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(Review Article)

Review: Hurdle Technologies in Food Microbial Preservation

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Abstract

Background: Hurdle technology is a food preservation strategy based on the deliberate combination of two or more preservation factors to inhibit microbial growth while maintaining food quality. Instead of focusing on a single severe treatment, multiple mild hurdles act synergistically to disrupt microbial homeostasis, prevent recovery, and extend shelf life.

Objective: This review examines hurdle technologies in food microbial preservation, focusing on the effects of multiple preservation factors and their impact on microbial inactivation and food quality. The narrative review synthesizes the foundational principles of research retrieved through a comprehensive search, highlighting key findings on combination antimicrobial synergies, preservation methods, and quality preservation outcomes.

Main Discussion Points: Key findings demonstrate that synergistic pairings such as high-pressure processing (HPP) combined with antimicrobials, pulsed electric fields (PEF) with cold storage or acidic conditions, and atmospheric cold plasma (ACP) with PEF yield significantly larger log reductions in microbial populations and extended shelf-life compared to individual treatments.

Conclusion: Hurdle technology represents a powerful and versatile approach that effectively enhances microbial safety while better preserving sensory, nutritional, and physicochemical food quality compared to single-hurdle methods.

Keywords: Hurdle technology; Food safety; Food preservation; Microbial inactivation; Non-thermal processing

1. Introduction

The challenges facing the global food system are the need to eliminate pathogens and spoilage organisms to safeguard public health, as well as the growing consumer demand for fresh-like, less processed foods with superior nutritional content. Due to the intensive thermal treatments used in conventional methods, like pasteurization and sterilization, vitamins are frequently destroyed, volatile aroma molecules are lost, and the texture color of the products change for the worse. As a result, the scientific community has placed a high priority on creating hurdle technology (HD). The deliberate application of numerous preservation factors physical, chemical, and biological to manage pathogenic and spoilage microbes in food is known as hurdle technology (HT). This concept was first highlighted by Leistner (1978) and focuses on the principle that microorganisms exposed to simultaneous stresses are less likely to survive or adapt than when exposed to a single preservation method [1, 2].

By applying mild hurdles in combination, food safety can be achieved with reduced negative impacts on sensory and nutritional quality. The basic idea acknowledges that when subjected to a combination of preservation factor, microorganisms experience several simultaneous stressors. Processors may attain better microbial safety while preserving product quality attributes by using a number of moderate barriers rather than relying on one harsh

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procedure. There are several benefits to the logic behind obstacle technology. Firstly, various preservation factors harm microbes by different means (e. g., DNA damage, membrane rupture, metabolic inhibition), and their combination has cumulative effects [3].

Furthermore, since antimicrobial action is spread out among many variables, each individual barrier can be used at a low intensity, leading to superior preservation of sensory and nutritional qualities when compared to harsh single treatments [1, 3]. Additionally, combined hurdles can eliminate cells that have survived the initial treatment in a damaged but liveable condition, preventing their regeneration during storage [1]. When compared to single-factor preservation, the probability of microbial adaptation and resistance development is reduced by the presence of many concurrent stressors. Specific preservation techniques, like high-pressure processing, are put inside the hurdle paradigm by reviewers, who point out that combinations overcome individual limitations, such as limited sporicidal action [3].

2. Major Hurdles Used in Food Preservation

2.1. Chemical Hurdles

2.1.1. pH and Acidity

Acidic environments inhibit microbial proliferation and the healing of cells that have been damaged by sub-lethal doses. The control of intracellular pH is required in order to prevent the denaturation of intracellular proteins. Most micro-organisms grow best at neutral pH (7.0). Yeasts and molds are typically tolerant of more acidic conditions than bacteria [4]. A common obstacle to preventing the development of *Clostridium botulinum* and other infections is keeping the pH under 4. 6. In fruit juices (cantaloupe juice), a low pH (4. 0) can greatly slow the healing of *Saccharomyces cerevisiae* following damage caused by pulsed electric fields, according to recent research [5]. Likewise, Luo et al. (2016) investigated the effect of dipping potatoes into slightly acidic electrolyzed water followed by ultrasound treatment at 40 ^{0}C for 3 minutes, which produced synergistic effects against *Bacillus cereus* and inhibited its growth under storage temperatures ranging from 5 to 35 ^{0}C [6].

2.1.2. Water Activity (aw)

Controlling water activity through salting, drying, or addition of humectants (sugars, glycerol) remains a classical hurdle. Reductions in aw are commonly paired with antimicrobials or HPP in industrial applications [3].

2.1.3. Redox Potential

Lowering redox potential inhibits aerobic microorganisms and enhances the effects of other hurdles. This is achieved through oxygen removal, addition of reducing agents, or modified atmosphere packaging [1].

2.1.4. Chemical Preservatives

Both natural and synthetic antimicrobial compounds serve as chemical hurdles. Natural antimicrobial are such as essential oils, plant extracts and organic acids. Nisin, enterocins, and other antimicrobial peptides produced by bacteria are called bacteriocins. Additional instances of chemical preservatives include synthetic preservatives like nitrites, benzoates, and sorbates. For instance, Pérez-Baltar et al. (2019) combined enterocins A and B with HPP to manage Listeria monocytogenes in sliced dry-cured ham, showing that the combined treatment initially decreased counts by more than 2.5 $\log^{10}$ and prevented recovery throughout storage [7].

2.2. Physical Hurdles

2.2.1. Temperature-Based Hurdles

One of the most fundamental preservation factors is temperature manipulation. Thermal processing is as conventional heat treatment and mild thermal pulses. Li et al. (2021) employed moderate heat combinations of mild heat (50–55^{0}C) and pulsed electric fields (PEF) along with refrigeration to prevent injured *saccharomyces cerevisiae* from recovering in cantaloupe juice. Additionally, temperatures between 0 and 7^{0}C are used for refrigeration and chilling to slow the growth of microorganisms. Finally, microbial activity is stopped by freezing at temperatures below 0^{0}C [5].

2.2.2. High Pressure Processing (HPP)

HPP is a mild nonthermal technology effective against vegetative bacteria, yeasts, and molds. A range of 300 to 600 MPa is considered normal. The use of antimicrobials or heat in conjunction with HPP, however, helps overcome its limitations against bacterial spores [3]. According to precious study, combining HPP (300 MPa) with antimicrobial films increased the shelf life of coconut water beyond that attained by 500 MPa HPP alone, while also achieving more than 5 log reductions for *E. coli O157:H7* and *Staphylococcus aureus* [8].

2.2.3. Pulsed Electric Fields (PEF)

PEF technology applies short bursts of high-voltage electricity to inactivate microorganisms through membrane disruption. Previous research in 2021 showed that for cantaloupe juice, combining PEF with 55°C heat or tea polyphenols delivered microbial inactivation comparable to thermal pasteurization while better preserving physicochemical properties and vitamin C [5].

2.2.4. Atmospheric Cold Plasma (ACP)

ACP generates reactive oxygen and nitrogen species that destroy microbial cells. Jamali-Hafshejani et al. (2025) created an ACP+PEF system that achieved 5.73 $\log_{10}$ reduction of *E. coli* in sour cherry juice while preserving phenolics and color [9].

2.2.5. Irradiation

Ionizing radiation (gamma rays, electron beams and X-rays) is often combined with modified atmosphere packaging (MAP), cold storage, or natural antimicrobials to decrease required dose and protect quality [1, 2].

2.3. Biological and Packaging Hurdles

2.3.1. Modified Atmosphere Packaging (MAP)

To reduce other treatment intensities and kill survivors during storage, MAP is frequently used in conjunction with irradiation or cold storage [2, 10].

2.3.2. Antimicrobial films and active packaging

Active packaging enhances food quality and prolongs shelf life by enabling direct interaction between food and incorporated bioactive agents. As an example, antimicrobial packaging relies on the controlled release of active molecules from the polymer matrix to inhibit microbial growth. Recent research trends focus on replacing fossil fuel-based materials with sustainable biopolymers, which can be combined with plant-derived antimicrobials to create functional films and coatings. For instance, Surendhiran et al., (2020) developed active nanofibers based on chitosan/poly (ethylene oxide) loaded with pomegranate peel extract. These nanofibers reduced the *Escherichia coli* O157:H7 population in raw beef by 3 log CFU g^{-1} during 10 days of storage at 4 °C [11]. Antimicrobial films or edible coatings act as surface or sustained-release hurdles. To increase the shelf life of coconut water, Li et al. (2024) employed HPP in conjunction with a polylactic acid (PLA) film containing lauroyl arginate ethyl (LAE) [8]. Pinto et al. (2021) reported that the in-package application of red thyme oil vapors effectively decreased the incidence of infected lesions, inhibited mycelial growth, and suppressed spore production of *Penicillium* strains on oranges during 12 days of refrigerated storage [12].

2.3.3. Competitive Microflora

Protective cultures and probiotics can compete with pathogens and spoilage organisms, serving as biological hurdles when combined with physical or chemical treatments. Lactic acid bacteria (LAB) are considered to have the greatest potential in bio preservation, functioning as starter or protective cultures because of their broad activity against undesirable microorganisms. Their inhibitory action arises from several mechanisms, including nutrient competition and the synthesis of organic acids, hydrogen peroxide, enzymes, antimicrobial peptides, and bacteriocins [13]. Karbowiak et al. (2023) conducted a systematic review on the synergistic effects of combining microbial hurdles in meat bio preservation and found that combining lactic acid bacteria (LAB) with other hurdles (e.g., high-pressure processing, modified atmosphere packaging, natural antimicrobials) enhances microbial inhibition [14].

3. The Synergistic Effects of Hurdle Combinations

3.1. The Concept of Synergy in Preservation

Using ideal hurdle combinations, researchers have documented 5–6 log10 decreases in pathogens such as *Staphylococcus aureus*, *Listeria monocytogenes,* and *Escherichia coli*. Membrane injury, metabolic depletion, suppression of cellular repair, and prevention of microbial recovery led to synergy [9, 15]. Recent studies demonstrate that combining mild or non-thermal technologies with plant-derived antimicrobials can produce synergistic effects in reducing microbial spoilage and pathogenic contamination. Light-based approaches, such as 405 nm LED treatment combined with citral, have shown remarkable efficacy for instance, reducing *Cronobacter sakazakii* in powdered infant formula by 6.5 log CFU mL^{-1} after 90 minutes of treatment compared to untreated samples. These findings highlight the potential of integrated strategies to enhance food safety while minimizing reliance on conventional thermal methods [16].

3.2. Quantitative Evidence of Synergistic Combinations

The following table reported the combination outcomes from key research studies:

Table 1 Different hurdle combinations and their microorganism's reduction

Hurdle Combinations	Target Microorganism	Reported Reduction	Reference
ACP + PEF (optimized conditions)	*Escherichia coli*	5.73 log_{10} reduction	[9]
Grapefruit juices treated by ultrasonic atomizing combined with UV light	*S. cerevisiae*	Effective in the inactivation of *S. cerevisiae*	[17]
HPP (300 MPa) + 2.0% LAE-PLA film	*Staphylococcus aureus*	>5 log_{10} CFU/mL reduction	[8]
HPP (300 MPa) + 2.0% LAE-PLA film	*E. coli* O157:H7	>5 log_{10} CFU/mL reduction (no synergy noted)	[8]
HPN_2O (15.2 MPa) + heat (65°C) + nisin (150 IU/mL)	*E. coli* and *Listeria Innocua*	5.9–≥6.0 log_{10} reductions for vegetative cells; up to 2.5 log_{10} for spores	[15]
HPP (450 MPa, 10 min) + enterocins A/B	*Listeria monocytogenes*	Enterocins reduced >2.5 log_{10}; combined treatment prevented recovery	[7]
PEF + mild heat/tea polyphenols/natamycin	*Saccharomyces cerevisiae*	Enhanced inactivation comparable to thermal pasteurization	[5]
Microwave + ginger essential oil	*Salmonella Typhi* and *L. monocytogenes*	Process time reduced from 240s to 30 s	[10]
US-HPP treatment at 450 MPa	Total plate counts, yeasts, and molds	Achieved complete inactivation in apple juice.	[18]
PEF combined with heat. Juice was heated to 55 ⁰C and 70 ⁰C prior to PEF	total mesophilic aerobes, yeasts and molds, and coliforms counts	(Reduced the aerobe, yeast/mold, and coliform counts in MH juice by 3.9, 4.3, and 0.8 log CFUmL, respectively).	[19]
Nanoemulsions of Mentha piperita L. essential oil in combination with mild heat (50, 52, 54⁰C; 10 min), PEF (20, 25, 30 kV cm1; 150 s) HHP (150, 200, 300 MPa; 15 min)	*Escherichia coli O157:H7*	average 5-log reduction of *E.coli* O157:H7 was achieved in Guava juice and Mango juice	[20]
PEF + mild heat	*Bacillus subtilis* spores	Effective against spores	[21]

HHP and ultrasound at 75⁰C	*Alicyclobacillus acidoterrestris* spores	Achieve inactivation of spores in apple juice.	[22]
Ultrasound waves: 600W 28, 45, and 100 kHz at 1 ms time. Heat treatment: 45, 50,52, 55, or 60 ⁰C. UV-C lamp: 15 W Additives: sodium benzoate, potassium sorbate, and pinene	*E. coli O157:H7*	5-log reduction pf E. coli O157:H7 could be achieved at 45, 50, 52, 55, and 60 ⁰C, equivalent to 481.5, 103.6, 45.0, 22.4, and 10.54min, in Orange and cloudy apple juices respectively.	[23]
Ultrasound: 40 kHz, 700W, 1, 2, 3, 4, and 5 min Fumaric acid (FA): 0%, 0.05%, 0.1%, and 0.15% (w/v)	Three strains each of: *E. coli O157:H7* *S. Typhimurium* *L. monocytogenes*	Combined US + 0.15% FA treatment for 5 min achieved 5.67, 6.35, and 3.47 log reductions in E. coliO157:H7, *S. Typhimurium*, and L. *monocytogenes,* respectively.	[24]

CFU = colony-forming unit; LAE = lauroyl arginate ethyl; PLA = polylactic acid.

4. The Synergistic Action Mechanisms

Research has identified many mechanisms underlying synergistic antimicrobial effects:

4.1. Membrane Damage and Sublethal Injury Elimination

HPP combined with antimicrobial films causes severe membrane damage and eliminates pressure-induced sublethal injuries. Li et al. (2024) reported that this mechanism explains synergistic inactivation of *S. aureus*, in which damaged membranes facilitate increased penetration of antimicrobial chemicals [8].

In research by Chen et al. (2021), the combination of nonthermal technologies high hydrostatic pressure at 400 and 600 MPa together with thermosonication at 25 ⁰C and 45 ⁰C resulted in a reduction of microbial populations to below 1 log CFU/mL and simultaneously inactivated enzymes such as polyphenol oxidase in blueberry juice. The synergistic interaction of both treatments induced mechanical disruption of microbial cell walls through pressure, cavitation, and free radical oxidation, ultimately leading to microbial inactivation [25].

4.2. Recovery Prevention by Environmental Hurdles

Sub-lethally injured cells may recover if environmental conditions permit damage repair. Li et al. (2021) found that cold storage and a low pH prevent the regeneration of cells damaged by PEF, successfully preventing the recovery of survivors [5].

4.3. Radio sensitization and Complementary Damage Modes

Different preservation factors harm different cell targets. By either sensitizing microorganisms or preventing regrowth during storage, as shown by previous research, antimicrobials or cold storage combined with irradiation can reduce the necessary radiation dose [1, 2].

4.4. Process Synergy Through Timing and Sublethal Priming

The timing and order of hurdle application can have an impact on synergy. Hashemi et al. demonstrated that using microwave heating in conjunction with essential oil-initiated inactivation earlier in heating profiles results in a reduction in energy consumption and a shorter thermal exposure time [10].

4.5. Target Microorganisms

In various trials where the total log reduction from the combined therapy was greater than the sum of the individual treatments, quantitative synergy was clearly demonstrated. For instance, each barrier utilized alone resulted in much lower decreases compared to the combination of HPN_2O, heat, and nisin [15]. Effective synergistic barrier combinations have been demonstrated against a variety of microbial groups, as shown in table 2:

Table 2 A variety of microbial groups

Types	Examples
Gram-negative bacteria	*E. coli* and *Salmonella* spp.
Gram-positive bacteria	*S. aureus, Listeria monocytogenes and Listeria innocua*
Yeasts	*Saccharomyces cerevisiae*
Bacterial spores	Partial inactivation (up to 2.5 $\log_{10}$) when multiple hurdles combined.

5. Impact on Microbial Inactivation

Microbial activity represents the primary factor responsible for food spoilage. The effective inactivation of these spoilage causing microorganisms, while maintaining the nutritional integrity of food products, can be accomplished through the application of multi-target, moderate technologies.

5.1. Effectiveness Against Different Microbial Groups

Hurdle technology demonstrates high effectiveness against vegetative bacterial cells. Multiple studies report 5-6 $\log_{10}$ reductions for both Gram-positive and Gram-negative bacteria when appropriate hurdle combinations are applied. However, Li et al. (2024) reported a synergistic impact with the same HPP + LAE film system for *S. aureus* but not for *E. coli O157:H7*, underscoring the necessity of pathogen-specific validation of hurdle combinations [8]. Furthermore, using HPN_2O + heat + nisin, Sikin et al. (2017) were able to achieve a $\log_{10}$ reduction of 5. 9 to 6. 0 or more for E. coli and L. innocua in skim milk [15]. In sour cherry juice, ACP + PEF resulted in a 5. 73 log10 decrease in *E. coli* [9]. Using LAE films with high pressure processing, Ting Li et al. (2024) were able to achieve reductions of more than 5 log10 for *S. aureus* and *E. coli O157:H7*. In yeasts, hurdle combinations are effective at inactivating them [8]. Li et al. (2021) found that PEF combined with moderate heat, tea polyphenols, or natamycin achieved inactivation of *S. cerevisiae* comparable to thermal pasteurization while better maintaining juice quality [5]. The greatest challenge for hurdle technology is posed by bacterial spores. The sporicidal effects of HPP and many nonthermal techniques are restricted unless they are used in conjunction with heat or other potent barriers [3].

A prior study found that the multi-hurdle treatment (HPN_2O + heat + nisin + lysozyme) produced only a 2. 5 $\log_{10}$ reduction in spore counts under harsh conditions, as opposed to the 5. 9–6. 0 $\log_{10}$ reduction in vegetative cell counts [15]. Recently, Wu et al. reported that the combination of HPP + modified atmosphere packaging + lactate extended the shelf life of chilled seafood by preventing *C. perfringens* sporulation, achieving a 4-log reduction of vegetative cells, and inhibiting outgrowth under water activity (aw) < 0.95, while minimizing additives for clean-label compliance [13].

In terms of applications against key foodborne pathogens, Pérez-Baltar et al. demonstrated effective control in dry-cured ham using HPP + enterocins for *Listeria monocytogenes* [7]. Similar results were reported for foods with low water activity (soy powder, rice, black pepper), where atmospheric oxygen and air cold plasma treatment has also been shown to successfully inactivate *Bacillus cereus* [26]. Different studies targeting E. coli O157:H7 pathogen in juices and beverages. In addition, Hashemi et al. targeted *Salmonella Typhi* in vegetable juice [10]. Li et al. achieved synergistic inactivation in coconut water for *Staphylococcus aureus* [8].

5.2. Microbial Inactivation Mechanisms

Hurdle combinations inactivate microorganisms through multiple simultaneous mechanisms. A consistent finding across the literature is that well-designed hurdle combinations achieve equivalent or superior microbial inactivation compared to single hurdles while using milder conditions. Li et al. reported that PEF + mild heat achieved microbial safety comparable to conventional thermal pasteurization in cantaloupe juice [5]. Ting Li et al. demonstrated that HPP (300 MPa) + LAE film exceeded the performance of HPP at 500 MPa alone [8]. In addition, researchers showed that ACP + PEF achieved superior microbial inactivation compared to thermal pasteurization while better preserving quality [9].

Table 3 Different Microbial Inactivation mechanisms with hurdles examples

Mechanisms	Examples of Hurdles Involved
Membrane disruption	Physical hurdles (HPP, PEF, ACP) damage cell membranes.
Metabolic inhibition	Chemical hurdles (pH, preservatives) interfere with cellular metabolism.
Oxidative stress	Reactive oxygen species from plasma or antimicrobials.
DNA damage	Chemical substances and Irradiation.
Protein denaturation	Heat and pressure denature essential enzymes.
Osmotic stress	Decreasing water activity.

5.3. Multi-Target Preservation: The "System-Level" Attack

The most effective hurdle systems utilize a multi-target approach, where different hurdles attack different cellular components simultaneously, such as the cell membrane, DNA, enzyme systems, and protein structures. By hitting multiple targets, the probability of the microorganism overcoming the collective barrier is minimized. For instance, the synergy between UV radiation (which damages DNA), pulsed electric fields (which disrupt the membrane), and organic acids (which disrupt internal pH) results in high lethality at intensities that are individually mild. Homeostasis is the process that maintains the stability and uniformity of the living cells internal environment in response to the changes in external environment [27].

Table 4 Mechanisms with their target function and effects

Mechanisms	Targeted Cellular Function	Effect on Microbial Survival
Homeostasis	Internal pH, aw, Eh maintenance	Energy diversion to force repairs and regulation
Metabolic Exhaustion	ATP and energy reserves	Cell death as a result of the failure of repair mechanisms
Stress Reactions	Protein synthesis and DNA repair	Need for a lot of energy to live; susceptibility to many obstacles
Multi-Targeting	Membrane, DNA, Enzymes, Cell Wall	Prevents adaptive resistance and recovery

6. Effects on the Quality of Food

Quality deterioration is observed in food after harvesting, slaughter or manufacture, the rate of deterioration varies according to food composition, handling method and properties of the storage condition. Quality deterioration by physical factors includes damage caused by cutting and bruises in perishable foods such as fruits, vegetables and tubers during handling, and losing or gaining of water through the vapor-permeable package in processed and packaged foods. Oxidation of fatty foods which causes rancidity, oxidative degradation of vitamin C, nonenzymic browning and color degradation by oxidation are examples of quality degradation by chemical reaction [28].

Biochemical reactions that can lead to quality degradation include a browning reaction initiated by polyphenol oxidase (naturally occurring enzyme in plant foods), destruction of lipid by lipolysis (a biochemical process catalyzed by lipases) and enzymic browning. The number of conventional techniques that were proven to solve food quality and safety-related problems was also reported to affect food qualities through the destruction of essential nutrients and the slashing of organoleptic qualities [28]. To minimize the negative effects of traditional preservation methods it’s imperative to use two or more hurdles in combination.

Hurdle technology generally preserves color, texture, flavor, vitamins, and bioactive compounds better than conventional thermal processing. Non-thermal hurdle combinations retain vitamin C, phenolics, and anthocyanins in fruit juices and beverages [5, 9]. Meat and dairy goods treated with combined hurdles also retain texture and sensory qualities more effectively [7].

Johnson, Sun, Cheng, and Li investigated the combined application of ultrasound and plasma-functionalized water as a nonthermal hurdle technology for preserving *Pampus argenteus* (silver pomfret). Plasma-functionalized water was generated by exposing double-distilled water to dielectric barrier discharge electrodes at 70 V and 10 kHz for 8 minutes. Subsequently, ultrasound treatment was applied at 500 W and 40 kHz for 5 minutes at 25 ^{0}C. The treated fish were vacuum-packed and stored at 4 ^{0}C for 15 days. Storage trials revealed alterations in myofibrillar proteins, enhanced retention of nutritional components, and favorable indices of fatty acids and lipids, accompanied by a reduced pH of 5.7 [29].

Fresh-cut fruits and vegetables are particularly susceptible to microbial growth due to the preliminary processes used (e.g., peeling, cutting, and slicing), in addition to their physicochemical, sensory, and nutritional qualities. Researchers investigate the effect of pre-treating fresh-cut potatoes with pulsed electric fields (PEF; 0.5 kV/cm, 200 pulses) or high hydrostatic pressure (HHP; 400 MPa, 1 min) before osmotic dehydration (35^{0}C, 120 min) markedly enhanced product quality attributes. These nonthermal interventions, combined with anti-browning agents like ascorbic acid and papain to suppress polyphenol oxidase (PPO) activity, improved texture firmness and color retention (L*, a*, b* values). During refrigerated storage (4^{0}C), control samples displayed pronounced enzymatic browning and microbial proliferation (≈6 log CFU/g by day 6), whereas pretreated samples sustained microbial loads below 4 log CFU/g and minimized quality deterioration, thereby extending shelf life while preserving sensory and nutritional properties [30].

6.1. Sensory Characteristics

In term of color preservation, multiple studies document superior color retention with hurdle technology compared to conventional thermal processing. Jamali-Hafshejani et al. found that ACP + PEF preserved color indices in sour cherry juice better than conventional thermal pasteurization [9]. In addition, throughout the 30-day storage period, sliced dry-cured ham treated with HPP + enterocins showed just slight color alterations [7]. Furthermore, skim milk that had been treated with HPN2O, heat, nisin, and lysozyme showed little color change [15].

Furthermore, hurdle technology generally maintains texture better than harsh thermal treatments. Pérez-Baltar et al. (2019) measured minimal changes in shear strength of dry-cured ham after HPP + enterocin treatment [7]. Also, Li et al. reported better preservation of physicochemical properties in cantaloupe juice with PEF + mild heat compared to thermal pasteurization [5]. Regarding flavor and aroma, while fewer studies quantitatively assess flavor and aroma, the use of milder processing conditions in hurdle technology generally results in better retention of volatile compounds and fresh-like sensory characteristics compared to high-temperature thermal processing.

6.2. Nutritional Value

For vitamin retention, nonthermal or mild multi-hurdle approaches preserve heat-sensitive vitamins better than conventional pasteurization. Li et al. found that PEF + gentle heat treatment of cantaloupe juice resulted in superior preservation of vitamin C [5]. Furthermore, researchers used ACP + PEF to preserve ascorbic acid in sour cherry juice. Furthermore, hurdle technology improves the retention of bioactive molecules such phenolics, anthocyanins, and other bioactive substances. Studies discovered that, in sour cherry juice, ACP + PEF maintained overall phenolics and anthocyanins more effectively than thermal pasteurization [9]. Li et al. discovered that PEF combinations improved the preservation of bioactive substances in cantaloupe juice [5]. Moreover, researchers found that the addition of sodium benzoate and potassium sorbate to blanched tamarillo fruit improves microbial stability and does not affect anthocyanins, antioxidant and phenolic content of tamarillo sweet product [31].

Functional juices can be formulated with various biologically active ingredients, such as polyphenols, which exhibit antioxidative activity, or probiotic lactic acid bacteria, which must be carefully processed to retain their beneficial properties in the final product. Putnik et al. reviewed the application of innovative hurdle technologies for preserving functional fruit juices while maintaining their nutritional and sensory qualities. The authors highlighted non-thermal methods including high-pressure processing, pulsed electric fields, ultrasound, and cold plasma which are often combined to achieve synergistic antimicrobial effects. These approaches extend shelf life, reduce microbial contamination, and preserve bioactive compounds, offering sustainable alternatives to conventional thermal treatments [32].

6.3. Shelf-Life Extension

Multiple studies document significant shelf-life extension with hurdle technology as shown in table 5:

Table 5 Shelf-life extension for different products with hurdle technology

Products	Effects	References
Coconut water	extended shelf life beyond that achieved with HPP alone	[8]
Cantaloupe juice	extended shelf life while maintaining quality	[5]
Dry cured ham	maintained low total viable counts during 30 days at 4^0C and 12^0C	[7]
Skim milk	had superior microbial stability	[15]

7. Advanced Research Techniques:

The decade leading to date has seen a transition from descriptive microbiology to predictive and mechanistic science, driven by advancements in computational modeling and "omics" technologies. Researchers increasingly use inoculated challenge models to quantify inactivation kinetics.

- Enumeration and Viability: beyond traditional plate counting, flow cytometry and molecular methods (PCR) are used to detect viable but non-culturable (VBNC) cells, providing a more accurate assessment of food safety [33].
- Kinetical Modeling: the Weibull model has gained popularity for characterizing nonlinear inactivation curves under hurdle treatments since it considers the distribution of resistance within a microbial community. Weibull analysis of PEF inactivation of Acetobacter aceti revealed a crucial threshold of 21. 64 kV/cm, for instance.
- Process Modeling: finite element analysis and computational fluid dynamics (CFD) are used to optimize heat and mass transfer in complex hurdle systems, such as microwave-assisted essential oil decontamination [34].
- Artificial intelligence (AI): has recently emerged as a powerful complement to traditional predictive microbial modeling in food safety research. While classical models such as Gompertz and Baranyi simulate microbial growth and inactivation under combined hurdles (e.g., pH, water activity, temperature), AI approaches extend these capabilities by integrating multimodal datasets from sensors, image analysis, and chemical indicators. For instance, Sonwani et al. (2022) demonstrated that machine learning algorithms can accurately distinguish spoiled from fresh products, offering scalable solutions for shelf-life management and waste reduction. Similarly, hurdle technology studies have employed predictive microbial models to forecast lag phases and log reductions when multiple preservation methods are combined, thereby guiding the optimization of nonthermal treatments such as pulsed electric fields, high-pressure processing, and modified atmosphere packaging [35].

Together, these methodologies illustrate a convergence of data-driven and mechanistic approaches: predictive models provide theoretical frameworks for microbial dynamics, while AI enhances real-time detection and decision support [35]. This integration strengthens hazard analysis systems, supports proactive risk mitigation, and advances sustainable food preservation strategies. An additional predictive model for estimating the shelf life, safety, and quality of ready-to-eat foods is SOPHY, a software tool designed for this purpose and accessible at https://dev2.chainfood.com [36].

8. Discussion, Future Directions and Challenges

The research from the previous ten years shows that barrier technology is now a vibrant discipline distinguished by technological convergence and sustainability driven innovation rather than a static one. Between 2015 and 2025, the most notable trend has been the shift from even moderate heat to completely non-thermal mixtures. To achieve safety at ambient temperatures, natural antimicrobials are increasingly utilized in conjunction with or in sequence with technologies such as ACP, PEF, and HPP. This trend is demonstrated by the 2025 ACP+PEF spraying system for sour cherry juice, which offers a cold pasteurization substitute that complies with strict safety regulations while still meeting consumer desire for unprocessed flavors [37].

Biofilms present on food processing surfaces are notoriously resistant to single sanitizers. Hurdle technology has emerged as a powerful tool for biofilm management. Recent research demonstrates that combining enzymes (cellulase, protease) with essential oils can synergistically remove biofilms. The enzymes degrade the extracellular polymeric matrix, while the essential oils then penetrate and kill the exposed cells. This strategy, which lessens the dependence on abrasive chemical cleansers, is in line with the objectives of environmental sustainability [38].

The role of packaging has shifted significantly. Processors have transitioned from basic vacuum packing to intelligent systems that are able to detect and react to their surroundings. For reactive materials, among the innovations are pH-responsive films that alter color when meat spoilage releases basic volatile nitrogen (TVB-N), and temperature-responsive coatings that release thymol when the temperature rises above 40^{0}C. Moreover, by allowing for directional liquid transport and the regulated release of actives, respectively, asymmetrical Janus films and Pickering emulsions enhance the stability of moisture-sensitive aquatic products [39].

In term of nanocomposites, the incorporation of metal-organic frameworks (MOFs) and carbon quantum dots (CQDs) into biopolymer films has greatly improved gas barrier capabilities and UV protection, creating additional barriers against oxidative and microbial degradation. Nanoparticles, owing to their high surface area to volume ratio and enhanced reactivity, represent efficient alternatives to conventional preservation methods that often depend on high energy inputs or chemical additives. Silver nanoparticles (AgNPs) are particularly effective, exhibiting broad-spectrum antimicrobial activity against bacteria, fungi, and viruses. When incorporated into food packaging materials, AgNPs inhibit microbial growth on product surfaces, thereby extending shelf life and reducing reliance on synthetic chemical preservatives [40]. This approach supports sustainability goals by lowering the environmental impact associated with chemical production and disposal.

In term of sustainability and Life Cycle Assessment (LCA), a major focus of the 2023-2025 period is the environmental impact of preservation. Hurdle technology, particularly non-thermal approaches, is increasingly viewed as a tool for sustainable food production. LCA studies have shown that HPP and PEF can significantly reduce energy demand and CO2 emissions compared to conventional thermal pasteurization. As an example, integrated systems like radiofrequency heating + HPP + solar energy offer a low-carbon option for industrial pasteurization, whereas HPP can reduce water consumption by as much as 75%. In term of circular economy: these technologies help reduce food waste by extending shelf life and promote the valorization of agro waste (such as extracting bioactive from tomato peel), which advances UN Sustainable Development Goals (SDG 12 and 13) [41, 42].

Future research should focus on smart and sustainable hurdle combinations, predictive modeling, clean-label antimicrobials, and industrial-scale validation. Integration of non-thermal technologies with active packaging and natural preservatives represents a promising direction. In term of smart and personalized preservation, using AI and real-time data from intelligent packaging to adapt hurdle protocols to the specific microbial load and matrix variations of a particular batch [43].

Integrating transcriptomics, proteomics, and metabolomics into predictive microbiology models to identify "molecular markers" of microbial injury and recovery [34]. For solutions for sustainable and clean labeling, replacing all synthetic additives with plant derived antimicrobials, bacteriocins, and nanoparticles, while using renewable energy for processing. For innovative biofilm interventions increase the use of plasma-based and enzyme-essential oil systems for surface decontamination in industrial settings [42]. The incorporation of plant-derived antimicrobials into plant-based food products, particularly fruit juices and fresh or ready to eat vegetables, has been shown to effectively limit microbial spoilage and extend product shelf life. Essential oils and their active constituents including *Mentha piperita* L. oil, thymol, carvacrol, trans cinnamaldehyde, as well as oregano and thyme oils exhibit pronounced antimicrobial properties against a range of spoilage microorganisms. Collectively, these findings highlight the potential of plant antimicrobials as promising natural preservatives for maintaining the safety and quality of plant-based foods [44].

In term of challenges, the initial consideration is spore resistance. The biggest barrier to the majority of non-thermal hurdles continues to be bacterial spores. The combination of high pressure with heat or potent chemical germicides is still necessary for effective spore inactivation, which might affect quality and make process design more challenging [38]. Second, diverse responses, microbial reactions to challenges can be extremely strain-specific. Recent film studies of HPP + LAE have demonstrated that a system designed specifically for *S. aureus* may be less successful against *E. coli O157:H7*. This necessitates pathogen specific verification for each culinary item. Other limiting factors for hurdle application in food preservation is changes in sensory attributes, particularly when the combination involves chemical hurdles. Adverse changes can occur and this can lead to total rejection of the food [45]. Process integration, in addition, without integration, a lot of bright or cutting-edge technologies have trouble gaining traction [46].

New technologies produce isolated efficiencies rather than unified advancement when they are introduced without aligning individuals and data processes. In significant capital outlay, the upfront cost of technologies like PEF and HPP is still too high for small and medium sized businesses (SMEs). Retrofitting a plant, for instance, may cost between $2 and $ 8 million. For regulatory approval, the routes for innovative hurdle combinations (such as cold plasma and new bacteriocins) differ by jurisdiction [47].

The FDA in the United States is considering requiring GRAS notifications for all food-related materials, including those used in packaging, which may extend the time it takes for new products to enter the market. The production of cutting-edge food processing equipment in 2025 has become even more complicated due to erratic trade policies and shortages in precision components (such as aluminum cold-finish bars used in machining) [48].

9. Conclusions

This comprehensive narrative review confirms that hurdle technology represents a paradigm shift in food preservation, moving away from single factor, intense treatments toward multi factor, mild interventions. The synergistic application of physical, chemical, and biological hurdles enables the achievement of high microbial log reductions (typically >5 $log10$) while maximally retaining the sensory and nutritional qualities that consumers demand. Advances in non-thermal technologies (PEF, ACP, HPP), active and intelligent packaging, and the application of omics to understand stress responses have significantly broadened the scope and efficacy of the hurdle approach between 2015 and 2025. While challenges related to capital investment, regulatory hurdles, and spore resistance remain, the integration of sustainability and precision modeling offers a clear path forward. As the food industry continues to prioritize safety, quality, and green production, hurdle technology will remain at the core of innovative food science and safety strategies. Hurdle technology represents a robust and flexible approach to food preservation. By combining multiple mild hurdles, it ensures microbial safety while preserving food quality. Continued research and technological innovation will further enhance its industrial applicability and contribution to sustainable food systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest To be disclosed.

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