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Recent advances in innovative strategies for controlling microbial growth in food system: a concise review

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REVIEW ARTICLE

Abstract

Food preservation is a longstanding discipline encompassing traditional techniques such as sun drying, roasting, smoking, fermenting, and salting to maintain agricultural products. Current estimates indicate that one-third of agricultural product is lost to food deterioration, with 25% of the overall food loss ascribed to microbiological spoiling. Microbiological contamination of food can occur at several stages in the supply chain: during harvesting, post-harvest, processing, and storage at the point of sale. This results in an elevated risk of human exposure to harmful microbes. To address this issue, several creative solutions have been developed to restrict microbial development across the food supply chain. This review succinctly addressed the innovative strategies both non-conventional and emerging to control the growth of pathogenic microorganisms in food. The innovative strategies reviewed in this paper were broadly classified into technological and non-technological-based methods. These alternative technologies might markedly reduce processing period, conserve energy, and enhance food safety, ultimately helping the food sector. Nevertheless, some emerging technologies have garnered significant interest from researchers, food producers, and consumers; yet various hurdles must be addressed before to achieving full industrial and consumer acceptance. Issues such as antibiotic resistance and the identification of novel pathogens persist, underscoring the necessity for ongoing study and development in this domain.

Keywords: antimicrobial mechanism; emerging technologies; food system; high-pressure processing; hurdle processing; microbial contamination; non-conventional technologies; ohmic heating

Introduction

Food systems are intricate networks of actors and systems essential for the production and transformation of food from farm to table, ensuring its delivery to consumers, which significantly varies by location and temporal conditions. It encompasses all approaches involved in the transformative change to secure sustainable and nutritious food that promote the health of the society and conserve planetary boundaries, especially within the one-health approaches to disease prevention (Elechi *et al.*, 2022). A common global approach is difficult to define as it is locality- and scale-dependent. However, irrespective of the approaches adopted, the common focus on food system transformation has revolved around four fundamental pillars: sustainably boosting the small farm holder in global south, transforming big industries in global north to adept to sustainable production practices, losing

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less, and eating smarter (Elechi *et al.,* 2022). The focus of the present review is on the third pillar—losing less. A detrimental combination of circumstances results in food systems failing to satisfy the demands of significant portions of society, with around 783 million people experiencing chronic hunger globally, while up to 1.26 billion people might be nourished with the food that is lost and wasted yearly (World Food Programme [WFP], 2025). Therefore, to function efficiently, food systems require a comprehensive approach that integrates production, consumption, and other intermediary processes (Elechi, *et al.,* 2022).

Food safety is a crucial component of this integrated strategy and a vital result of the functioning of the agrifood system (Food and Agriculture Organization [FAO], 2023). Safe food is essential for improved health, food security, livelihoods, economic growth, commerce, and the international standing of any nation. Foodborne infections are presently impacting the global population, hindering socioeconomic progress and burdening healthcare systems. Unsafe food is detrimental to national economies, with low- and middle-income countries incurring around US$95 billion in lost output annually (FAO, 2023).

Microorganisms are crucial to food safety, manufacturing, processing, preservation, and storage. Microorganisms, including bacteria, molds, and yeasts, are utilized in the creation of food and food components, such as wine, beer, baked products, and dairy products. The proliferation and contamination of spoilage and harmful microbes are regarded as primary contributors to food loss in contemporary times (Lorenzo *et al.*, 2018). Consequently, undesired microbial populations may proliferate during food preparation and storage, resulting in spoiling or rendering the food unfit for human consumption, thus increasing the risk of human illnesses (Yousef and Abdelhamid, 2019). Food loss because of spoilage or contamination impacts the food business and customers, resulting in economic losses and heightened hospitalization expenses, as indicated previously. Unsafe foods diminish both amount and quality of agricultural output, thereby impairing food supply and access for households reliant on their sale (Nwiyi and Elechi, 2022). Furthermore, the use of contaminated food elevates the risk of malnutrition and disease (Nwiyi and Elechi, 2022). Current estimates indicate that one-third of agricultural output is lost due to food deterioration, with 25% of the overall food loss ascribed to microbial spoiling (Cederberg and Sonesson, 2011; Nwabor *et al.*, 2022). Consequently, microbial-mediated food degradation is probably the predominant cause of food loss and waste in agricultural products. Absence of adequate preservation and storage facilities significantly exacerbates the global food security crisis (Nwabor *et al.,* 2022). Despite substantial advancements in food preservation and processing science, the objective of attaining natural and unmodified food with optimal safety continues to be unattainable (Nwabor *et al.,* 2022).

Foodborne pathogens are bacteria that induce human illnesses through their virulence mechanisms, even at low infectious doses (Yousef and Abdelhamid, 2019). The dissemination of pathogenic microbes, microbial toxins, and other pollutants via food and beverages is a significant cause of disease and infection. Mortality and morbidity because of foodborne illnesses and intoxication are significant sources of economic loss (Nwabor *et al.*, 2022). The management of such microbes has progressed throughout human history to enhance food shelf-life and provide safer and more nutritious meals. Microbial control approaches primarily seek to suppress the proliferation of unwanted bacteria through the implementation of physical or natural antimicrobial treatments (Abdelhamid and El-Dougdoug, 2020). Consequently, food preservation has been a fundamental technique throughout human history to guarantee a consistent food supply and avert wasting.

Food safety and quality are crucial in the food sector to satisfy customer expectations and comply with regulatory criteria (Vaishnav *et al.,* 2024). Food-processing procedures are essential for suppressing microbial growth, enzymatic activity, and chemical reactions that contribute to spoiling and deterioration (World Health Organization [WHO], 2021). Throughout history, several food-processing methods have been utilized to safeguard food against microbial degradation and prolong the shelf life of food items, all while preserving their nutritional value and sensory qualities (Smith, 2020; Vaishnav *et al.,* 2024). These strategies have progressed over time, according to technology improvements and food industry demands, providing effective solutions to reduce food waste, improve food security, and promote sustainable food production and distribution (Vaishnav *et al.,* 2024).

Recent years have witnessed substantial progress in the formulation of solutions for microbial control in food. The solutions encompass classic measures, such as antibacterial drugs and food-processing techniques, as well as novel ways using upcoming technologies, such as nanotechnology and gut microbiota (Herrera *et al.,* 2023). Ancient civilizations utilized various physical methods, such as sun-drying, roasting, smoking, fermenting, and salting, to preserve agricultural products. The emergence of science and technology led to the adoption of compounds with antibacterial and antioxidant capabilities as optimal food preservatives (Nwabor *et al.,* 2022).

Contemporary customers, influenced by scientific findings on the detrimental health effects of several food preservatives, now prefer minimally preserved foods deemed wholesome and safe. Synthetic preservatives, such as butylated hydroxytoluene, butylated hydroxyanisole, sorbic acid, propyl gallate, and sodium nitrate, have been associated with cytotoxicity, immune response suppression, and genotoxicity (Nwabor *et al.*, 2022; Pandey *et al.*, 2014; Sarıkaya and Cakır, 2005; Winkler *et al.*, 2006). To meet the evolving preferences of consumers and guarantee their safety, numerous advancements in food science and technology have developed as alternative, effective, and secure methods for preserving food products and agricultural produce (Hernández-Hernández *et al.*, 2019; Khouryieh, 2021; Rifna *et al.*, 2019). The application of various food preservation procedures is recommended to improve food safety and prolong product's shelf-life (Leistner and Gould, 2002; Nwabor *et al.*, 2022; Singh and Shalini, 2016).

Regrettably, the optimal preservation approach faces significant demands, because the execution of good microbial control tactics in food presents several problems. Antibiotic resistance is a critical concern, as certain pathogenic bacteria have acquired resistance to standard antibiotic drugs, complicating their eradication. The identification and management of newly developed infections pose a continual challenge, because microorganisms adapt to novel strains with arousal of distinct features (Herrera *et al.*, 2023). The adoption of preservation techniques is contingent upon various factors, such as health implications, cost and energy requirements, length of shelf-life extension, efficacy in inactivating foodborne pathogenic and spoilage microorganisms and spores, impacts on nutritional and organoleptic qualities of food, timing, and adaptability (Nwabor *et al.*, 2022).

Consequently, considering the emergence of food system sustainability, circular economy, and One Health approaches to global health challenges, the pursuit of sustainable technologies for food processing persists to regulate microbial growth and maintain consumer safety. Several studies have been conducted to develop and assess strategies and technologies for controlling microbial growth and food spoiling, thus ensuring food quality and safety for consumer well-being. This research aims to elucidate fundamental ideas of new food technologies, emphasizing their practical implications for microbial development in relation to food safety and quality, based on recently published sources.

Literature Search Strategy

This paper employs a thorough review technique to present an extensive summary of the current advancements and problems in control of microbial growth in food. The approach specifics are as follows:

Search platforms

The database employed for this study was constructed by querying the Scopus database from 2 February 2025 to 10 February 2025, considering publications from 2014 to 2025. The Scopus database was employed to get published papers because of its extensive coverage of contemporary publications and articles in the English language and scientific sciences. Additionally, the Google search engine was utilized to obtain valuable studies that may not be indexed in Scopus.

Keywords and search terms

A mix of keywords and Boolean operators was utilized. The search terms were enclosed in the Boolean operator (" ") to guarantee the retrieval of articles containing one or more of the precise keywords used in the search without modifications. Publications were obtained by a targeted search of keywords ("Microorganism in food processing," "Food processing technologies," OR "Microbial growth control") in the "Topic" tab to identify publications containing these terms in the title, abstracts, and keywords. Retrieved publications were filtered to include only papers published within the recent decade (2014–2025). The selected range for this year was intended to get the most recent studies in the subject. The decade-long range enables the acquisition of sufficient papers to discern a thorough trend in the evolution and emphasis of publications within the discipline.

Criteria for inclusion and exclusion

Inclusion criteria: Papers published in peer-reviewed journals that addressed food-processing technology and innovation aimed at inactivating foodborne pathogens or surrogate microorganisms in food and agro-food products were included in this study.

Exclusion criteria: Studies not published in English, lacking significance to developments in microbial detection techniques, or not available in full text were eliminated.

The screening, selection, and data extraction method involved manually analyzing the acquired papers from the scientific database using a reference management application (Zotero version 6.2) to eliminate duplicates and irrelevant materials. Articles were evaluated according to their titles and abstracts to determine relevancy. Comprehensive evaluations were subsequently performed to verify the congruence of the selected research with the aims of this review. Data pertinent to the research focus and control techniques were retrieved and synthesized to yield a full grasp of the subject.

This methodology facilitates a comprehensive examination, guaranteeing the incorporation of varied viewpoints and contemporary developments in the discipline. The technique prioritizes thoroughness and inclusion above the rigid procedural standards of a complete review (Abdelshafy *et al.,* 2025).

Microorganisms and Innovation in Food Processing

Microbial food processing utilizes bacteria to convert basic food into a value-added product. Furthermore, it entails transforming low-value, sometimes inedible, perishable natural resources into high-value and safe food items. Recently, microbial methods of food processing have attracted international interest as an effective means of food preservation and a significant supply of essential nutrients (Gholami-Shabani *et al.,* 2024). Consequently, advancements in microbial technology have transformed food sciences, facilitating the creation of novel food items and ingredients, enhancing food safety, and deepening the comprehension of gut microbiome interactions (Xia *et al.,* 2023).

Traditional food fermentation is an ancient method employed to preserve and alter foods via microbial activity. Microorganisms are essential in the manufacture of several foods, including dairy products (yoghurt and cheese), fermented vegetables (olives, pickles, and sauerkraut), fermented meats (salami), sourdough bread, and alcoholic drinks (Mazhar *et al.*, 2022; Xia *et al.,* 2023). Recently, the food industry has increasingly utilized microbes for the creation of chocolate, food coloring, preservation of fruits, vegetables, and meat, as well as for probiotics beneficial to human health. Various bacteria generate enzymes of nutritional significance, including microbial transglutaminase utilized in fish production (Mazhar *et al.,* 2022). Chinese liquor fermentation and yoghurt manufacture are among the most recognized traditional fermentation processes (Xia *et al.,* 2023). Advancements in microbial technology have enabled a deeper comprehension and manipulation of microbes, resulting in present and prospective advancements. The establishment of starting cultures represents a major advancement in microbial technology (Xia *et al.,* 2023). Shi *et al.* (2022) conducted a study on the yeast *Wickerhamomyces anoma*lus Y-1, prevalent in Chinese liquor fermentation starters. The researchers employed genomic and transcriptomic analyses to identify genes implicated in flavor metabolism within this yeast, discovering its production of various volatile compounds that enhance the aroma and flavor of Chinese liquor (Xia *et al.,* 2023). The microbial synthesis of food using synthetic biology is increasingly acknowledged as a sustainable and efficient method for enhancing food production (Arun *et al.,* 2023; Lv *et al.,* 2021). Synthetic biology facilitates the design and assembly of innovative biomolecular components, pathways, and networks that reprogram organisms to function as designed cellular factories (Khalil and Collins, 2010; Lv *et al.,* 2021). Hu *et al.* (2022) delineated a sustainable method for the production of isomaltulose, a non-cariogenic, slow-release carbohydrate, utilizing a genetically modified food-grade strain of *Corynebacterium glutamicum* (Xia *et al.,* 2023).

The metabolic alteration of microbial hosts for the production of nutraceutical compounds offers a remarkable alternative to chemical methods and extraction, enabling the synthesis of clean products under mild circumstances without the necessity for elevated heat and pressure (Luo *et al.,* 2015). Microbial engineering at metabolic level is an environmentally acceptable alternative to the chemical production of nutraceuticals. Microorganisms are more amenable to genetic modification than plants and have emerged as superior candidates for synthesizing plant-derived natural bioactive and other compounds (Madhavan *et al.*, 2023). Widely used microbial systems, such as *Escherichia coli (E. coli)* and *Saccharomyces cerevisiae*, have been engineered as adaptable cell factories for producing various nutraceuticals. Beekwilder *et al.* (2006) conducted the initial synthesis of resveratrol using yeast. The heterologous expression of 4-coumarate CoA ligase and stilbene synthase from tobacco and grapes in *Saccharomyces cerevisiae* led to the synthesis of resveratrol (6 mg/L) (Madhavan *et al.,* 2023). Subsequently, the microbial production of resveratrol has improved markedly by molecular biology techniques (Thapa *et al.*, 2019).

Food-Processing Strategies in Microbial Control

Food safety is a fundamental principle that has propelled the advancement of contemporary food processing. In recent years, there has been a significant demand for premium foods that preserve their inherent freshness and other sensory attributes (Ngadi *et al.,* 2012). The traditional tactics have been modified, and emergent strategies are examined briefly.

Conventional methods and limitations

Traditional techniques for microbial control mostly depend on refrigeration, thermal treatment, and/or chemical preservatives (Ngadi *et al.,* 2012). Despite the considerable effectiveness of these procedures, their primary disadvantages are their impact on the freshness and nutritional content of processed food, in addition to their substantial energy requirements. Traditional heat processing of food items remains the most straightforward and efficient technique for averting microbiological deterioration. Nevertheless, it predominantly depends on convective and conductive heat transmission and is excessively cautious in guaranteeing microbiological safety, thereby frequently undermining product quality (Lee *et al.,* 2016). Excessive heat processing of food items often results in significant degradation of qualitative attributes, such as texture, color, flavor, and the degradation of bioactive components (Choi *et al.,* 2006). Conversely, traditional chemical antimicrobials have been utilized for several decades and sanctioned by numerous governments. Conventional chemicals employed in food preservation include, but are not limited to, sulphites and nitrites. Organic acids, including benzoic, sorbic, acetic, lactic, and propionic acids, are frequently utilized as conventional food preservatives (Abdelhamid and El-Dougdoug, 2020). Nevertheless, conventional antimicrobials present some concerns, because some may provide health risks to humans (e.g., nitrites associated with cancer in young children), influence essential nutrients for consumers, or alter food flavor. Sulphite induces the breakdown of thiamine, a vital vitamin (Garcia-Fuentes *et al.,* 2015).

Emerging strategies

The drawbacks of conventional techniques resulted in the creation of several unique and inventive approaches to microbial control in food processing. The literature review identifies a diverse array of creative tactics employed in the control of microbial development in food. The tactics evaluated in this review are classified into two categories: non-technological antimicrobials and technological techniques. Non-technological antimicrobials include natural antimicrobial agents, bacteriophages, nanotechnology, and gut microbiota. Technological techniques primarily include microwave (MW) and radiofrequency (RF) heating, pulsed electric fields (PEFs), high-pressure processing (HPP), and ionizing radiation. Additional promising methods are ohmic heating (OH), UV light, and ozonization (Ngadi *et al.,* 2012). The subsequent sections offer a comprehensive examination of the present state-of-the-art applications, and problems associated with these unique technologies.

Non-Technological-Based Antimicrobials Strategies

Notwithstanding centuries of strategy development to avert foodborne infections, food safety continues to be a substantial issue, despite several technology breakthroughs. Consumers are progressively pursuing minimally processed and organically preserved food alternatives. A possible strategy is food bio-preservation, which employs natural antimicrobials present in food that has a long history of safe eating, thus diminishing dependence on chemically synthesized food preservatives (Muthuvelu *et al.,* 2023).

Natural antimicrobial agents

Synthetic antimicrobial compounds are extensively employed to regulate microbial proliferation in processes and products within the food sector. Nonetheless, they have raised apprehensions over possible adverse consequences on human health and the environment as well as the emergence of antibiotic resistance (Sar *et al.,* 2023). Synthetic chemicals in the food business are formally controlled due to their excessive use and are banned in certain countries (Elshama, 2020). Consequently, there is a growing desire for natural antibacterial agents. Natural antimicrobials which impede microbial proliferation encompass conventional drugs, naturally derived antimicrobials, or biological preservation methods (e.g., helpful bacteria, bacteriocins, or bacteriophages). Naturally occurring food preservatives are predominantly organic and derived from natural sources. Naturally occurring antimicrobials encompass lysozymes, spices, essential oils, isothiocyanates, avidin, lactoferrin, phenolic compounds, and garlic oil (Abdelhamid and El-Dougdoug, 2020; Davidson *et al.,* 2013; Raybaudi-Massilia *et al.,* 2009).

Plant-based antimicrobials

Enhancing nutritional content, inhibiting microbial deterioration, and prolonging the shelf life of food items are paramount in the food sector (Wang and Teplitski, 2023). Interest in natural antimicrobials, which serve as alternatives to the typically favored synthetic compounds, is growing daily (El-Saber Batiha *et al.,* 2021). Natural plant-derived antimicrobials, including phenolics and organic acids, are becoming recognized as viable alternatives to traditional chemical antibacterial agents because to their safety (Vaou *et al.,* 2021).

Polyphenols possess one or more aromatic rings and one or more hydroxyl (-OH) groups, which confer their antibacterial characteristics (Bodie *et al.,* 2024; Santiesteban-López *et al.,* 2022). These phytochemical substances are categorized into extracts (typically hydrophilic, derived from aqueous extractions) and essential oils (lipophilic, produced by distillation or extraction using organic solvents) (Alirezalu *et al.,* 2020b; Santiesteban-López *et al.,* 2022). The utilization of food-processing by-products, such as olive oil, mill wastewater, along with fruit and vegetable remnants (peels, seeds, and pomace), and diverse herbs, spices, and flowers (essential oils), is recognized for their natural antimicrobial properties because of their bioactive compounds (Balaban *et al.,* 2021, 2022; Plaskova and Mlcek, 2023; Sar and Akbas, 2023).

Extracts and powders from these plant-based products, exhibiting inherent antimicrobial properties, have been assessed for their ability to enhance the quality of bakery (El-Beltagi *et al.,* 2022), meat (Zaki *et al.,* 2022), and dairy products (El-Kholany *et al.,* 2022) as well as to prolong their shelf life (Sar *et al.,* 2023). These compounds have antibacterial capabilities that suppress the proliferation and viability of harmful microorganisms in food.

However, it is essential to isolate and purify secondary plant metabolites to validate their antibacterial properties and explore possible uses for creating healthier and more stable food products (Alirezalu *et al.,* 2020b; Bodie *et al.,* 2024; Santiesteban-López *et al.,* 2022). Moreover, employing plant extracts in lieu of directly incorporating plant powders offers several benefits. The extracts contain concentrated bioactive molecules, enabling them to demonstrate significant antimicrobial activity at reduced concentrations (Awad *et al.,* 2022), enhance the stability of antimicrobials, lower transport and storage expenses, standardize their composition, and simplify their application in food products (Bodie *et al.,* 2024; Santiesteban-López *et al.,* 2022). Nonetheless, polyphenol combinations exhibit more efficacy than individual compounds; hence, the use of plant extracts is more advantageous than that of singular components (Efenberger-Szmechtyk *et al.,* 2021).

Beetroot is a potential vegetable utilized for the extraction of important compounds. A study demonstrated the antibacterial efficacy of beetroot extract against *L. monocytogenes* in grilled pork (Gong *et al.,* 2022). The findings demonstrated that this extract induces apoptosis-like death in *L. monocytogenes* and exhibits significant promise as a natural antibacterial, particularly against *L. monocytogenes*, with log reductions of 0.27 and 0.84 at 1 MIC and 2 MIC doses, respectively (Santiesteban-López *et al.,* 2022). The authors attributed the bioactivity of beetroot extract to the reduction of intracellular adenosine triphosphate (ATP), leading to the dissipation of proton motive force components, membrane depolarization, depletion of reactive oxygen species (ROS), and DNA fragmentation in *L. monocytogenes* (Gong *et al.,* 2022). An extract from *Amaranthus tricolor* was evaluated for its antibacterial properties against *Staphylococcus aureus* and its potential use in reducing foodborne infections in cooked meat (Guo *et al.,* 2020). This extract demonstrated bioactivity against this pathogen (yielding a decrease of 0.5 to 1 log) and, as per the authors, harbors potential to serve as an exceptional biopreservative for ensuring the safety of cooked pork (Santiesteban-López *et al.,* 2022). The antimicrobial activity mechanisms are attributed to the extract, which is abundant in alkaloids, polyphenols, terpenoids, and saponins, resulting in membrane depolarization, pH reduction, intracellular component leakage, DNA cleavage, cell deformation, and ultimately, membrane structural destruction and cell disintegration (Guo *et al.,* 2020). Table 1 summarizes the antimicrobial efficacy of plant-based extracts and essential oils used to control microbial growth in food.

According to Santiesteban-López *et al.* (2022), the antibacterial efficacy of phenolic compounds may be succinctly stated as follows: hydroxyl groups induce leakage of cellular contents and dissipation of cellular energy (ATP), resulting in cell death. The rise in proton concentration results in a fall in pH and lowers the internal cellular pH. Phenolic acids influence membrane integrity by inducing membrane disruption (e.g., effective against *Listeria monocytogenes*) and causing coagulation of cellular contents (Santiesteban-López *et al.,* 2022). Anthocyanins exhibit a potent inhibitory effect on *E. coli* by increasing the Gibbs free energy of adhesion to cells, thereby deterring bacterial attachment. Tannins interact with bacterial polysaccharides and essential metals for microbial metabolism, leading to the precipitation of membrane proteins, which result in enzymatic inhibition, oxidative phosphorylation disruption, lysis, and microbial mortality (Santiesteban-López *et al.,* 2022). Flavonoids interact with membrane proteins, diminishing membrane fluidity, and also induce alterations in energy metabolism, as well as in the synthesis of DNA, proteins, and RNA. Ultimately, certain plant-extract components, including alkaloids, exert their antibacterial effects by DNA intercalation and the suppression of nucleic acid synthesis, thus impeding microbial multiplication (Santiesteban-López *et al.,* 2022).

Nonetheless, essential oils frequently possess a robust aroma and taste, potentially affecting consumer approval and restricting their application in food products (Cao and Miao, 2023). Besides their sensory impacts, botanical-based antimicrobials may exhibit poor compatibility with food matrices or may be rendered ineffective by conventional processing methods (Jackson-Davis *et al.,* 2023). Additional factors encompass discrepancies in the efficacy of extracts derived at various periods from distinct batches of plant material and the potential for bacteria to acquire resistance to chemicals (Bodie *et al.,* 2024; Pinto *et al.,* 2023). Concerns regarding the safety of these chemicals have arisen due to the possible contamination of plants with heavy metals (Iordache *et al.,* 2022), mycotoxins (Ałtyn and Twarużek, 2020), or pesticides (Fillâtre *et al.,* 2017). Hurdle technology should be investigated using essential oils in conjunction with other substances or processing techniques to mitigate the

Table 1. Application and efficacy of plant-based antimicrobials in food safety.

Plant-based antimicrobials	Mechanism of action	Target microorganisms	Concentration/ conditions	Food matrix	Prominent discoveries	References
Protocatechuic acid (PCA)	Suppressing the release of signaling molecules inside the quorum-sensing (QS) system.	*Yersinia enterocolitica*	MIC: 2.5 mg/mL	Pork	The results demonstrate that PCA can inhibit flagellar assembly genes and diminish swimming capability, thereby impairing adhesion and colonization. This also functions to downregulate genes responsible for extracellular polysaccharide (EPS) synthesis, thereby diminishing EPS creation and modifying the expression of associated genes through the regulation of c-di-GMP and acyl homoserine lactones (AHLs) content, eventually inhibiting biofilm development.	Gao *et al.*, 2024; Wu *et al.*, 2022
Pomegranate peel extract	The antibacterial efficacy of pomegranate extract is likely attributable to the presence of anthocyanins, such as cyanidin-3-glucoside, cyanidin-3,5-diglucoside, and pelargonidin-3,5-diglucoside in peel extracts.	*P. italicum* and *P. digitatum* *Salmonella* spp. *L. monocytogenes*, *Bacillus subtilis*, *Escherichia coli*, *S. aureus*, or *P. aeruginosa*.	Dipping in 25-g L^{-1} extract for 2 min	Mandarins dry-cured ham	Decrease in lesion dimensions and infection rate (80–90%). Pomegranate extracts show antilisterial action in dry-cured ham.	Dos Santos *et al.*, 2022; Givi *et al.*, 2019
Cinnamon essential oil			1–10% concentration	Dry-cured ham	A 10% concentration of cinnamon essential oil effectively inhibited complete bacterial growth.	Dos Santos *et al.*, 2022
Strawberry leaf extracts	Gallic acid glucoside, cyanidin-3-galactoside, and quercetin-3-galactoside in strawberry tree leaf extracts often elicit a potent bactericidal effect	*L. monocytogenes*	-	Dry-cured ham	Strawberry tree extracts show antilisterial action against *L. monocytogenes.*	Dos Santos *et al.*, 2022; Santiesteban-López *et al.*, 2022
Black and white pepper (Piper L.) essential oils (EOs)	Pepper EOs suppressed type III secretion system (TTSS) gene transcription in food spoilage bacteria.	*P. fluorescens*	Black pepper MIC (5.0 µL mL^{-1}); white pepper MIC (3.1 µL mL^{-1}) β-caryophyllene MIC (2.8 µL mL^{-1}). 3–5 µL mL^{-1} addition in salad dressing	Fresh-cut lettuce	Reduction of *P. fluorescens* biomass by 30–40%	Myszka *et al.*, 2017

(*continues*)

Table 1. Continued

Plant-based antimicrobials	Mechanism of action	Target microorganisms	Concentration/ conditions	Food matrix	Prominent discoveries	References
Grapes (*Vitis vinifera*) seed extract (GSE)	GSE likely targets the cell wall or membrane because of the polyphenols contents that can permeate the membrane and interact with intracellular proteins. It has been posited that the mechanism of action may involve metal chelation, decrease of hydrogen peroxide production, modulation of cell signaling pathways, and alteration in gene expression.	*Aeromonas* spp. *Aeromonas hydrophila, Bacillus cereus, Enterobacter aerogenes, Enterococcus faecalis, Escherichia coli, Klebsiella pneumoniae, Mycobacterium smegmatis, Proteus vulgaris, Pseudomonas aeruginosa, Pseudomonas fluorescens, Salmonella enteritidis, Salmonella typhimurium, Staphylococcus aureus* and *Yersinia enterocolitica*	0.52 mg GAE mL^{-1} for 20 min 1–5% 850–1,500 ppm	Snakehead (*Channa argus*) fillets Pork loin	GSE suppressed the proliferation of *Aeromonas* spp. and impeded the degradation of fillet quality. GSE suppressed Gram-positive foodborne bacteria but not Gram-negative ones. Concentration of 850–1,000 ppm suppressed Gram-positive bacteria whereas concentration of 1,250–1,500 ppm inhibited Gram-negative bacteria.	Cordery *et al.*, 2018; Corrales *et al.*, 2009; Jayaprakasha *et al.*, 2003 ; Li *et al.*, 2020; Pinto *et al.*, 2023
Thymoland carvacrol from oregano, thyme, sweet basil, black cumin, and savory	Thymol and carvacrol are documented to: (i) compromise bacterial cell membranes; (ii) diminish biofilm formation; (iii) impede microbial motility; (iv) suppress microbial ATP-ases; and (v) obstruct bacterial efflux pumps	*Z. rouxii* *Staphylococcus aureus*	MIC of 0.1–0.16 mM, treatment time 9 days MIC of 384.21 µg/mL for carvacrol and 511.84 µg/mL for thymol	Concentrated apple juice Milk and meat	Reduction of *Z. rouxii* load by 99% The mean minimum bactericidal concentration (MBC) against *Staphylococcus aureus* strains was 433.33 µg/mL for carvacrol and 561.64 µg/mL for thymol whereas if used in combination, they exhibited 1013.33-µg/mL MBC.	Kachur and Suntres, 2020; Pinto *et al.*, 2023; Rathod *et al.*, 2021; Rúa *et al.*, 2019; Wang and Sun, 2020
Green tea extract (GTE)	-	*C. jejuni, Staphylococcus aureus, E. coli, L. monocytogenes, S. typhimurium, V. parahaemolyticus, B. cereus, P. shigelloides, Cl. perfringens,* and *P. fluorescens.*	500 ppm	Frankfurter-type sausage	Extracts derived from green tea applied at 500 ppm demonstrated significant antimicrobial (total viable count) and antifungal (yeast and molds) efficacy during the storage of frankfurter-type sausages, inhibiting microbial growth (>1 log reduction with green tea), thereby extending the shelf life.	Alirezalu *et al.*, 2017; Santiesteban-López *et al.*, 2022
Cranberry pomace extract	Cranberry antimicrobial mechanism is likely due to the downregulated carbon starvation (slp) genes, hypothetical protein hdeA, and cyclopropane fatty acyl phospholipid synthase.	*B. thermospacta* and *P. putida*	2% extract 16 days of storage	Pork burgers	Bacteriostatic effect on *B. thermospacta* and *P. putida* during cold storage.	Pinto *et al.*, 2023; Tamkutė *et al.*, 2019
Olive leaf (extract)		*Listeria monocytogenes, Escherichia coli O157:H7,* and *Salmonella enteritidis*	Concentration of 62.6 mg/mL	-	Olive leaf extract at a dosage of 62.6 mg/mL was found to entirely suppress the development of *Salmonella enteritidis* and *Listeria monocytogenes,* attributed to the components oleuropein and verbascoside.	Liu *et al.*, 2017

organoleptic impacts of essential oils (Bodie *et al.,* 2024). Proposed methods involve encapsulating essential oils in nanostructures to enhance the shelf life and safety of ready-to-eat (RTE) meats (Jackson-Davis *et al.,* 2023).

Antimicrobial peptides (AMPs)

Notwithstanding the use of several preservatives to inhibit or slow microbial proliferation in food, the deterioration of food and the incidence of foodborne illnesses remain significant concerns. The resistance of microbes to antimicrobial drugs is becoming problematic, mostly linked to the misuse of these agents in medicine, animal husbandry, and agriculture, especially in developing nations. Numerous studies have documented significant levels of antibiotic residues in food products, including meat (Kamal *et al.,* 2023). The prevalence of multidrug-resistant (MDR) bacterial infections is rising in clinical environments; hence, rapid remedial actions are necessary to treat these bacterial species (Aslam *et al.,* 2021a, 2021b). Unlike traditional antimicrobial agents that target a restricted number of microbial sites, AMPs possess a broad spectrum of targets, presenting a robust method to mitigate the emergence of resistance (Maria-Neto *et al.,* 2015). AMPs may target many components within bacterial cells, including the cell wall, DNA, RNA, and regulatory enzymes, so enabling them to eliminate diverse bacterial strains, includingMDR bacteria. Besides direct assault, the AMPs safeguard the host through several methods, including the modulation of immunological and inflammatory responses and the preservation of normal gut homeostasis (Kamal *et al.,* 2023). Research on AMPs is proliferating, and substantial data about diverse AMPs are archived in databases (Silveira *et al.,* 2021).

Peptides are among the biomolecules that are responsible for the innate immune system. AMPs are the building blocks of the defense system in any living organism. They are found in almost all living organisms, from bacteria to plants and invertebrates to vertebrates, including mammals (Liu *et al.,* 2021). The AMPs obtained from bacteria are typically referred to as bacteriocins (Rai *et al.* 2016). Thuricin CD (a two-peptide antimicrobial produced by *Bacillus thuringiensis*), colicins, microcins, tailocins, pediocins, nisin, enterocins, aureocins, vibriocins, mutacin, cereins, reutericyclin, acidocin, halocins, and sakacin represent significant AMPs of bacterial origin (Huan *et al.*, 2020). AMPs are present in plants, mammals, amphibians, insects, fungi, and many animal species (Huan *et al.* 2020; Rai *et al.* 2016). Plant-derived AMPs are amphipathic, cysteine-rich short molecules with a molecular weight of roughly 2–10 kDa (Barashkova and Rogozhin 2020). A diverse array of AMPs is synthesized by insects, offering primary defense against biotic and abiotic stressors (Manniello *et al.* 2021). Insect AMPs exhibit significant antibacterial efficacy and a reduced likelihood of resistance development against these peptides. Defensins and cathelicidins are the principal AMPs in mammals, exhibiting antiviral, antibacterial, antifungal, antiprotozoal, and antioxidant properties (Dutta and Das 2015; Huan *et al.,* 2020; Kamal *et al.,* 2023).

Employing AMPs to mitigate microbial contamination can circumvent the toxicity associated with chemical additions and the emergence of antibiotic resistance. Furthermore, in contrast to low molecular-weight molecules, AMPs are subject to biodegradation by protease species (Xu *et al.,* 2023). The role of AMPs has facilitated their application in the preservation or storage of several food items, including cheese (Dinika *et al.,* 2020), yoghurt, juice (El-Saber Batiha *et al.,* 2021), vegetables, drinks, and meats (Borrajo *et al.,* 2019). Antimicrobial agents (AMPs) are mostly administered to fresh foods, such as vegetables, fruits, and meats by dipping and spraying techniques (De Souza De Azevedo *et al.,* 2019). A 1% (w/v) Nisaplin solution effectively inhibits *Lactobacillus sakei* infection in pig samples when applied via spraying (De Souza De Azevedo *et al.,* 2019).

Utilizing a singular sort of antimicrobial agent can preserve meat from contamination for one week at 4°C, irrespective of the application technique. A combination of nisin, natamycin, and citric acid can extend the shelf-life of fruit and vegetable smoothies by up to 14 days (Nieva *et al.,* 2022). In addition to fresh foods, the incorporation of nisin can increase the shelf-life of draft beer by 36 days (Sun *et al.,* 2012; Xu *et al.,* 2023), while the addition of AMPs can prolong the shelf-life of canned products by over 10 days (André *et al.,* 2017). Recent innovative applications of AMPs to control pathogenic microorganisms in food are summarized in Table 2. Enhancing the specificity and stability of AMPs is crucial for maintaining their functionality and preventing the elimination of nontarget cell types (Xu *et al.,* 2023). The characteristics of AMPs dictate their actions against their targets, including microorganisms and human cells (Lazzaro *et al.,* 2020). Numerous studies have shown that AMPs might eradicate species within multi-species communities (Franzenburg *et al.,* 2013; Guo *et al.,* 2015; Xu *et al.,* 2023), suggesting that their specificity may be tailored. Moreover, conjugating an AMP with a targeted moiety is an alternative method to enhance specificity (Song *et al.,* 2020). The categories of AP stability characteristics that can be enhanced are thermostability, pH stability, and protease cleavage tolerance. Numerous ways have been employed to engineer AMPs with specific functionalities and stability, including site-directed mutagenesis (Torres *et al.,* 2019), rational design of AMP secondary structures (Tripathi *et al.,* 2015), and modulation of charge and hydrophobicity (Khara *et al.,* 2017; Xu *et al.,* 2023).

Antimicrobial peptides have been thoroughly investigated as prospective bio-preservatives; however, their

Table 2. Innovative application of antimicrobial peptides to control pathogenic microorganisms in food.

Antimicrobial peptides	Source	Antimicrobial activity spectrum	Antimicrobial effect	References
Plantaricins	*Lactobacillus plantarum*	*Listeria monocytogenes* *Phytophthora infestans*	Plantaricin interacts with membrane lipids in a nonchiral manner and adopts an α-helical conformation prior to binding to the receptor that activates the pheromone action. It acts on cytoplasmic membrane, resulting in the dissipation of proton motive force and release of intracellular chemicals (e.g., glutamate and ATP) in susceptible cells.	Kareem and Razavi, 2020
Cecropin	Insects	*B. subtilis, Staphylococcus aureus, E. coli, B. thuringiensis, L. monocytogenes,* and *Phytophthora infestans*	The process by which host defence peptides, such as cecropins, operate on bacterial cells is believed to entail the interaction of amphipathic cationic peptide with the phospholipids of the target cell membrane, leading to either channel creation or membrane breakdown.	Brady *et al.,* 2019
Defensins	Insects	*Lactococcus, Pediococcus* spp., and *Pectinatus*	Host defense is the essential function of defensins as effectors and regulators. They are cationic peptides containing arginine residues that have antibiotic action against a wide range of bacteria.	Mohideen and Louis, 2021
Nisin (N)	*Lactococcus lactis* spp.	*Staphylococcus epidermidis* Shiga toxin-producing *E. coli* (STEC), *Salmonella* spp., *L. monocytogenes*, and *Staphylococcus aureus*	Inhibit the attachment of *Staphylococcus epidermidis* and prevent biofilm formation Composite antimicrobial film (CAFs) containing Nisin were ineffective against pathogens. Nonetheless, immobilized Nisin demonstrates varied *in vitro* anti-infective activity against Gram-negative *Escherichia coli* and Gram-positive *Staphylococcus aureus*, exhibiting a higher capacity to disrupt biofilm formation on polymer surfaces when combined with nitric oxide (NO).	Fael and Demirel, 2020; Hassan and Cutter 2020; Mondal *et al.,* 2021
Lactoferrin		Gram-positive bacteria (*Bacillus* spp., *Clos tridium* spp., *Enterococcus faecalis, Listeria monocytogenes*, and *Streptococcus* spp.), Gram-negative bacteria (*E. coli* O157:H7, *Pseu domonas aeruginosa*, and *Salmonella* spp.), yeasts (*Trichosporum cutaneum* and *Candida albicans*), fungi as well as parasites and viruses.	The antibacterial effects of lactoferrin are recognized for their potency, as follows: (1) Binding to cell surfaces, such as those of *Bacillus subtilis* and *E. coli*; (2) induction of bacterial cell damage through membrane disruption and alteration of ultrastructural characteristics in fungi; (3) release of lipopolysaccharides, leading to external membrane disruption; (4) interaction with bacterial phospholipid membranes; (5) disruption of primary cell membrane functions via ion channel formation in artificial membranes; and (6) impact on cytoplasmic contents and subsequent cell surface activity.	Dinika *et al.,* 2020

(*continues*)

Table 2. Continued.

Antimicrobial peptides	Source	Antimicrobial activity spectrum	Antimicrobial effect	References
Pediocin	*Pediococcus pentosaceus* and *Pediococcus acidilactici* strains	*Listeria monocytogenes, Clostridium perfringens, Bacillus, Enterococcus, Micrococcus, Lactobacillus, Staphylococcus, Leuconostoc*, and *Propionibacterium*	The antibacterial efficacy of pediocin is contingent upon its structure and executed by the development of holes in the target membrane. The holes facilitate ion and cellular compound leakage, release of cytoplasmic ATP, and suppression of proton motive force (PMF) essential for energy generation; ultimately, ensuing cell death when the leakage is beyond a critical threshold.	Khorshidian *et al.*, 2021
Enterocin	*Enterococcus* spp.	*Clostridium perfringens, Clostridium botulinum, Listeria monocytogenes, Staphylococcus aureus, Klebsiella pneumoniae, Escherichia coli, Pseudomonas* spp, and *Shigella sonnei, Salmonella enterica, Staphylococcus carnosus, Bacillus cereus, Bacillus licheniformis, Bacillus macroides, Paeni bacillus spp, Lactobacillus sakei, Alicyclobacillus acidoterrestris,* and *Geobacillus stearothermophilus*	The exceptional ability of enterocins to operate at severe temperatures, pH levels, and elevated salt concentrations renders them a promising bactericidal.	Kamal *et al.*, 2023; Soltani *et al.*, 2021
Epsilon-poly-L-lysine	*Streptomyces albulus, Streptomy ces noursei* NRRL5126, *Streptomyces aureofaciens, Streptomyces diastatochromogenes, Streptomyces griseofuscus, Bacillus subtilis* spp. *Kitasatospora*, and *Streptoverticillum*	Owing to its elevated cationic charge density, ε-polylysine has remarkable efficacy against Gram-positive and Gram-negative bacteria, bacteriophages, yeasts, and molds.	Upon entering the cytoplasm, ε-PL induces the generation of ROS, influencing cellular responses to oxidative stress and defense mechanisms, eventually hindering respiration, compromising cell viability, and potentially initiating cell death.	Wang *et al.*, 2021
Natamycin	*Streptomyces natalensis* and *Streptomyces chattanogenesis*	*Aspergillus* spp., *Fusarium* spp., *Candida* spp., *Cephalosporium* spp., *Penicillium* spp., and *Fusarium* spp.	Natamycin inhibits fungus by targeting ergosterol, the principal sterol in fungal cell membranes that causes cell lysing.	Davidson and Doan 2020; Ojaghian *et al.* 2020
Reuterin	*Lactobacillus reuteri*	*Listeria monocytogenes* and *Escherichia coli*	Demonstrates antimicrobial activity by functioning as a competitive inhibitor of ribonucleotide reductase, which is essential for cellular DNA synthesis, thereby inducing oxidative damage to bacteria through the depletion of free sulfhydryl groups in small proteins and other molecules, including reduced glutathione and enzymes.	Sun *et al.*, 2022
Pleurocidin	Fish	*L. monocytogenes, Escherichia coli* O157:H7, and *Vibrio parahaemolyticus* and *Penicillium expansum*	Pleurocidin demonstrates a robust capacity for membrane translocation and pore creation, interacting with both neutral and acidic anionic phospholipid membranes.	Kamal *et al.*, 2023; Villalobos-Delgado *et al.*, 2019

interactions with specific food constituents (proteins and fats) and their stability, including proteolytic degradation, may lead to diminished antimicrobial efficacy. To address these limitations, AMPs are utilized for encapsulation (Liu *et al.,* 2021). The encapsulation of peptides in liposomes is extensively documented in prior research, as it offers stability and safeguards against external environmental influences, including chemical and enzymatic alterations, thermal effects, and pH fluctuations (Becerril *et al.,* 2020; Liu *et al.,* 2021).

Biologically based antimicrobials

Biologically derived antimicrobials, mostly from microbes and bacteriophages, together with their metabolites, are utilized to inhibit the proliferation of unwanted bacteria and enhance food safety and quality. Microbially derived biologically based antimicrobials demonstrated efficacy in reducing mycotoxins in food products. The biological management of aflatoxins in maize grains, predicated on the competitive exclusion of toxigenic strains by the application of non-toxigenic strains, demonstrated some efficacy (Abbas *et al.,* 2006; Abdelhamid and El-Dougdoug, 2020). Multiple strains of *Lactobacillus* spp. demonstrated efficacy in the treatment and control of aflatoxins (Abdelhamid and El-Dougdoug, 2020; Palumbo *et al.,* 2006; Sangsila *et al.,* 2016).

Lactic acid bacteria (LAB) and bacteriocins

Lactic acid bacteria (LAB) are regarded as a method of biopreservation via food fermentation. Consumers embrace them as natural biopreservatives and health-enhancing microorganisms. LAB are incorporated into food to generate lactic acid, thus facilitating biopreservation through regulated acidification (Abdelhamid and El-Dougdoug, 2020). The effectiveness of lactic acid generation by LAB is contingent upon several conditions, including the fermentable carbohydrates in diet, the starting pH, and the development rate of LAB strains (Gobbetti and Di Cagno, 2017). Additional LAB metabolites, including diacetyl, hydrogen peroxide, and notably, bacteriocins, may impede the proliferation of foodborne pathogens (O'Bryan *et al.*, 2015). Over the last two decades, small compounds, such bioactive peptides, generated by LAB, have been developed and used in food applications aimed at mitigating microbial pathogenicity (Abdelhamid and El-Dougdoug, 2020) as discussed previously.

Numerous studies have investigated the application of several bacteriocins as biopreservatives in food to suppress harmful microorganisms (De Souza De Azevedo *et al.,* 2019; Furlaneto-Maia *et al.,* 2020; Xu *et al.,* 2022). Bacteriocins are antibacterial peptides or proteinaceous toxins produced by the ribosomes of bacteriocinogenic organisms, such as *Lactococcus lactis*, *Pediococcus acidilactici*, and *Enterococcus faecalis* (Balandin *et al.,* 2019; Pilevar *et al.,* 2020; Song *et al.,* 2017; Yoon and Kang, 2020). These natural food biopreservatives eliminate or inhibit the proliferation of many Gram-positive foodborne pathogens and spoilage bacteria (Pilevar *et al.,* 2020). They do not eliminate producer microorganisms and are synthesized ribosomally. Their mechanism of action is believed to impact exclusively Gram-positive bacteria, while some may also antagonize Gram-negative bacteria. Bacteriocins often induce damage to the cell membranes of target bacteria, and their application is becoming prevalent in food safety. Nisin and pediocin are the most extensively researched bacteriocins that may be employed commercially as natural preservatives (Acuña *et al.,* 2011; Khorshidian *et al.,* 2021) and authorized in over 50 countries, utilized as a preservative for processed vegetables, canned products, and fresh cheese (Abdelhamid and El-Dougdoug, 2020). Numerous studies indicate that bacteriocins generated by *L. sakei* and *L. curvatus* can reduce the population of *L. monocytogenes* in meat products (Casaburi *et al.,* 2016; Castellano *et al.,* 2018; De Souza Barbosa et al., 2015). They appear to exert their antimicrobial effects by creating holes in target cell membranes, obstructing nucleic acid production, altering the electrostatic potential of bacteria, and inhibiting certain enzyme activities (Khorshidian *et al.,* 2021). Nisin exhibits extensive inhibitory effect against Gram-positive bacteria, including *staphylococci*, and inhibits spore germination in *Clostridium* and *Bacillus* (Biswaro *et al.,* 2018; Gut *et al.,* 2011).

The application of effective bacteriocins against meat pathogens has garnered interest in the food sector, particularly for ready-to-eat or fresh-tasting meals, because their usage can reduce reliance on severe heat treatments and chemical preservatives (Hernández-Aquino *et al.*, 2019). Conversely, a daily intake of 2.9 mg per person is deemed safe for human consumption (Cleveland *et al.,* 2001; Khorshidian *et al.,* 2021). The identification of new bacteriocins, comparable to, or more potent than nisin or pediocin, is an expanding area of study in food safety (Wu *et al.,* 2019; Yang *et al.,* 2016).

Use of bacteriophages

Bacteriophages, viruses that specifically target bacteria, offer a precise and selective method for managing microbial contamination in food. These viruses have a particular affinity just for their specified bacterial targets, leaving helpful bacteria and host cells unscathed (Yan *et al.,* 2024). Bacteriophages are viruses that infect bacteria, multiply within the host, and those that are lytic induce cell lysis (Labrie *et al.,* 2010). Bacteriophages can be directly administered to food or utilized in the manufacture of food components to mitigate bacterial contamination (Herrera *et al.,* 2023). The use of bacteriophages for the biocontrol of foodborne pathogens has garnered heightened interest in recent years, although their application as preservatives is very novel. The primary benefits of using lytic bacteriophages to eliminate foodborne infections are their specificity, effective mode of action (Spricigo *et al.,* 2013), minimal impact on the organoleptic qualities of foods (Sharma *et al.,* 2005), and ubiquity (Abdelhamid and El-Dougdoug, 2020; Hughes *et al.,* 1998).

Increase in research about the effectiveness of bacteriophages in managing spoilage, pathogenic, and biofilm-forming bacteria is encouraging. Bacteriophages, characterized by cheap production costs and the capacity to augment existing antimicrobial techniques, improve the overall bactericidal efficacy (Yan *et al.,* 2024). Their integration with food packaging materials guarantees ongoing protection throughout storage (Vikram *et al.,* 2022). With the increasing customer desire for raw or minimally cooked seafood (Lee *et al.,* 2023), bacteriophages provide a viable option. Research indicates that they do not modify the sensory attributes of seafood and are safe for human eating, fully meeting practical application standards (Olatunde *et al.,* 2021; Yan *et al.,* 2024).

A substantial quantity of bacteriophages was isolated and utilized in various food matrices to mitigate Gram-positive (e.g., *Staphylococcus aureus* and *L. monocytogenes*) and Gram-negative (e.g., Salmonella spp., *E. coli* O157:H7, and *Pseudomonas syringae*) bacterial pathogens, with efficacy contingent upon food type and phage concentration. Bacteriophage DT1 and DT6 achieved total elimination of *E. coli* O157:H7 in milk (Tomat *et al.,* 2013) whereas a bacteriophage cocktail applied to spinach blades resulted in a decrease of 4.5 log colony-forming units (CFU) per blade (Patel *et al.,* 2011).

This indicates that the efficacy of bacteriophages is greater in liquid meals, compared to solid foods. While not an absolute guideline, elevated titres (often termed plaque-forming units [PFU]) of bacteriophages employed in food applications correlate with increased inactivation proportions of foodborne pathogens. Commercial bacteriophage formulations, including ListShield™, SalmoFresh™, and EcoShield™ (Intralytics, Columbia, MD, USA), have received approval for use in food to combat *L. monocytogenes*, *Salmonella* spp., and *E. coli*, respectively, within food and food-processing settings (Abdelhamid and El-Dougdoug, 2020).

Application of natural antimicrobial hurdle strategies

Natural antimicrobials have significant potential to inhibit the proliferation of foodborne pathogens in food by targeting microbial cellular structures or maintaining microbial cell homeostasis. The antibacterial efficacy of these natural agents in food diminishes due to the physical and chemical constituents of the food environment. Consequently, ways are perpetually devised to enhance antimicrobial efficacy by synergism, regulating the administration of antimicrobials in food, or integrating them into packaging materials (Abdelhamid and El-Dougdoug, 2020).

Enhancing the antimicrobial efficacy of natural antimicrobials can be achieved through synergistic interactions among several antimicrobials or between antimicrobials and food-related stresses. This synergistic interaction, referred to as the hurdle strategy, seeks to achieve optimal lethality against foodborne pathogens (Leistner, 2000). The sequential application of lipopeptide paenibacterin and desiccation stress led to a substantial decrease in the population of *S. enterica* serovars (1.5–1.9 log CFU/mL) in contrast to desiccation stress alone, which resulted in little reduction (<0.1 log CFU/mL) (Abdelhamid and Yousef, 2019). The slow release of antimicrobials into the food environment might boost the suppression of target foodborne bacteria. A bimodal delivery strategy for nisin was developed, with an initial rapid release followed by a gradual decline in release rate over time (Abdelhamid and El-Dougdoug, 2020; Balasubramanian *et al.,* 2011). This method of controlled administration proved more successful in suppressing *Micrococcus luteus*, a model bacterium, than the immediate addition of nisin. The use of natural antimicrobials as coatings or their integration into packaging materials often diminishes the prevalence of foodborne infections and prolongs the shelf life of food items. Chitosan films, including 60% lysozyme, effectively decreased *E. coli* by 2.7 log units (Abdelhamid and El-Dougdoug, 2020; Park *et al.,* 2004).

Antivirulence strategies

These natural preservatives may prolong the shelf life of food products; nevertheless, some exhibit some limitations (Davidson *et al.,* 2013). Certain naturally occurring antimicrobials are present in minimal quantities, and elevated levels may alter the flavor and aroma of foods (e.g., spices). Despite their significant antimicrobial efficacy, difficulties arising from the adaptability of foodborne pathogens to these control approaches are becoming evident. This adaptation facilitates the survival of infections in food or food-contact situations. This critical issue motivates the current research and the food business to create solutions that do not inhibit bacteria growth but rather neutralize pathogenic virulence factors. These technologies, termed 'antivirulence', incapacitate the microbe's ability to induce disease while providing minimal or no chances for harmful bacteria to acquire resistance (Abdelhamid and El-Dougdoug, 2020). Antivirulence methods have emerged as a novel approach to manage harmful microorganisms in food. Virulence factors are bacterial compounds that enable adherence, colonization, invasion, evasion of the host immune system, or harm to the host (Defoirdt, 2018).

The emergence of antibiotic resistance and the advancing comprehension of virulence determinants across diverse infections have catalyzed increased interest in antivirulence strategies (Abdelhamid and El-Dougdoug, 2020). The optimistic potential of antivirulence agents is ascribed to their swift target inactivation, minimal effect on commensal microbiota, and reduced pressure on the target pathogen, thereby diminishing opportunities for resistance development (Fleitas Martínez *et al.,* 2019; Langdon *et al.,* 2016; Vale *et al.,* 2016). One of the rapidly developing antivirulence techniques is quorum-sensing (QS) inhibitors. Quorum sensing is a communication mechanism that regulates bacterial behavior, such as the orchestration of virulence gene expression in a manner dependent on cell density, facilitated by signaling molecules termed 'autoinducers' (Papenfort and Bassler, 2016). Anti-QS agents seek to eliminate autoinducers or disrupt their interaction with the host, resulting in diminished expression of virulence genes (Abdelhamid and El-Dougdoug, 2020; Mundi *et al.,* 2013). QS autoinducers have a role in the capacity of microbial pathogens to develop biofilms. Biofilm is a multicellular phenotype of bacterial cells that aggregate, adhere to surfaces, and are encased in a polymeric matrix. Biofilm is essential for pathogenesis in some microbial illnesses (Wu *et al.,* 2015).

Research highlighted the efficacy of employing helpful bacterial cells (e.g., *Lactobacillus* and *Bifidobacterium*), chemical agents (e.g., chalcone), or biological molecules (e.g., mucin) to mitigate the virulence of both Gram-positive and Gram-negative pathogenic bacteria (Abdelhamid and El-Dougdoug, 2020). Instances of the most efficacious antivirulence agents, probiotics, which are characterized as 'live microorganisms that, when administered in sufficient quantities, confer a health benefit to the host' (Abdelhamid *et al.,* 2019; Hill *et al.,* 2014) are demonstrating significant potential. Peptide-based small compounds released by probiotics effectively decreased the virulence of *E. coli* O157:H7, *Salmonella typhimurium*, and *Campylobacter jejuni* (Abdelhamid and El-Dougdoug, 2020; Bayoumi and Griffiths, 2012; Ding *et al.,* 2005; Medellin-Peña and Griffiths, 2009).

Technological-Based Food-Processing Strategies

Minimally processed food items that preserve their freshness and nutritional qualities have garnered significant attention from consumers in recent years. To address increasing client needs, the investigation of new technologies to supplant traditional ways has become essential. Meal-processing methods can effectively eliminate unwanted bacteria while preserving the quality and nutritional attributes of the meal. Innovative food-processing techniques, utilizing advanced technologies, such as nanotechnology, high hydrostatic pressure (HHP), electrical pulses, heat treatment, ionizing radiation, microwave, ohmic heating, and HPP, have demonstrated efficacy in diminishing microbial load in food items, including meat, fruits, and vegetables (Herrera *et al.,* 2023; Lee *et al.,* 2016). Emerging technology in food processing may substantially reduce processing period, conserve energy, and enhance food safety, thereby helping the food business (Lee *et al.,* 2016; Nguyen *et al.,* 2013).

The future and success of these innovative technologies are likely to be propelled by customer demand for safe and fresh processed foods and the necessity for sustainable, energy-efficient methods in the food sector (Ngadi *et al.,* 2012). This section categorizes emerging technological-based food-processing solutions into thermal, nonthermal, and combination of processing approaches. The principle, advantages, limitations, and applications of thermal and nonthermal technologies are summarized in Table 3.

Novel thermal technologies

The challenges inherent in conventional food-processing technologies have necessitated the development of innovative food-processing technologies. The principal obstacles in improving traditional heating technology in heat-applied food processing are the excessive utilization of heat sources, extended heating periods, and the degradation of product quality (Maspeke *et al.,* 2024; Moreno-Vilet *et al.,* 2018). Unlike conventional heat technologies that utilize conduction, convection, or radiation for pathogen and enzyme inactivation and food preservation, modern heat technologies employ electromagnetic fields or electrical conductivity to generate heat via dipole molecular rotation and ionic migration, thereby replacing electric fields or electrical conductivity (Maspeke *et al.,* 2024). This substitution diminishes heating duration relative to traditional heating systems (Fellows, 2017). This heating system offers time efficiency along with other benefits, such as energy conservation, superior sensory attributes, and increased functional characteristics, relative to conventional heating methods. Thus, this nascent technology possesses significant potential for future applications (Pereira and Vicente, 2010). Recent improvements in thermal technology encompass microwave heating, radiofrequency heating, infrared heating, induction heating, and ohmic heating (Maspeke *et al.,* 2024).

Microwave Heating

Microwaves (MW), a segment of the electromagnetic spectrum with a frequency range of 300 MHz–300 GHz, are widely utilized in food-processing applications, such

Table 3. **Principle, advantages, limitations, and applications of thermal and nonthermal technologies.**

Method	Category	Principle	Advantages	Limitations	Applications
Microwave	Thermal	Radiowaves absorbed by water, fats, and sugars and other dielectric fluids are converted to atomic motion causing frictional heat (dielectric heating).	Fast and efficient process, retains product quality, easy melting process, sterilization effect.	Metal constraint, difficulty in heat control, water evaporation.	Used for drying, blanching, sterilization, tempering, cooking, and baking.
Radiofrequency	Thermal	Electric field production and movement of charged particles cause heat generation.	Faster healing and drying time, uniform heating, moisture levelling, contactless heating, energy efficiency.	Expensive equipment and operating cost.	Used for drying, post-baking, thawing of frozen foods, pasteurization, sterilization, disinfestations, cooking.
Infrared	Thermal	Provides electromagnetic radiations, which are absorbed by the objects and heated directly.	High heat transfer capacity, homogenous heating, low heating time and energy consumption, improved product quality.	High heat exposure and limiting penetration power.	Used for roasting, frying, cooking, dehydration, pathogen inactivation.
Ohmic heating	Thermal	Passage of electric current through a body, which serves as electrical resistance by which heat generates.	High conversion efficiency, quickly achieve required temperature, high heating rate, and uniform heating.	Difficult to monitor and control, high installation cost, cannot apply to all foods, increased electrical conductivity of food material.	Used for peeling, thawing, blanching, evaporation, and dehydration.
Cold plasma	Nonthermal	Passage of processed gas through electric field generates the collision of free electron with gas atoms, transferring their energy and generating highly reactive species.	High chemical reactivity, low operating cost, short treatment time, low temperature-dependent, environment-friendly.	High investment and complexity, insufficient to kill all microorganisms, can affect the constituents of food, ineffective against virus.	Used for the surface of raw produce and the packaging materials.
Ozonization	Nonthermal	Combination of ozone gas produced by high electrical voltage that reacts with microorganisms and pollutants.	Effective and rapid against bacteria and viruses, strong oxidizing power, strong germicidal properties, short reaction time.	Expensive methods, less soluble in water, fire hazards and toxicity issues.	Used for sanitization, deodorization, and preservation of food products.
Pulsed light (PL)	Nonthermal	Damages DNA/RNA strands of bacteria through high-intensity light pulses of short duration.	Fast and effective against bacteria, viruses, and short reaction time.	Uneven exposure, sample browning, limited penetration.	Used for the surface of food, equipment, and foodpackaging materials.
Ultrasound (US)	Nonthermal	Cavitation by contraction and rarefaction causing bubble implosions, leading to localized rise of temperature and pressure that causes decontamination.	Faster energy and mass transfer, reduced thermal and concentration gradient, faster response to process extraction control.	Texture deformation, modification of macromolecules, undesired compounds formed.	Used for food emulsification, sterilization, extraction, and freezing fresh foodstuffs.
Irradiation	Nonthermal	Uses ionizing radiations generated by radioactive sources.	Reduction of chemical use, can be used for packed foods, can control sprouting period, no residual trace of treatment.	High process cost, adequate product volume required, not effective against viruses, no inconsistency in standards.	Used for prepackaged of bulk foodstuffs, bacterial inactivation by DNA damage.
High hydrostatic pressure (HHP)	Nonthermal	Application of pressures >100 MPa and upto 900 MPa (usually 600 MPa) on food enclosed in packages that can withstand high pressure.	Retains polyphenols, minimal impact on nutrients, fast processing period.	Batch or semi-continuous process, bacterial spores not inactivated using pressure alone.	Used for protein denaturation and bacterial destruction.

Note. Reproduced from Sirohi *et al.* (2021).

as drying, tempering, and frying, because of their ability to heat food rapidly and directly (Lee and Jun, 2011). Figure 1 illustrates the microwave-processing system. Consequently, microwave heating can significantly reduce processing duration and effectively preserve important thermo-labile components of food (Coronel *et al.,* 2003; Lee *et al.,* 2016). Microwave treatment is linked to several detrimental effects on seed germination and may lead to diminished grain quality (Dalmoro *et al.,* 2018; Taheri *et al.,* 2020). The detrimental impact of microwaves arises from nonuniform heating resulting from temperature disparities between cold and hot spots (Taheri *et al.,* 2020). Microwaves operate through the dielectric effect, therby heating only regions containing dielectric fluids (e.g., water), resulting in localized hot spots (Sirohi *et al.,* 2021). The adverse effects of microwave therapy can be mitigated by enhancing the homogeneity of radiation and the temperature of hot spots. Methods to mitigate the detrimental impact of microwaves encompass the use of mode stirrers (Ye *et al.,* 2017), the agitation of particles by hot air (Kudra, 1989; Sirohi *et al.,* 2021), and the meticulous regulation of surface temperature and microwave power (Koné *et al.,* 2013).

Radiofrequency heating

Analogous to microwave heating, radio frequency (RF) heating, categorized as dielectric heating, swiftly and uniformly warms solid or semisolid food products (Lee *et al.,* 2016; Wang *et al.,* 2003). Radio frequency is a nonionizing wave with a wavelength of up to 11 m and a frequency range of 1–300 MHz (Hassan *et al.,* 2019). Radio frequency waves are electromagnetic waves capable of penetrating dielectric materials and generating heat volumetrically by ionic polarization or dipole rotation (Hassan *et al.,* 2019; Hou *et al.,* 2016). The schematic oultine of the radio frequency heating process is shown in Figure 2. Radio waves have greater penetration capabilities than microwaves, attributable to their longer wavelength, resulting in a larger penetration depth (Sirohi *et al.,* 2021). The moisture content of material is the primary component influencing the dielectric characteristics and enhancing heating uniformity throughout the radio frequency process (Sacilik and Colak, 2010). Food grains function as dielectric materials, serving as electric capacitors and resistors to store and transfer electrical energy into heat energy when exposed to an electromagnetic field (Ling *et al.,* 2020).

Jiao *et al.* (2017) indicated that the modest radio frequency heating for 5 min effectively eradicated juvenile rice weevils (eggs and adults) in rough, brown, and milled rice. Radio frequency treatment of maize seeds indicated that elevated moisture content decreased the thermal resistance of *Aspergillus parasiticus*, resulting in a 5–6 log reduction at 70°C in hot air for 12 min at 15% moisture content on a wet basis (Zheng *et al.,* 2017). It may be inferred that an increase in the moisture content of grain seeds enhances fungus suppression by radio frequency therapy (Ling *et al.,* 2020). Besides the disinfestation and disinfection of grains, the impact of radio frequency treatment on grain quality is examined to assess storage stability, customer acceptance, and market viability (Hassan *et al.*, 2019; Ling *et al.,* 2020).

The radio frequency treatment of maize grains (14% moisture on a wet basis) infected with maize weevils at 50–60°C did not modify the main structure of proteins and enhanced the emulsifying and oil-holding characteristics (Hassan *et al.,* 2019). Radio frequency treatment at 57°C resulted in the total eradication of rice moths without affecting the fat, protein, or moisture content of milled rice while enhancing sensory characteristics and cooking quality (Yang *et al.,* 2018). Radio frequency treatment at temperatures of more than 100°C may enhance the creation of superior emulsions and adsorbents, while lower temperatures might maintain functional qualities and diminish infestations (Sirohi *et al.,* 2021). Radio frequency heating may improve uniformity in surface heating of food products, thereby reducing thermal lag between the surface and the interior (Richardson, 2001);

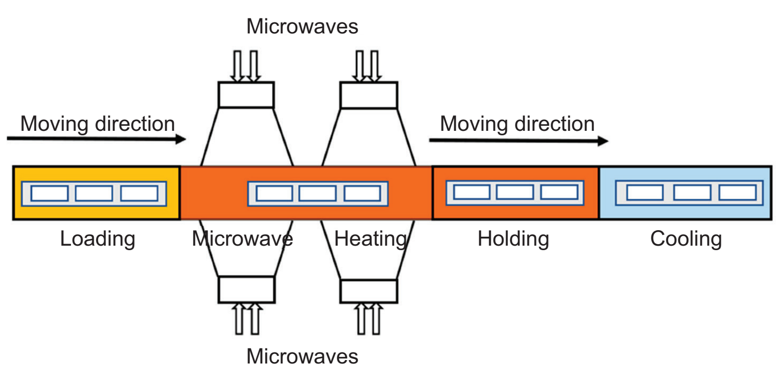

Figure 1. The microwave-processing system (896 MHz). (Reproduced from Wang *et al.*, 2023).

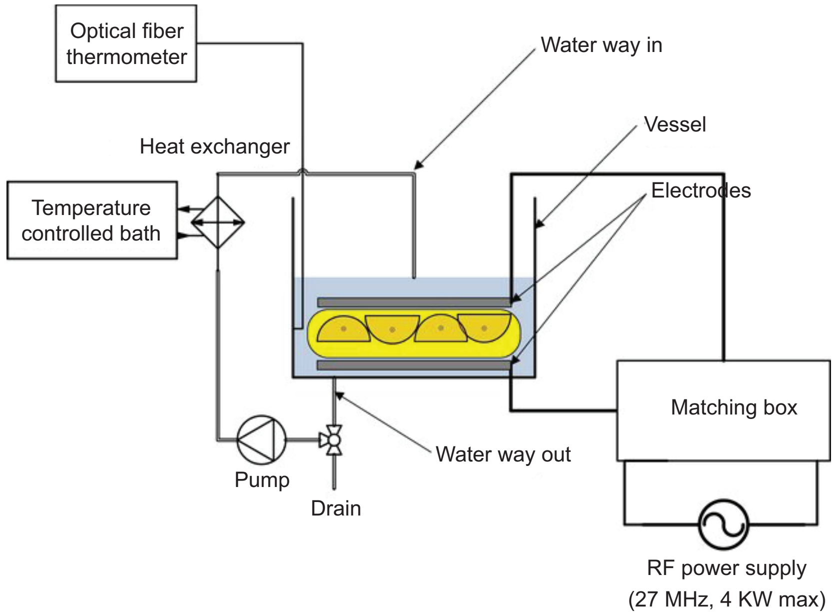

Figure 2. Schematic diagram of the radio frequency heating process. (Reproduced from Lara *et al.,* 2022).

however, the rate of radio frequency heating is significantly influenced by the dielectric properties of food (Birla *et al.,* 2008; Lee *et al.,* 2016).

Ohmic heating

Ohmic heating, also known as Joule heating, electrical resistance heating, or electroconductive heating, operates on the basis that most food items possess the capacity to resist the flow of electric current (Pereira and Vicente, 2010). This is a contemporary thermal-processing method that involves passing an electric current through food, producing heat because of food's electrical resistance (Maspeke *et al.,* 2024; Varghese *et al.,* 2014). In contrast to microwave and radio frequency heating, ohmic heating possesses an unrestricted penetration depth. In ohmic heating, the electrode must maintain contact with food that possesses adequate volumetric heat to regulate energy. Unlike conventional thermal processing, ohmic heating consistently elevates the temperature of food, resulting in a superior product with minimum nutritional degradation (Deeth and Datta, 2011). Ohmic heating preserves nutrients by averting the scorching of some regions of the product (Maspeke *et al.,* 2024). This method can uniformly heat bigger food particles (up to 2.54 cm), a capability that conventional heating fails to provide (Deeth and Datta, 2011; Kaur and Singh, 2016).

Ohmic heating has potential for food processing, particularly for heating liquid meals with substantial particles, such as soups, stews, and fruit slices in syrups and sauces, as well as heat-sensitive liquids (Cho *et al.,* 2016; Kaur and Singh, 2016; Saxena *et al.,* 2016; Soisungwan *et al.,* 2020). Ohmic heating offers the food business the potential to produce products of higher quality, increased value, and better nutritional preservation (Turgut *et al.,* 2021; Varghese *et al.,* 2014). Ohmic heating demonstrates effective preservation of nutritional and phytochemical content as well as sensory attributes of food items (Gavahian and Chu, 2022; Guida *et al.*, 2013; Makroo *et al.,* 2017; Negri Rodríguez *et al.*, 2021). Moreover, the synthesis of furan, a carcinogenic substance generated during heating, transpires at a diminished rate in ohmic heating, compared to conventional heating (Hradecky *et al.,* 2017; Maspeke *et al.,* 2024).

Additional significant advantages attributed to ohmic heating technology, as noted by Pereira and Vicente (2010), encompass the rapid attainment of temperatures necessary for high-temperature short-time (HTST) processes, compatibility with continuous processing devoid of heat transfer surfaces, uniform heating of liquids with accelerated heating rates, diminished issues of surface fouling or product overheating, and the production of fresher-tasting, higher-quality products. Additional advantages encompass the absence of residual heat transfer post-current cessation, minimal heat losses, efficacy in pre-heating items prior to canning, reduced maintenance expenses because of the absence of moving components, and elevated energy conversion efficiencies within an environmentally sustainable framework. The potential industrial uses of ohmic heating are extensive and encompass blanching, drying, evaporation, dehydration, and fermentation (Alkanan *et al.,* 2021). Ohmic heating technique facilitates the use of elevated pasteurization temperatures because of its very quick heating proportions, thereby enhancing refrigerated shelf life without causing coagulation or severe denaturation of the constituent proteins (Alkanan *et al.*, 2021). Consequently, the emphasis of ohmic heating is presently directed on thermal-processing procedures for food preservation, because this technology may be realized in a continuous in-line heater for cooking and sterilization (Pereira and Vicente, 2010).

Nonetheless, ohmic applications in the food sector have many drawbacks, including the possible loss of heat-sensitive elements, such as vitamins and polyphenols, elevated equipment costs, and the necessity for rigorous process control to guarantee uniform heat dispersion. Ohmic heating presents significant challenges at the industrial scale, since differences in particle size and food content could affect heat dispersion (Alkanan *et al.,* 2021; Maspeke *et al.,* 2024; Rinaldi *et al.,* 2020).

Infrared radiation (IR) heating

Infrared is a segment of the electromagnetic spectrum situated between microwaves and the visible area, with wavelengths ranging from 0.5 μm to 100 μm (Sirohi *et al.,* 2021). Infrared radiation, a segment of electromagnetic spectrum, is categorized into three sections (near-, mid-, and far-infrared) based on their spectral wavelengths (Lee *et al.,* 2016). Infrared radiation is utilized in several thermal processes because of its intrinsic benefits, including surface radiation impact on food and swift penetration into food items (Datta and Ni, 2002; Lee *et al.,* 2016; Sakai and Hanzawa, 1994). Infrared light penetration induces vibrational motion in water molecules, resulting in heat creation (Aboud *et al.,* 2019; Sakai and Hanzawa, 1994). Infrared technology is energy-efficient, environmentally sustainable, and requires less water than traditional heating methods. It demonstrates several benefits, including reduced heating duration, uniform heating, minimal energy usage, elevated heat-transfer efficiency, and enhanced product quality (Sirohi *et al.,* 2021). Owing to these characteristics, infrared technology is utilized in numerous food-manufacturing processes, including drying, peeling, boiling, polyphenol recovery, antioxidant recovery, heating, freeze-drying, roasting, microbiological inhibition, sterilization of grains, juice and bread production, and cooking (Aboud *et al.,* 2019). Infrared treatment of mung beans for 5 min at an intensity of 0.29 kW/m^2 at a temperature of 70°C resulted in total visible suppression of fungal growth (Meenu *et al.,* 2018). The limited penetration depth of infrared diminishes its efficacy with greater food thickness, making it more suitable for sterilizing food surfaces (Aboud *et al.,* 2019). The catalytic infrared emitter is employed to combat rice weevils, merchant grain beetles, and saw-toothed grain beetles (Sirohi *et al.,* 2021). A brief exposure of 60 s is often adequate to manage insects that infest the exterior or inside of stored grains (Ramaswamy *et al.,* 2012; Sirohi *et al.,* 2021). Infrared tempering treatment is beneficial for grain modification. Freshly harvested raw and stored rice contaminated with *Aspergillus flavus* spores underwent infrared tempering treatment and infrared heating (Wang *et al.,* 2014).

Novel nonthermal-processing technologies

Thermal treatment is a predominant method for microbial inactivation in food products. Heat induces undesirable impacts on the sensory, nutritional, and functional attributes of foods. The rising consumer desire for 'fresh-like' less processed foods has spurred the advancement of sophisticated and gentler food preservation techniques (Niakousari *et al.,* 2018). The phrase 'nonthermal processing' commonly refers to technologies that operate effectively at ambient or sublethal temperatures (Pereira and Vicente, 2010). Cold plasma technology, nanotechnology, PEF, HPP, HHP, high-intensity ultrasound (US), ultraviolet (UV) light, pulsed light (PL), ionizing radiation, and oscillating magnetic fields exhibit significant potential for the inactivation of microorganisms to varying extents (Butz and Tauscher, 2002; Pereira and Vicente, 2010). Certain treatments may involve heat through the generation of internal energy (e.g., adiabatic heating and resistive heating during HHP and PEF, respectively); however, they are categorized as nonthermal because, unlike thermal-processing technologies, they can eradicate microorganisms without employing high temperatures, thereby preventing adverse effects on flavor, color, and nutritional value of foods (Pereira and Vicente, 2010).

Ultraviolet (UV-C) radiation

Ultraviolet radiation technology is a nonthermal method and a viable alternative to conventional thermal treatments for the pasteurization of food items (Ashrafudoulla *et al.*, 2023).

Ultraviolet radiation is an economical therapy that does not produce chemical residues, thus qualifying as green technology (Yuan *et al.,* 2021). In the food business, ultraviolet light is mostly utilized for the decontamination of surfaces, equipment, food packaging, and air disinfection (Ashrafudoulla *et al.,* 2023). The various categories of ultraviolet light include UV-A (315–400 nm), which has a relatively longer wavelength and penetrates the epidermis and dermis; UV-B, known as 'burn rays' (280–315 nm), which can cause skin burns and skin cancer; UV-C, referred to as the 'germicidal range' (200–280 nm), which effectively eliminates pathogenic microbes; and vacuum-UV (100–200 nm), which can inactivate various human microbes (Ashrafudoulla *et al.,* 2023;

Delorme *et al.* 2020). Consequently, UV-C radiation represents the greatest energy segment of the Ultraviolet radiation spectrum and is among the most effective developing technologies utilized in food processing, exhibiting superior energy efficiency relative to traditional heat treatments (Ramos *et al.,* 2024).

Ultraviolet irradiation induces DNA damage, resulting in a fatal impact on microorganisms. Exposure to ultraviolet light generates cyclobutene pyrimidine dimers in DNA, thereby obstructing fresh DNA synthesis and eventually hindering microbial development. UV-C radiation (200–280 nm) is an effective method for destroying microbial DNA (Ashrafudoulla *et al.*, 2023). Ultraviolet irradiation is suggested as a germicide because of its fatal impact on several microorganisms, including bacteria, viruses, fungus, and algae (Shin *et al.,* 2016).

Among the four ultraviolet wavelength ranges, UV-C light has significant germicidal efficacy (Ashrafudoulla *et al.,* 2023). Historically, UV-C has primarily been utilized for surface disinfection; however, recent decades have demonstrated its potential for direct application in various food matrices, including vegetables, meat products, and beverages (Atik and Gumus, 2021; Hosseini *et al.,* 2019; Yang *et al.*, 2017). The germicidal efficacy of UV-C light on human enteroviruses in water was investigated by utilizing a device that emits polychromatic light wavelengths of 260 and 280 nm (Woo *et al.,* 2019). Findings indicated that ultraviolet light-emitting diodes (LEDs) efficiently inactivated the examined enteroviruses (Ashrafudoulla *et al.,* 2023). Ultraviolet radiation at 260 nm or 280 nm is the most effective wavelength for demonstrating significant inactivation properties in water treatment; however, because to its reduced cost and enhanced effectiveness, the 280-nm wavelength is preferred (Ashrafudoulla *et al.,* 2023; Li *et al.,* 2019).

UV-C light was employed to cleanse vegetative cells and spores of *Alicyclobacillus acidoterrestris* introduced in orange juice (Zhai *et al.,* 2021). Vegetative cells and spores were decreased by 6.04 log CFU/mL and 2.49 log CFU/mL, respectively, following UV-C treatment at 275 nm for 220 mJ/cm². Despite observable color alterations and a little reduction in total phenolic content, the UV-C light treatment did not significantly affect the physicochemical qualities of the juice (Ashrafudoulla *et al.,* 2023). Furthermore, UV-C radiation is regarded as an effective method for diminishing harmful microorganisms in dairy products. The efficacy of UV-C light in eradicating pathogenic bacteria in skimmed milk was assessed utilizing a collimated beam at a wavelength of 253.7 nm (Delorme *et al.*, 2020). The findings indicated that a UV-C dosage of 40 mJ/cm² effectively inactivated over 5 log of *E. coli* ATCC 25922, *Salmonella typhimurium* ATCC 13311, and *L. monocytogenes* ATCC 19115 (Ashrafudoulla *et al.,* 2023; Gunter-Ward *et al.* 2018).

Cold plasma technology

In the food business, several green technologies are implemented to eliminate germs from manufacturing lines and products, thereby preventing quality deterioration, recalls, and outbreak of foodborne diseases (Nwabor *et al.,* 2022). This has resulted in a boom of discussions on the applicability of green technology in the preservation and shelf-life extension of processed food, ensuring that this remains unmodified while maximizing consumer safety and protection. The efficacy of most green technologies is constrained by the development of resistant spores in specific foodborne bacteria and the synthesis of poisons. In the last decade, plasma technology has been widely utilized in the food sector as a novel and promising nonthermal cleaning method. Despite the necessity for elevated energy levels in plasma induction, recent progress in plasma physics has enabled the production of 'cold plasma' at ambient temperatures and atmospheric pressures. Cold plasma, a unique nonthermal method, has demonstrated significant efficacy in spore inactivation and deactivation of enzymes and toxins to assure the microbiological safety of food (Nwabor *et al.,* 2022). Figure 3 outlines the reactive species in cold plasma responsible for the surface decontamination of food grains. The approach employs plasma, including ionized or partly ionized gases, to deactivate food contaminants, such as microbial cells, enzymes, and toxins. Plasma is generated by either heating gas in a sealed container under high vacuum or by employing radiofrequency or microwave energy to energize gas molecules, resulting in the formation of free radicals, which are the primary components of plasma (Nwabor *et al.,* 2022). The technology's efficacy has been shown in several published publications across a diverse range of food items, encompassing both natural and processed foodstuffs. The method's application to surface sanitization of in-package fruit and various food products, such as vegetables, meat, and cereal grains, has yielded promising results, effectively eradicating microorganisms, extending shelf life, minimizing spoilage losses, and enhancing the nutritional, functional, and sensory attributes of food products (Starek *et al.,* 2019). Moreover, cold plasma technology presents various benefits, such as expedited processes, increased efficiency, reduction of procedural steps, superior product quality, preservation of product attributes (e.g., texture, nutritional value, and organoleptic properties), and extended shelf life (Nwabor *et al.,* 2022).

Nanotechnology

Nanotechnology involves the examination and utilization of minuscule entities at the nanometre scale throughout several scientific domains. Increasing customer apprehensions over food quality and health advantages are driving researchers to identify methods that might

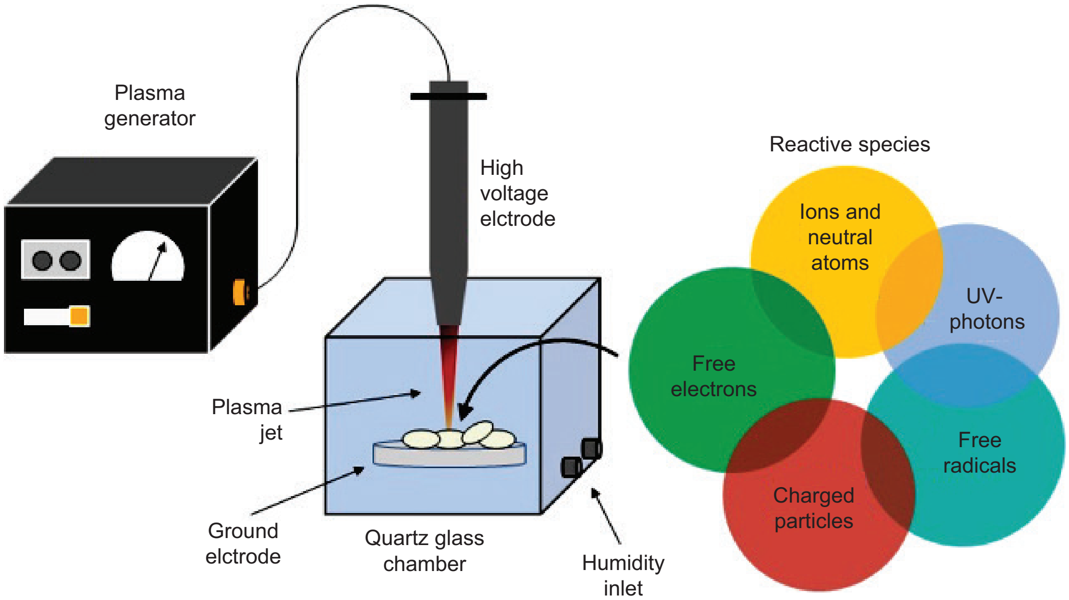

Figure 3. Reactive species in cold plasma responsible for surface decontamination of food grains. (Reproduced from Sirohi *et al.*, 2021).

improve food quality while minimally affecting the product's nutritional value. The need for nanoparticle-based products in the food sector has risen, as many include vital nutrients and are deemed nontoxic (Roselli *et al.*, 2003; Singh *et al.*, 2017). Nanotechnology enables the manipulation and modification of materials and systems at the nanoscale, resulting in properties that differ markedly from those at a larger scale.

The uses of nanotechnology in the food business may be categorised into two primary groups: food nanostructured ingredients and food nanosensing (Singh *et al.*, 2017). Food nanostructured substances span a broad spectrum, including food processing and packaging. In food processing, these nanostructures serve as food additives, carriers for the intelligent delivery of nutrients, anti-caking agents, antimicrobial agents, and fillers to enhance the mechanical strength and durability of packaging materials. Additionally, food nanosensing is utilized to improve food quality and safety assessment (Ezhilarasi *et al.*, 2013; Singh *et al.*, 2017). Nanotechnology has novel prospects for microbial regulation in food. Antimicrobial nanomaterials, including silver and copper nanoparticles, have inhibitory effects against many foodborne bacteria. These compounds are integrated into food packaging, coatings, and surfaces to inhibit microbial contamination (Herrera *et al.*, 2023). Nanotechnology in the food industry includes the use of nanosensors, nanomaterials, nanocomposites, nanoencapsulation, and nanocoatings. Nanosensors detect carcinogens in food products, signal food spoilage by indicating minor alterations in gas composition and color, raise awareness among consumers and distributors regarding food safety by identifying pathogens, and monitor changes in the storage environment, including microbial contamination and fluctuations in temperature and humidity that may lead to food degradation (Girthie John Britto *et al.*, 2023).

Inorganic and organic nanoparticles are employed in antibacterial food packaging to preserve the color and stability of food items while preventing development of microbial biofilm. Figure 4 outlines the nanoformulation-based system for food grain decontamination. Nanoparticles inhibit moisture loss by limiting oxygen permeation into food containers, thus preserving food freshness for extended storage period. Nanocomposites, formed by integrating nanoparticles with polymers, enhance quality and extend the shelf life of many food items. Many bioactive chemicals found in dietary items frequently degrade under severe environmental circumstances (Girthie John Britto *et al.*, 2023). The nanoencapsulation of bioactive substances prolongs food's shelf life by mitigating or preventing degradation until reaching the target location.

Nanocoatings comprise homogenous layers of nanoparticles measuring between 10 nm and 100 nm, utilized for detecting small storage pollutants. Nanocoatings efficiently preserve antibrowning agents, antioxidants, enzymes, flavors, and colors by inhibiting gaseous exchange and moisture in diverse food substances. One notable benefit of nanocoatings is their ability to preserve the shelf life of processed food items even after opening of packaging. Although nanotechnology offers

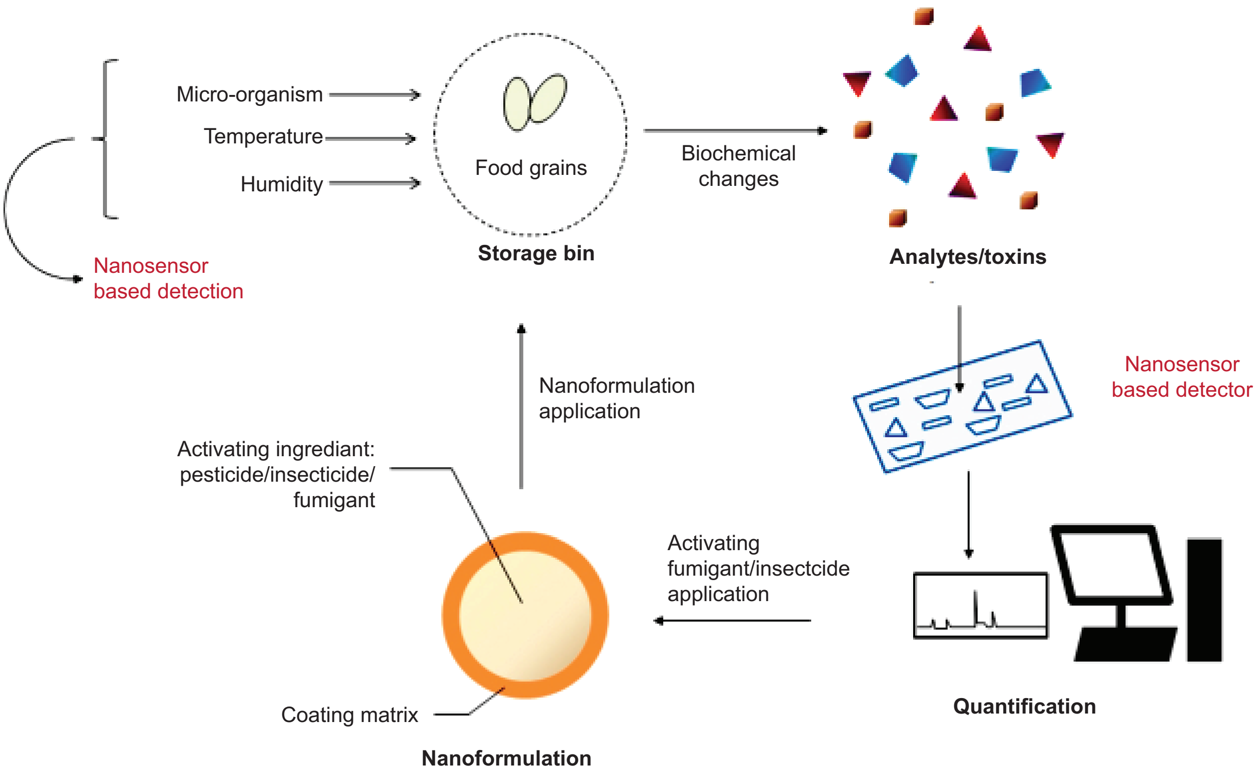

Figure 4. Nanoformulation-based system for food grain decontamination. (Reproduced from Sirohi *et al.*, 2021).

benefits in food safety, other potential problems still remain. Controversies surrounding the use of nanoparticles in food-processing sectors and their potential toxicological consequences must be addressed to alleviate public apprehensions (Girthie John Britto *et al.*, 2023).

High-pressure processing

High-pressure processing, a highly advanced nonthermal method, is extensively utilized to inactivate pathogenic microorganisms and enzymatic activity, including pectin methyl esterases (PMEs), in food products without prior thermal treatment at isostatic pressure (Lee *et al.*, 2016; Torrecilla *et al.*, 2005). HPP is a pasteurization method that subjects a food product to ultra-high pressure between 100 MPa and 600 MPa. During pasteurization, food is enclosed in an airtight vessel and subjected to ultra-high pressure, utilizing water as a pressure medium (Yamamoto, 2017). Furthermore, the pasteurization impact of HPP is unaffected by the packing volume of the food; hence, items of varying quantities may be treated concurrently in the same batch. In contrast to traditional thermal food-processing methods, HPP may be conducted at ambient temperature, thus reducing production costs by conserving energy related to heating and subsequent cooling during sterilization (Ashrafudoulla *et al.*, 2023). It deactivates harmful microbes and enzymes while preserving the food's sensory and nutritional attributes (Khaliq *et al.*, 2021). HPP can inactivate vegetative microorganisms by compromising cell membranes, denaturing proteins, and degrading intracellular proteins (Yang *et al.* 2021). Spores, the most dormant form of dangerous bacteria, such as Bacilli and Clostridia, exhibit remarkable resistance to heat, dehydration, and both physical and chemical stressors. Consequently, HPP may serve as a promising method to suppress spore-forming microbes in both raw and processed post-packaged food, thereby attaining improved quality, safety, and stability (Ashrafudoulla *et al.*, 2023; Huang *et al.*, 2020).

High-pressure processing has the potential to eradicate pathogens in packaged products and can serve as an antibacterial component within hurdle technology, in combination with other nonthermal food sterilization methods, without modifying the original process (Ashrafudoulla *et al.*, 2023). The use of HPP for a treatment duration of 30 s effectively inactivates harmful bacteria, molds, and yeasts in food, hence enhancing food safety and prolonging the shelf life of final products (Hwang and Fan 2015). For example, apple juice subjected to HPP pressure ranging from 139 MPa to 561 MPa for 39–181 s resulted in the inactivation of *L. monocytogenes*, *E. coli* O157:H7, and *S. enterica* (Petrus *et al.*, 2020). Another investigation indicated that *L. monocytogenes* strains exhibited little resistance to pressure treatments of 450 MPa for 10 min and 600 MPa for 5 min at low water activity in sliced dry-cured ham (Pérez-Baltar *et al.*, 2020). The examination of

Aspergillus flavus conidia inactivation using HPP showed that a treatment at 600 MPa for 3 min eradicated 107 CFU/mL of viable fungus and reduced spore viability (Ashrafudoulla *et al.*, 2023; Hsiao *et al.* 2021).

A solitary HPP treatment may be inadequate for eradicating pathogens; nevertheless, when coupled with additional methods, such as heat, it can efficiently eliminate foodborne bacterial spores (Ashrafudoulla *et al.*, 2023). Ultra-high temperature system utilizing pressure assistance successfully inactivated spores of *Bacillus subtilis* 168 and *Clostridium sporogenes* PA3679 when subjected to 600 MPa and 700 MPa at 121°C for <1 min (Liang *et al.* 2019). A log decrease of 6.75 was observed for *Bacillus subtilis* spores and a reduction of >5 logs for spores of *Clostridium sporogenes*. The HPP facilitated spore germination, making the spores vulnerable to inactivation by elevated temperatures (Ashrafudoulla *et al.*, 2023).

Pulsed light

Pulsed light is a recognized alternative method for pathogen inactivation in food. It comprises powerful, brief bursts of broad-spectrum light with a wavelength distribution ranging from 100 nm to 1100 nm: ultraviolet light (100–400 nm), visible light (400–700 nm), and infrared light (700–1,100 nm) (Ashrafudoulla *et al.*, 2023). In contrast to ultraviolet light, which uses low- or medium-pressure mercury lamps for germicidal radiation in the treatment of liquid foods and drinks, pulsed light disinfection utilizes inert-gas flash lamps (Delorme *et al.* 2020; Li and Farid 2016). The process of photoluminescence is nearly analogous to ultraviolet light, which may similarly harm cellular structure by destroying DNA. The antibacterial efficacy of pulsed light against *E. coli* was examined (Zhu *et al.* 2019). Pulsed light was observed to alter the morphology, endoenzymes, enterocytes, respiratory metabolism, and DNA synthesis of *E. coli* O157:H7. Pulsed light therapy significantly decreased proteins, ATP, and DNA levels. It decreased the activity of ATPase, β-galactosidase, and alkaline phosphatase as well as the metabolism of *E. coli* O157:H7 (Ashrafudoulla *et al.*, 2023). Microscopic investigation revealed that pulsed light treatment significantly compromised the cell membrane of *E. coli* O157:H7. Consequently, pulsed light can serve as an efficacious solution for eradicating dangerous bacteria while extending the shelf life of food products (Ashrafudoulla *et al.*, 2023).

Pulsed light is a potential method for deactivating unwanted and spoilage bacteria, both *in vitro* and in food, without compromising quality features (Ashrafudoulla *et al.*, 2023). The application of pulsed light at varying fluences (1.25–18 J/cm^2) effectively diminished numerous pathogens present in fresh chicken meat, achieving reductions of 0.9–2.4 log for *Salmonella enteritidis*, 1.1–2.0 log for *Listeria monocytogenes*, 1.3–3.0 log for *Staphylococcus aureus*, 1.1–2.9 log for *Pseudomonas*, 1.3–3.0 log for *Brochothrix thermosphacta*, and 1.5–1.8 log for *Carnobacterium divergens* (Ashrafudoulla *et al.*, 2023). The elimination of pathogens in strawberries with pulsed light processing extended fruit's shelf life and preserved physicochemical properties (Cao *et al.*, 2019). The results indicated a marginal drop in artificially deposited *Salmonella* levels (0.4 to 0.8 log) and a significant reduction in mould proliferation by 2 to 4 days relative to the untreated control. Ultraviolet and pulsed light exhibit promising efficacy in eradicating bacteria in food; yet a coordinated effort is required in the future to comprehensively elucidate their effects and antimicrobial mechanisms (Ashrafudoulla *et al.*, 2023).

Pulsed electric field

Pulsed UV-A radiation within the wavelength range of 315–400 nm has bactericidal properties by damaging the DNA/RNA strands of bacteria (Sirohi *et al.*, 2021). PEF is a novel food-processing technique that utilizes the phenomena of electroporation or electropermeabilization of the cell membrane by brief electrical pulses (Ashrafudoulla *et al.*, 2023). Successful decontamination of specific microorganisms via PEF necessitates the careful selection of operational parameters, such as electric field strength and the duration and frequency of pulse treatment, as these factors influence the reversibility of cell membrane permeability (Ashrafudoulla *et al.*, 2023). Brief bursts of high-intensity ultraviolet light can efficiently eliminate pathogenic microbes in low-moisture foods, including cereal grains (Sirohi *et al.*, 2021). The use of 395-nm pulsed light may achieve a 2.91 log decrease of Salmonella spp. in wheat flour following a 60-min treatment (Du *et al.*, 2020). The efficacy of PEF treatment in inactivating food spoilage bacteria in apple juice was evaluated (Dziadek *et al.* 2019). Consequently, PEF reduced bacterial load in apple juice while preserving the concentration of beneficial chemicals. The use of PEF is gaining commendation as a substitute for heat treatment in the preservation of juice, liquid eggs, milk, and soups (Nowosad *et al.* 2021).

While PEF technology has considerable potential, its efficacy in addressing some infections found in milk products is restricted if utilized in isolation (Ashrafudoulla *et al.*, 2023). Consequently, the synergistic use of PEFs alongside a moderate thermal treatment was investigated to enhance the safety and preserve the quality of dairy products. Mild heating with PEF enhanced the shelf life of milk products by achieving a 3.0–6.0 log decrease in microbial load (Alirezalu *et al.* 2020a). Despite PEF being a viable food-processing technique, now employed by several enterprises for the treatment of liquids (such as tomato juice) and solids (such as potatoes) (Ostermeier *et al.* 2020), its adoption within the food sector remains limited. This arises from some challenges intrinsic to the technology, including the initial requirement to pressurize and degas the product to prevent electrical discharge difficulties (Ostermeier *et al.* 2020). Nonetheless, PEF must be integrated with additional processing techniques to get improved inactivation proportions (Ashrafudoulla *et al.*, 2023).

Ultrasonication (US)

Ultrasound is considered as a nonthermal-processing technique with the potential to serve as a viable alternative to thermal food-processing methods (Rastogi, 2011). It involves the utilization of ultrasound at low temperatures, applicable to temperature-sensitive items in which there is apprehension over nutritional degradation, such as vitamin C loss, protein denaturation, and nonenzymatic browning (Ravikumar *et al.*, 2017). Ultrasound is employed for biofilm removal and should be augmented by further inactivation techniques. Consequently, high-power, low-frequency ultrasound (20–100 kHz) is deemed effective in inhibiting microorganisms during food processing because of its capacity to induce cavitation (Jiang *et al.*, 2020). An examination of the inactivation of *E. coli*, *Saccharomyces cerevisiae*, and *Bacillus subtilis* using ultrasonic cavitation established that the frequency and acoustic strength were contingent upon specific bacteria or fungi (Hashimoto *et al.* 2020). While disinfection with ultrasonic waves is a novel method for enhancing food quality because of its bactericidal properties (Ashrafudoulla *et al.*, 2023; Cao *et al.* 2018), its standalone application at ambient temperature has demonstrated limited effectiveness against microbes. Consequently, it is advisable to integrate this technology with additional challenges (pressure, heat, or both) to enhance total disinfection (Ashrafudoulla *et al.*, 2023). Ultrasound primarily inactivates bacteria through cavitation phenomena. This gadget generates ultrasonic vibrations that induce the formation of gas bubbles in the liquid media (Ashrafudoulla *et al.*, 2023). Upon reaching a specific size threshold, the bubbles collapse, producing intense shear forces within the fluid and severe temperatures and pressures at the point of implosion (Delmas and Barthe 2015). These severe circumstances incapacitate microorganisms. The efficacy of ultrasonic therapy primarily relies on specific targeted microorganisms (Ashrafudoulla *et al.*, 2023). Prolonged ultrasonication reduced inoculated vegetative cells (5 log CFU/mL) of thermoduric *Bacillus coagulans* in skimmed milk (Bawa, 2016). A 92% inactivation rate was observed following 12 rounds, with each pass lasting for 80 s. The inactivation rate mounted to 99.98% with the combination of ultrasonication and pasteurization at 63°C for 30 min. This outcome indicated enhanced efficiency of ultrasonication if coupled with thermal treatment (Ashrafudoulla *et al.*, 2023).

Nonetheless, prolonged exposure is necessary to eliminate or inactivate stable enzymes and/or bacteria, which may result in significant energy demands. The use of ultrasound may increase temperature, contingent upon ultrasonic strength and duration of application, necessitating regulation to optimize the process (Zheng and Sun, 2006). Ultrasonic treatment may effectively inactivate foodborne microorganisms, with enhanced effectiveness, if used in conjunction with other methods, such as heat or chemicals.

Food irradiation

Food irradiation employs low-ionizing radiation for the purpose of microbiological disinfection. Ionizing radiation sources for food irradiation have encompassed gamma rays, electron beams (e-beams), and X-rays (Ashrafudoulla *et al.*, 2023; Ehlermann, 2016). Food irradiation is a safe technology that has been deemed 'wholesome,' indicating that the consumption of irradiated food poses no damage to human health (Levy and Villavicencio, 2020). Nonetheless, consumers consider ionization irradiation as unacceptable, perceiving it as an unsafe processing procedure because of a misconception conflating radioactive food with irradiated food (Levy and Villavicencio, 2020).

Notwithstanding consumer hesitance, China and Vietnam are among the nations now employing irradiation on specific items, including herbs, spices, and vegetables (Ashrafudoulla *et al.*, 2023). Products subjected to irradiation must adhere to international criteria for radiation sources: X-rays (bremsstrahlung), electron beams (up to 10 MeV), and gamma rays (from radionuclides or caesium-137 isotopes) (Ashrafudoulla *et al.*, 2023). Gamma irradiation has greater penetrating depth, compared to electron beams and X-rays. Food irradiation is the favored approach because of its beneficial effects on harmful bacteria and its ability to preserve the quality of dairy products (Levy and Villavicencio, 2020). Nonetheless, the necessary radiation can affect microbial burden as well as microbial resistance. Additional factors influence irradiation efficiency, including the product's status (fresh or frozen), ambient temperature, chemical makeup, and moisture content (Ashrafudoulla *et al.*, 2023).

Irradiation eliminates foodborne pathogens by destroying microbial DNA and obstructing cell division through the inhibition of DNA synthesis. Ionizing radiation possesses adequate strength to penetrate bacterial cell membranes and impact cellular components (Ashrafudoulla *et al.*, 2023). It induces DNA mutations and generates peroxides. As these mutations proliferate, they ultimately result in cellular demise. The buildup of oxidizing agents results in cell lysis and subsequent cell death (Li and Farid 2016). This method is suitable for sterilizing items that are marketed without heat treatment, diminishing hazardous substances in food, and decelerating the deterioration of fruits and vegetables (Bevelacqua and Mortazavi, 2020).

The efficacy of food irradiation (gamma radiation) treatment (0.5–5 kGy) was evaluated to ensure microbiological safety of a ready-to-bake vegetable products and its impact on nutritional properties during cold storage (Bandyopadhyay *et al.* 2020). A food irradiation treatment dosage of 2 kGy reduced the microbial load encompassing yeast and mould. The nutritional content of vegetables was maintained with the same irradiation dose, even after 20 days of storage (Molina-Chavarria *et al.* 2020). Food irradiation remains an excellent nonthermal technique for diminishing foodborne bacteria; nonetheless, meticulous and precise radiation dosimetry is essential for regulating the irradiation process. Subjecting food to high amounts of irradiation can produce radioactive materials, offering possible health concerns to consumers, such as health malfunction or cancer (Ashrafudoulla *et al.*, 2023).

Combined hurdle processing technology

A variety of thermal and nonthermal methods are employed for the disinfection of food grains. Given that some procedures may not consistently be feasible or ecologically sustainable, the integration of thermal and nonthermal technologies with alternative processing methods could be employed to disinfect and maintain the quality of food grains (Sirohi *et al.*, 2021). The amalgamation of two or more natural antimicrobials or physical approaches, referred to as the 'hurdle approach,' has garnered the attention of the food industry because of its negligible effect on the nutritional content and sensory attributes of foods (Abdelhamid and El-Dougdoug, 2020; Singh and Shalini, 2016). Recently, Nadon *et al.* (2025) used cold plasma (CP) to modify polybutylene succinate (PBS)-starch films by incorporating Makwaen essential oils to enhance shelf life of pork sausage: 'when the essential oil was applied at a concentration of 80% v/v and stored at 25°C for 72 h, the coated film extended the shelf life of packaged pork sausages to 40 h, compared to 36 h for the control group' (Nadon *et al.*, 2025). Although HPP and PEF exert minimal or no impact on dietary ingredients, they are often fatal to various spores, non-spore-forming bacteria, yeasts, molds, and viruses. They possess potential for industrial usage, especially when integrated with thermal or other nonthermal preservation methods.

Sonication alone is ineffective in eradicating bacteria in food; however, thermosonic (heat and sonication), manosonic (pressure and sonication), and manothermosonic (heat, pressure, and sonication) treatments are likely the most successful modes for microbial inactivation (Niakousari *et al.*, 2018). Ae unique combination of methods utilized for thermal and nonthermal food-processing may inflict little physical and chemical property harm on food items. The integration of technologies significantly enhanced the inactivation proportions of enzymes and microorganisms during pasteurization, potentially streamlining food production by decreasing processing time and energy usage, especially in the drying phase (Lee *et al.*, 2016).

Conclusions

The future of the global food business depends on technical advances that are well positioned to convert food systems into more economically, ecologically, and socially sustainable entities. The successful use of these novel and developing technologies necessitates adherence to the highest standards throughout the food supply chain to ensure the safety and health of food products and meet customer expectations. This study illustrated the existence of several strategies and successful methods for microbial control in food products. Progress in this domain has facilitated the creation of novel instruments and technologies that aid in preventing contamination and guaranteeing food safety. These alternative technologies might markedly reduce processing periods, yield energy savings, and ensure optimal food safety, thereby helping the food sector. Despite the actual use of several developing technologies in food processing, certain inherent drawbacks persist, resulting in unresolved issues that hinder the preservation of the anticipated quality of agricultural products. Consequently, the integration of many developing technologies has garnered significant attention in mitigating the limitations associated with each technology. Nonetheless, issues such as antibiotic resistance and the identification of novel pathogens persist, underscoring the necessity for ongoing study and development in this domain. Numerous innovative technologies have garnered significant interest from researchers, food producers, and consumers; nevertheless, major hurdles must be addressed before achieving full industrial and consumer acceptance. Challenges encompass substantial investment and operational expenses that must be surmounted to validate the industrial usage of these strategies.

Author Contributions

All authors contributed equally to this article.

Conflicts of Interest

Authors declare no conflict of interest.

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