresh product.

5. Conclusions

This review synthesized the current knowledge on the microbiological and physical mechanisms underlying the inactivation of microorganisms by emerging non-thermal preservation technologies, with particular emphasis on high hydrostatic pressure (HPP), pulsed electric fields (PEF), ultrasound, and their integration with modern active and intelligent packaging systems. These technologies represent a significant advance over conventional thermal processing by preserving the nutritional, sensory, and functional quality of foods while achieving effective microbial control and reducing environmental impacts.

Among the available non-thermal technologies, high hydrostatic pressure (HPP) currently stands out as the most mature and widely implemented industrial technology due to its proven effectiveness against vegetative microorganisms, its compatibility with a broad range of food products, and its ability to process foods within their final packaging, thereby minimizing post-processing contamination. Pulsed electric fields (PEF) show considerable potential for liquid and pumpable foods because of their high energy efficiency and minimal thermal damage, whereas ultrasound and cold plasma represent promising complementary technologies whose industrial applications continue to expand.

Despite these advances, several important scientific and technological gaps remain. The mechanisms responsible for irreversible microbial inactivation under pressure are not yet fully understood, particularly regarding the interactions among membrane disruption, protein denaturation, enzyme inactivation, and genetic damage. Furthermore, the reliable inactivation of bacterial spores—especially those belonging to *Bacillus* and *Clostridium* species—remains one of the greatest challenges for non-thermal preservation, requiring the development of optimized hurdle strategies combining pressure, mild heat, antimicrobial compounds, or other complementary technologies.

From an industrial perspective, broader implementation is still constrained by several factors, including the high capital investment required for HPP equipment, limited processing capacity for certain food categories, the need for process standardization across different food matrices, and regulatory challenges associated with the

validation of novel preservation systems. Additional research is also needed to optimize energy consumption, improve process scalability, evaluate long-term economic feasibility, and develop sustainable active packaging materials that are fully biodegradable without compromising food safety or shelf life.

Future developments should therefore focus on integrating multiple preservation hurdles, advancing intelligent packaging technologies capable of real-time quality monitoring, and improving the sustainability and affordability of non-thermal processing equipment. Such advances will support the transition toward safer, minimally processed, environmentally responsible foods that meet consumer expectations while contributing to more sustainable food production systems.

6. Authors' Contributions

Pylypenko Liudmyla Mykolaivna: conceptualization, methodology, investigation, data curation, formal analysis, validation, visualization, writing – original draft. *Verkhivker Yakov Grygorovych*: conceptualization, methodology, supervision, project administration, resources, validation, writing – review & editing, funding acquisition.

7. Conflicts of Interest

No conflicts of interest.

8. Ethics Approval

Not applicable.

9. Artificial Intelligence Statement: Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that no generative artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript, including in the writing, editing, analysis, interpretation, or creation of figures, images, schemes, and tables. The authors assume full responsibility for the accuracy, integrity, and originality of the content presented. AI tools are not listed as authors and do not assume responsibility for the content of this manuscript.

10. References

- Aganovic, K., Hertel, C., Vogel, R. F., Johne, R., Schlüter, O., & Schwarzenbolz, U. (2021). Aspects of high hydrostatic pressure food processing: perspectives on technology and food safety. *Comprehensive Reviews in Food Science and Food Safety*, 20(4), 3225-3266. <https://doi.org/10.1111/1541-4337.12763>
- Agregán, R., Munekata, P. E. S., Zhang, W., Zhang, J., Pérez-Santaescolástica, C., & Lorenzo, J. M. (2021). High-pressure processing in the inactivation of *Salmonella* spp. in food products. *Trends Food Science & Technology*, 107, 31-37. <https://doi.org/10.1016/j.tifs.2020.11.025>
- Ali, N. D., & Ibrahim, H. M. (2026). Review: Hurdle technologies in food microbial preservation. *World Journal of Advanced Research and Reviews*, 29(1), 1596-1609. <https://doi.org/10.30574/wjarr.2026.29.1.0231>
- Aslam, M. U., Aslam, E., & Shahbaz, M. (2025). Emerging technologies in food processing: A narrative review. *Insights-Journal of Health and Rehabilitation*, 3(8), 786-793. <https://doi.org/10.71000/8ksb5n90>
- Balasubramaniam, V. M., Martínez-Monteaudo, S. I., & Gupta, R. (2015). Principles and application of high pressure-based technologies in the food industry. *Annual Review of Food Science and Technology*, 6, 435-462. <https://doi.org/10.1146/annurev-food-022814-015539>
- Bansal, V., Jabeen, K., Rao, P. S., Prasad, P., & Yadav, S. K. (2019). Effect of high-pressure processing on microbial safety, physicochemical properties, and bioactive compounds of whey-based sweet lime beverage. *Journal of Food Measurement and Characterization*, 13, 454-465. <https://doi.org/10.1007/s11694-018-9959-1>
- Berdejo, D., García-Gonzalo, D., Oulahal, N., Denkova-Kostova, R., Shopska, V., Kostov, G., Degraeve, P., & Pagan, R. (2023). Minimal processing technologies for production and preservation of tailor-made foods.

- Food Technology and Biotechnology*, 61(3), 357-377. <https://doi.org/10.17113/ftb.61.03.23.8013>
- Chuang, S., Sheen, S., Sommers, C. H., Sheen, L. Y. (2021). Modeling the reduction of *Salmonella* and *Listeria monocytogenes* in ground chicken meat by high-pressure processing and trans-cinnamaldehyde. *LWT – Food Science and Technology*, 139, 110601. <https://doi.org/10.1016/j.lwt.2020.110601>
- Daher, D., Le Gourrierec, S., & Pérez-Lamela, C. (2017). Effect of high pressure processing on the microbial inactivation in fruit preparations and other vegetable-based beverages. *Agriculture*, 7(9), 72. <https://doi.org/10.3390/agriculture7090072>
- Daryaei, H., Yousef, A. E., & Balasubramaniam, V. M. (2016). Microbiological aspects of high-pressure processing of food: inactivation of microbial vegetative cells and spores. In: Balasubramaniam, V. M., Barbosa-Cánovas, G. V., & Lelieveld, H., eds. *High Pressure Processing of Food*, Springer; 271-294. https://doi.org/10.1007/978-1-4939-3234-4_14
- Daryaei, A., Jones, E. E., Ghazalibiglar, H., Glare, T. R., & Falloon, R. E. (2016). Effects of temperature, light and incubation period on production, germination and bioactivity of *Trichoderma atroviride*. *Journal of Applied Microbiology*, 120(4), 999-1009. <https://doi.org/10.1111/jam.13076>
- DSTU. (2016). 8302:2015. Information and documentation. Bibliographic reference. General provisions and rules of compilation. Kyiv: State Enterprise "UkrNDNTs".
- Gėdas, A. (2025). Inactivation mechanisms of pathogenic bacteria in fruit juices by conventional and non-thermal treatments [dissertation]. Hamburg, Germany: University of Hamburg, Hamburg School of Food Science, Department of Food Microbiology.
- Gracia, M. J., Lázaro, R., Pérez-Arquillué, C., Pagán, R., Ramos, S., Garcia, J. L., & Bayarri, S. (2020). High-pressure processing of raw and dry-cured ham from experimentally infected pigs as a potential tool for the risk control of *Toxoplasma gondii*. *Innovative Food Sci & Emerging Technologies*, 61, 102315. <https://doi.org/10.1016/j.ifset.2020.102315>
- Gautier, Y., Stirnemann, G., & Hénin, J. (2026). Molecular signatures of pressure-induced phase transitions in a lipid bilayer. *The Journal of Physical Chemistry B*, 130(13), 3795-3716. <https://doi.org/10.1021/acs.jpcc.5c08607>
- Gonzalez, M. E., & Barrett, D. M. (2010). Thermal, high pressure and electric field processing effects on plant cell membrane integrity and relevance to fruit and vegetable quality. *Journal of Food Science*, 75(7), R121-R130. <https://doi.org/10.1111/j.1750-3841.2010.01763.x>
- Guillou, S., & Membré, J. M. (2019). Inactivation of *Listeria monocytogenes*, *Staphylococcus aureus* and *Salmonella enterica* under high hydrostatic pressure: a quantitative analysis of existing literature data. *Journal of Food Protection*, 82(10), 1802-1814. <https://doi.org/10.4315/0362-028X.JFP-19-132>
- Heinz, V., Alvarez, I., Stefan, A., & Knorr, D. (2001). Preservation of liquid foods by high-intensity pulsed electric fields: basic concepts for process design. *Trends in Food Science & Technology*, 11(11), 397-407. [https://doi.org/10.1016/S0924-2244\(01\)00064-4](https://doi.org/10.1016/S0924-2244(01)00064-4)
- Hiremath, N. D., & Ramaswamy, H. S. (2012). High-pressure destruction kinetics of spoilage and pathogenic microorganisms in mango juice. *Journal of Food Processing and Preservation*, 36(2), 113-125. <https://doi.org/10.1111/j.1745-4549.2011.00559.x>
- Hiremath, N. D., & Ramaswamy, H. S. (2011). High-pressure destruction kinetics of spoilage and pathogenic microorganisms in mango juice. *Journal of Food Processing and Preservation*. <https://doi.org/10.1111/j.1745-4549.2011.00559.x>
- Huang, H-W., Hsu, C-P., & Wang, C-Y. (2020). Healthy expectations of high hydrostatic pressure treatment in food processing industry. *Journal of Food and Drug Analysis*, 28(1), 1-13. <https://doi.org/10.1016/j.jfda.2019.10.002>
- Huang, H. W., Hsu, H. M., Yang, B. B., & Wang, C. Y. (2014). Responses of microorganisms to high hydrostatic pressure processing. *Food Control*, 40, 250-259. <https://doi.org/10.1016/j.foodcont.2013.12.007>
- Jay, J. M., Loessner, M. J., & Golden, D. A. (2014). *Modern Food Microbiology*. 8th ed. Springer.
- Kalagatur, N. K., Kamasani, J. R., Mudili, V., Krishna, K., Chauhan, O. P., & Sreepathi, M. H. (2018). Effect of high pressure processing on growth and mycotoxin production of *Fusarium graminearum* in maize. *Food Bioscience*, 21, 53-59. <https://doi.org/10.1016/j.fbio.2017.11.005>

- Kameník, J., Dušková, M., Dorotíková, K., Hušáková, M., & Ježek, F. (2023). The effect of high-pressure processing on the survival of non-O157 shiga toxin-producing *Escherichia coli* in steak tartare: The good-or best-case scenario? *Microorganisms*, 11(2), 377. <https://doi.org/10.3390/microorganisms11020377>
- Kaushik, N., Kaur, B. P., Rao, P. S., & Mishra, H. N. (2014). Effect of high-pressure processing on color, biochemical and microbiological characteristics of mango pulp (*Mangifera indica* cv. *Amrapali*). *Innovative Food Science & Emerging Technologies*, 22, 40-50. <https://doi.org/10.1016/j.ifset.2013.12.011>
- Kaur, B. P., & Rao, P. S. (2017). Process optimization for high-pressure processing of black tiger shrimp (*Penaeus monodon*) using response surface methodology. *Food Science and Technology International*, 23(3), 197-208. <https://doi.org/10.1177/1082013216673460>
- Kaur, B. P., & Rao, P. S. (2017). Modeling the combined effect of pressure and mild heat on the inactivation kinetics of *Escherichia coli*, *Listeria innocua*, and *Staphylococcus aureus* in black tiger shrimp (*Penaeus monodon*). *Frontiers in Microbiology*, 8, 1311. <https://doi.org/10.3389/fmicb.2017.01311>
- Kerry, J. P., Grady, M. N., & Hogan, S. A. (2006). Past, current and potential utilisation of active and intelligent packaging systems for meat and muscle-based products: A review. *Meat Science*, 74(1), 113-130. <https://doi.org/10.1016/j.meatsci.2006.04.024>
- Kerry, J., & Malley, D. (2014). *Active Packaging*. CRC Press.
- Klotz, B., Mañas, P., & Mackey, B. M. (2010). The relationship between membrane damage, release of protein and loss of viability in *Escherichia coli* exposed to high hydrostatic pressure. *International Journal of Food Microbiology*, 137(2-3), 214-220. <https://doi.org/10.1016/j.ijfoodmicro.2009.11.020>
- Knorr, D., Froehling, A., Jaeger, H., Reineke, K., Schlueter, O., & Schoessler, K. (2011). Emerging technologies in food processing. *Annual Review of Food Science and Technology*, 2, 203-235. <https://doi.org/10.1146/annurev.food.102308.124129>
- Landi, G., Benedetti, M., Sforzini, M., Eslami, E., & Pataro, G. (2025). Comparative analysis of cost, energy efficiency, and environmental impact of pulsed electric fields and conventional thermal treatment with integrated heat recovery for fruit juice pasteurization. *Foods*, 14(13), 2239. <https://doi.org/10.3390/foods14132239>
- Lee, Y. C., Hsieh, C. Y., Chen, M. L., Wang, C. Y., Lin, C. S., & Tsai, Y. H. (2020). High-pressure inactivation of histamine-forming bacteria *Morganella morganii* and *Photobacterium phosphoreum*. *Journal of Food Protection*, 83(4), 621-627. <https://doi.org/10.4315/0362-028X.JFP-19-267>
- Lee, S., Vigoureux, T. F., Hyer, K., Small, B. J. (2020). Prevalent insomnia concerns among direct-care workers JAG. *Journal of Applied Gerontology*, 41(1), 274-284. <https://doi.org/10.1177/0733464820978612>
- Leistner, L. (2000). Basic aspects of food preservation by hurdle technology. *International Journal of Food Microbiology*, 55(1-3), 181-186. [https://doi.org/10.1016/S0168-1605\(00\)00161-6](https://doi.org/10.1016/S0168-1605(00)00161-6)
- Li, J., Wang, J., Zhao, X., Wang, W., Liu, D., Chen, S., Ye, X., & Ding, T. (2019). Inactivation of *Staphylococcus aureus* and *Escherichia coli* in milk by different processing sequences of ultrasound and heat. *Journal of Food Safety*, 39(2), e12614. <https://doi.org/10.1111/jfs.12614>
- Li, Y., & Padilla-Zakour, O. I. (2021). High pressure processing vs thermal pasteurization of whole Concord grape puree: effect on nutritional value, quality parameters and refrigerated shelf life. *Foods*, 10(11), 2608. <https://doi.org/10.3390/foods10112608>
- Loeffler, H., Waletzko-Hellwig, J., & Fischer, R. J. (2024). Systematic enhancement of microbial decontamination efficiency in bone graft processing by means of high hydrostatic pressure using *Escherichia coli* as a model organism. *Journal of Biomedical Materials Research Part B Applied Biomaterials*, 112(2), e35383. <https://doi.org/10.1002/jbm.b.35383>
- Lyu, F., Zhang, T., Gui, M., Wang, Y., Zhao, L., Wu, X., Rao, L., & Liao, X. (2023). The underlying mechanism of bacterial spore germination: an update review. *Comprehensive Reviews in Food Science and Food Safety*, 22(4), 2728-2746. <https://doi.org/10.1111/1541-4337.13160>
- Maldonado, J. A., Schaffner, D. W., Cuitiño, A. M., & Karwe, M. V. (2016). In situ studies of microbial inactivation during high-pressure processing. *High Pressure Research*, 36(1), 79-89. <https://doi.org/10.1080/08957959.2015.1111887>
- Marsh, K., & Bugusu, B. (2007). Food packaging--roles, materials, and environmental issues. *Journal of Food Science*, 72(3), R39-R55. <https://doi.org/10.1111/j.1750-3841.2007.00301.x>

- Marx, G., Moody, A., & Bermúdez-Aguirre, D. (2011). A comparative study on the structure of *Saccharomyces cerevisiae* under nonthermal technologies: high hydrostatic pressure, pulsed electric fields and thermosonication. *International Journal of Food Microbiology*, 151(3), 327-337. <https://doi.org/10.1016/j.ijfoodmicro.2011.09.027>
- Misra, N. N., Yepez, X., Xu, L., & Keener, K. M. (2019). In-package cold plasma technologies. *Journal of Food Engineering*, 244, 21-31. <https://doi.org/10.1016/j.jfoodeng.2018.09.019>
- Mok, J. H., Sun, Y., Pyatkovskyy, T., Hu, X., Sastry, S. K. (2022). Mechanisms of *Bacillus subtilis* spore inactivation by single- and multi-pulse high hydrostatic pressure. *Innovative Food Science & Emerging Technologies*, 81, 103147. <https://doi.org/10.1016/j.ifset.2022.103147>
- Mombert, P., Díaz-Otero, B., & Alonso-Prados, J. L. (2022). Study of the different evaluation areas in the pesticide risk assessment process: focus on pesticides based on microorganisms. *EFSA Journal*, 20(S1), e200412. <https://doi.org/10.2903/j.efsa.2022.e200412>
- Moussa, M., Perrier-Cornet, J. M., & Gervais, P. (2007). Damage in *Escherichia coli* cells treated with a combination of high hydrostatic pressure and subzero temperature. *Applied and Environmental Microbiology*, 73(20), 6508-6518. <https://doi.org/10.1128/AEM.01212-07>
- Pang, Y., Wu, R., Cui, T., Zhang, Z., Dong, L., Chen, F., & H, X. (2022). Proteomic response of *Bacillus subtilis* spores under high pressure combined with moderate temperature and random peptide mixture LK treatment. *Foods*, 11(8), 1123. <https://doi.org/10.3390/foods11081123>
- Pavuluri, S. R., Kaur, B. P. (2014). High pressure inactivation kinetics of *Escherichia coli* in black tiger shrimp (*Penaeus monodon*). In: Proceedings of the International Conference on Biological, Civil and Environmental Engineering, Dubai, UAE, 17-18 p.
- Pilavtepe-Çelik, M., Yousef, A. E., & Alpas, H. (2013). Physiological changes of *Escherichia coli* O157:H7 and *Staphylococcus aureus* following exposure to high hydrostatic pressure. *Journal für Verbraucherschutz und Lebensmittelsicherheit*, 8, 175-183. <https://doi.org/10.1007/s00003-013-0828-x>
- Pilavtepe-Çelik, M. (2012). High hydrostatic pressure (HHP) inactivation of foodborne pathogens in low-acid juices. *International Journal of Food Science + Technology*, 48(4), 673-677. <https://doi.org/10.1111/j.1365-2621.2012.03218.x>
- Pereira, R. N., & Vicente, A. A. (2010). Environmental impact of novel thermal and non-thermal technologies in food processing. *Food Research International*, 43, 1936-1943. <https://doi.org/10.1016/j.foodres.2009.09.013>
- Pyatkovskyy, T. (2023). Inactivation of microorganisms by high hydrostatic pressure: a literature review. *Bulletin of Medical and Biological Research*, 5(4), 53-61. <https://doi.org/10.61751/bmbr/4.2023.53>
- Pylypenko, L. N., Verkhivker, Y. H., Pylypenko, I. V. (2015). Preservation of Food Products. Microbiology, Energy, Control. Odessa.
- Realini, C. E., & Marcos, B. (2014). Active and intelligent packaging systems for a modern society. *Meat Science*, 98(3), 404-419. <https://doi.org/10.1016/j.meatsci.2014.06.031>
- Regulation. (2004). (EC) No. 1935/2004 of the European Parliament and of the Council of 27 October 2004 on materials and articles intended to come into contact with food.
- Rendueles, E., Omer, M. K., Alvseike, O., Alonso-Calleja, C., Capita, R., Prieto, M. (2011). Microbiological food safety assessment of high hydrostatic pressure processing: a review. *LWT Food Science and Technology*, 44(5), 1251-1260. <https://doi.org/10.1016/j.lwt.2010.11.001>
- Rocha-Pimienta, J., Martillanes, S., Ramírez, R., Garcia-Parra, J., & Delgado-Adámez, J. (2020). *Bacillus cereus* spores and *Staphylococcus aureus* vegetative cells inactivation in human milk by high- pressure processing. *Food Control*, 113, 107212. <https://doi.org/10.1016/j.foodcont.2020.107212>
- Sarker, M. R., Akhtar, S., Torres, J. A., & Paredes-Sabja, D. (2015). High hydrostatic pressure-induced inactivation of bacterial spores. *Critical Reviews in Microbiology*, 41(1), 18-26. <https://doi.org/10.3109/1040841X.2013.788475>
- Sehrawat, R., Kaur, B. P., Nema, P. K., Tewari, S., & Kumar, L. (2021). Microbial inactivation by high pressure processing: principle, mechanism and factors responsible. *Food Science and Biotechnology*, 30(1), 19-35. <https://doi.org/10.1007/s10068-020-00831-6>

- Schrawat, R., Kaur, B. P., Nema, P. K., Tewari, S., & Kumar, L. (2021). Microbial inactivation by high pressure processing: principle, mechanism and factors responsible. *Food Science and Biotechnology*, 30(1), 19-35. <https://doi.org/10.1007/s10068-020-00831-6>
- Serment-Moreno, V., Barbosa-Cánovas, G. V., Torres, J. A., & Welti-Chanes, J. (2014). High-pressure processing: kinetic models for microbial and enzyme inactivation. *Food Engineering Reviews*, 6(3), 56-88. <https://doi.org/10.1007/s12393-014-9075-x>
- Soni, A., Oey, I., Silcock, P., & Bremer, P. (2016). *Bacillus* spores in the food industry: a review on resistance and response to novel inactivation technologies. *Comprehensive Reviews in Food Science and Food Safety*, 15(6), 1139-1148. <https://doi.org/10.1111/1541-4337.12231>
- Suppakul, P., Miltz, J., Sonneveld, K., & Bigger, S. W. (2003). Active packaging technologies with an impact on food quality and safety. *Journal of Food Science*, 68(2), 408-420. <https://doi.org/10.1111/j.1365-2621.2003.tb05687.x>
- Toepfl, S., Heinz, V., Knorr, D. (2014). High-intensity pulsed electric fields applied for food preservation. In: Sun, D. W., ed. *Emerging Technologies for Food Processing*. Academic Press, 163-181 p.
- Tomasula, P. M., Datta, N., Yee, W. C., McAloon, A. J., Nutter, D. W., Sampedro, F., & Bonnaillie, L. M. (2014). Computer simulation of energy use, greenhouse gas emissions, and costs for alternative methods of processing fluid milk. *Journal of Dairy Science*, 97(7), 4594-4611. <https://doi.org/10.3168/jds.2013-7546>
- Yadav, B., Roopesh, M. S. (2022). Synergistically enhanced *Salmonella Typhimurium* reduction by sequential treatment of organic acids and atmospheric cold plasma and the mechanism study. *Food Microbiology*, 104, 103976. <https://doi.org/10.1016/j.fm.2021.103976>
- Yang, D., Li, R., Dong, P., Rao, L., Wang, Y., & Liao, X. (2023). Influence of pressurization rate and mode on cell damage of *Escherichia coli* and *Staphylococcus aureus* by high hydrostatic pressure. *Frontiers in Microbiology*, 14, 1108194. <https://doi.org/10.3389/fmicb.2023.1108194>
- Yang, B., Shi, Y., Xia, X., Xi, M., Wang, X., Ji, B., & Meng, J. (2012). Inactivation of foodborne pathogens in raw milk using high hydrostatic pressure. *Food Control*, 28(2), 273-278. <https://doi.org/10.1016/j.foodcont.2012.04.030>
- Yang, Y., Li, X. M., Sun, Z. H., Yang, T., Tan, Z. L., Wang, B. F., Han, X. F., & He, Z. X. (2012). The growth performance and meat quality of goats fed diets based on maize or wheat grain. *Journal of Animal Feed Sciences*, 21(4), 587-598. <https://doi.org/10.22358/jafs/66133/2012>
- Wang, C. Y., Hsu, C. P., Huang, H. W., & Yang, B. B. (2013). The relationship between inactivation and morphological damage of *Salmonella enterica* treated by high hydrostatic pressure. *Food Research International*, 54, 1482-1487. <https://doi.org/10.1016/j.foodres.2013.08.004>
- Wang, C. Y., Huang, H. W., Hsu, C. P., Shyu, Y. T., & Yang, B. B. (2013). Inactivation and morphological damage of *Vibrio parahaemolyticus* treated with high hydrostatic pressure. *Food Control*, 32(2), 348-353. <https://doi.org/10.1016/j.foodcont.2012.12.023>
- Wiśniewski, P., Chajęcka-Wierzchowska, W., & Zadernowska, A. (2024). Impact of high-pressure processing (HPP) on *Listeria monocytogenes*: an overview of challenges and responses. *Foods*, 13(1), 14. <https://doi.org/10.3390/foods13010014>
- Woldemariam, H. W., & Emire, S. A. (2020). Recent trends in cold pasteurization of fruit juices using pulsed electric fields: a review. *Annals of Food Science and Technology*, 21(1), 1-15. Available in: www.afst.valahia.ro. Accessed on: May 14, 2026.
- Wu, C. P., Wu, S. M., Lin, Y. H., Wu, Y. H., Huang, B. C., Huang, H. W., & Wang, C. Y. (2022). High-pressure processing-based hurdle strategy for microbial shelf life of packed food in the cold chain. *Food Package ShelfLife*, 34, 100983. <https://doi.org/10.1016/j.fpsl.2022.100983>

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