Urmia University

Food Safety and Packaging

2026, 2 (1): 1-14

Journal Homepage: fsp.urmia.ac.ir

FOOD Safety and Packaging

Review Article

Bacteriophages: Promising biologic approach to combat pathogenic *Enterobacteriaceae* in the food industry

Raheleh Majdani*, Samira Ghaemi

Department of Biology, Faculty of Basic Sciences, University of Mragheh, Maragheh, Iran

Abstract

With the increasing global population and growing demand for safe, high-quality food, ensuring sustainable food security has become a major concern worldwide. One of the fundamental challenges in this regard is bacterial foodborne illness. The use of antibiotics and other chemical antimicrobials as food preservatives has significant undesirable side effects and can damage the texture of food. In addition, consumers believe that the use of natural antimicrobials is beneficial. Therefore, bacteriophages (phages), effective re-emerging viral agents, can be introduced as good antimicrobial candidates in different stages of the food industry. They are unique and biological with highly specific functions against pathogens. The current study addresses the important properties of phages for use as biological antimicrobials. Several studies on isolating appropriate bacteriophages against pathogenic genera of Enterobacteriaceae bacteria were reviewed. From an applied perspective, studies that have used phages to reduce or eliminate the microbial load of Enterobacteriaceae pathogens have been analyzed.

Keywords: Bacteriophage, Enterobacteriaceae, Food industry, Preservative.

Introduction

Concerns regarding sustainable food security have intensified in recent decades as population growth and demand for safe, high-quality food continue to rise, particularly in developing countries. A major challenge in this context is the bacterial contamination of food, which is a leading cause of foodborne illnesses. For example, a Salmonella outbreak in the United States between 2018 and 2019 was linked to contaminated raw turkey meat, highlighting the public health significance of this issue (Rashida et al., 2019).

To reduce microbial load, the use of synthetic chemical preservatives, such as sorbates, nitrates, and sulfites, is common in food industry. Despite the effectiveness of these compounds in extending the shelf life of food products, concerns regarding their safety (potential carcinogenicity and allergenicity) have been raised (Bensid et al., 2020). Consequently, attention has shifted toward natural bioactive compounds, which generally exhibit lower toxicity. These include plant essential oils, animal-derived enzymes such as lysozyme and lactoferrin, organic acids, and polymers such as chitosan (Hintz et al., 2015), which not only reduce pathogenic

* **Correspondence**: R. Majdani (r.majdani@maragheh.ac.ir).
https://doi.org/10.30466/fsp.2026.56864.1027
Received: 12 December 2025 **Accepted**: 12 February 2026 **Available online**: 15 February 2026

microorganisms but also enhance the quality and functionality of food.

With the emergence of antibiotic-resistant strains, the need for novel strategies to combat foodborne pathogens has become increasingly urgent (Bensid et al., 2020; Moye et al., 2018). In this context, bacteriophages, viruses that specifically target bacteria, have been introduced as effective, safe, inexpensive, and readily available agents for controlling microbial contamination in the food industry (Endersen & Coffey., 2020). Although initially confined to clinical settings, the application of bacteriophages has expanded into industrial and biotechnological fields, including the food sector (Sillankorva et al, 2012). Phages can reduce foodborne infections and prevent spoilage without adversely affecting the organoleptic or rheological properties of foods. Numerous studies have confirmed the efficacy of phages in controlling *Salmonella, Shigella*, and *Escherichia coli* in various food products, such as milk, poultry meat, cheese, vegetables, and fresh fruits (Islam et al., 2019, Huang et al., 2018, Lukman et al., 2020).

In spite of the significant role of *Enterobacteriaceae* pathogens in food borne illnesses, most of the previous studies have concentrated on antibacterial effects of bacteriophages against *Listeria monocytogenes* and *Salmonella* spp., and some others studied bacteriophages effect on *E. coli* O157:H7 strain, and studies with the special insight on effects of *Enterobacteriaceae* pathogens on their biocontrol activity in foods was not found. Then, this article reviewed the application of bacteriophages in reducing microbial contamination caused with the focus on three important pathogenic genera of the *Enterobacteriaceae* family (*Salmonella*, *E. coli*, *Shigella*) and analyzed phage-based biological strategies that can be effectively applied in food industry.

Foodborne diseases with *Enterobacteriaceae*

Foodborne diseases caused by microbial contamination are a major cause of morbidity and mortality worldwide (Murray et al., 2017). Annually, contaminated foods are responsible for approximately 600 million cases of foodborne illness and 420000 deaths, with children under five years of age accounting for 40% of these fatalities (Sarno et al., 2021). A significant proportion of these illnesses are attributed to specific foodborne pathogens, including *Shigella*, *Salmonella*, *Campylobacter*, *L. monocytogenes*, and *E. coli*, as well as other intestinal microorganisms (Murray et al., 2017; Scallan et al., 2010). The consumption of raw and minimally processed foods, which often have not undergone sufficient heat treatment, as well as contamination of equipment and utensils during food processing, are major contributors to the occurrence of these diseases (Żaczek et al., 2015). In the following sections, several bacterial agents belonging to the Enterobacteriaceae family, which play a key role in foodborne microbial contamination and associated diseases, are discussed in terms of their involvement in food contamination.

Salmonella

Recently, *Salmonella* has emerged as one of the most common foodborne pathogens worldwide, typically transmitted through water or food products, such as lettuce, milk, beef, and poultry. Individuals infected with *Salmonella* exhibit symptoms of salmonellosis, including acute fever, abdominal pain, diarrhea, nausea, and vomiting (Shang et al., 2021; Zhang et al., 2023). Annually, approximately 90 million cases of foodborne illness and around 155000 deaths occur globally as a result of salmonellosis, posing a serious threat to human health. Therefore, the biological control of *Salmonella* contamination in food and the environment is critical (Papoula-Pereira et al., 2025).

Antibiotics have been widely used to biologically control *Salmonella* due to their inhibitory effects. However, the overuse and misuse of antibiotics have led to an increasing prevalence of multidrug-resistant bacterial strains. Alternative approaches have been proposed, however, many of these methods are unable to provide sustained control over the spread of resistant bacteria and may negatively affect the sensory properties of food, limiting their practical application in the food industry. Consequently, there is a need for novel antimicrobial agents with fewer side effects. Bacteriophages represent a particularly promising strategy for controlling *Salmonella* contamination (Alomari et al., 2021).

Escherichia coli

Both pathogenic and non-pathogenic strains of *E. coli* reside in the gastrointestinal tracts of mammals and are commonly used as indicators of fecal contamination in various environments. The detection and control of these pathogens are essential for safeguarding human health. One of the hazardous foodborne microorganisms is Shiga toxin-producing *E. coli* (STEC). The most well-known STEC strain associated with foodborne outbreaks is *E. coli* O157:H7, which was first identified as a pathogen in 1982 (Carstens et al., 2019). According to the Centers for Disease Control and Prevention, between 2009 and 2015, 191 foodborne outbreaks, 2378 illnesses, and 672 hospitalizations in the United States were linked to STEC, with an estimated annual cost of $254.8 million. Although *E. coli* O157: H7 is the most commonly recognized STEC strain, it also includes six non-O157 serotypes: O121, O111, O145, O26, O45, and O103 (Bain et al., 2014).

Shigella

Shigella is a major microbial contaminant of both plant- and animal-based foods, infecting millions of people annually and causing thousands of deaths worldwide. Multidrug-resistant isolates of *Shigella* species have been recovered from various food sources, including red meat, poultry, and fresh vegetables such as carrots, lettuce, and parsley, as well as from raw and processed food products. Members of the genus *Shigella* belong to the family *Enterobacteriaceae* and are the causative agents of shigellosis, resulting in approximately 80–165 million cases of intestinal infection and nearly 600000 deaths each year globally. These Gram-negative, non-motile, facultatively anaerobic bacteria are classified into four serogroups: A, B, C, and D (Shahin, et al., 2020).

With a relatively low infectious dose of only 200 bacterial cells, *Shigella* can be transmitted through direct contact (person-to-person) or indirectly via contaminated food and water (Shahin et al., 2021). *S. dysenteriae* is responsible for more severe forms of shigellosis, while *S. sonnei* and *S. flexneri* have been reported as the predominant species in developed and developing countries, respectively, over recent decades (Shahin et al., 2021). *Shigella* species have been isolated from a variety of foods, including fresh vegetables and poultry. The uncontrolled use of antibiotics and horizontal gene transfer of antibiotic resistance in medical, industrial, and food production settings have led to a significant increase in multidrug-resistant *Shigella* strains.

Other pathogenic species of *Enterobacteriaceae*

In addition to well-characterized foodborne pathogens such as *Salmonella enterica*, *Shigella* spp., and pathogenic *E. coli*, a diverse community of other *Enterobacteriaceae* members is frequently isolated from food matrices and may contribute to contamination and hygiene failures in the food chain. Retail food surveillance studies have documented the presence of species such as Proteus mirabilis, *Klebsiella* spp., *Enterobacter* spp., *Hafnia* spp., *Citrobacter* spp., and *Kluyvera* spp. at appreciable frequencies, often with noteworthy antimicrobial resistance profiles and biofilm-forming capabilities that complicate sanitation efforts (Ramos-Vivas et al., 2022). Many of these organisms are considered opportunistic rather than primary foodborne pathogens, and their high prevalence in products such as vegetables, dairy, and meat highlight their utility as hygiene indicator organisms and the need for targeted control strategies (Igbinosa et al., 2019).

Biological control potential of bacteriophages on foodborne pathogens

Since the discovery of bacteriophages nearly a century ago, researchers have recognized the ability of bacteriophages to treat cholera and a wide range of acute and chronic pathogens in cardiology, gastroenteritis, neonatal diseases, and various surgical contexts. These infectious particles have been applied in diverse human, animal, and agricultural settings, however, their use in food production remains largely unexplored (Sillankorva et al., 2012). The contamination of raw food products highlights the need for reliable methods to eradicate harmful bacteria from food. Traditional approaches have limitations in removing pathogens from fruits and vegetables (Bhardwaj et al., 2015). To identify better alternatives for eliminating bacterial contamination in fresh produce, researchers have investigated methods including radioactivity, edible coatings, nitrogen oxides, ultraviolet radiation, controlled atmosphere storage, potassium permanganate, water, and viral proteins (Islam et al., 2022; Mahajan et al., 2014).

Bacteriophages, as practical and rational options for organic management, similar to conventional sanitation methods, do not compromise the taste of fresh foods. Viral formulations have been explored for their overall biological control potential against foodborne pathogens associated with fruits and vegetables. However, unexpected outcomes have posed challenges for phage applications in plant-based foods, which have been attributed to unfavorable treatment conditions during viral concentration and limited knowledge of phage ecology (McCallin et al., 2013). Addressing these concerns could unlock the potential of phage-based biological control strategies in ensuring food safety.

Bacteriophages

Bacteriophages are viruses that infect bacteria and display extensive diversity in size, structure, and genome composition. Bacteriophages were first discovered in 1917 by Félix d'Herelle. These viruses exhibit two main life cycles: the lytic cycle, in which the host bacterium is lysed and newly produced virions are released, and the lysogenic cycle, during which the phage genome integrates into the bacterial chromosome without causing immediate harm to the host bacterium. The majority of characterized phages (approximately 96%) belong to the order *Caudovirales,* which are tailed viruses possessing double-stranded DNA genomes. A typical phage structure consists of an icosahedral capsid enclosing the viral genome and a tail that facilitates attachment to the host cell, although some phages exhibit alternative morphologies, including enveloped and filamentous forms (Wagh et al., 2023). Phages are classified based on factors such as nucleic acid type, capsid architecture, host range, and pathogenic properties (**Fig. 1**).

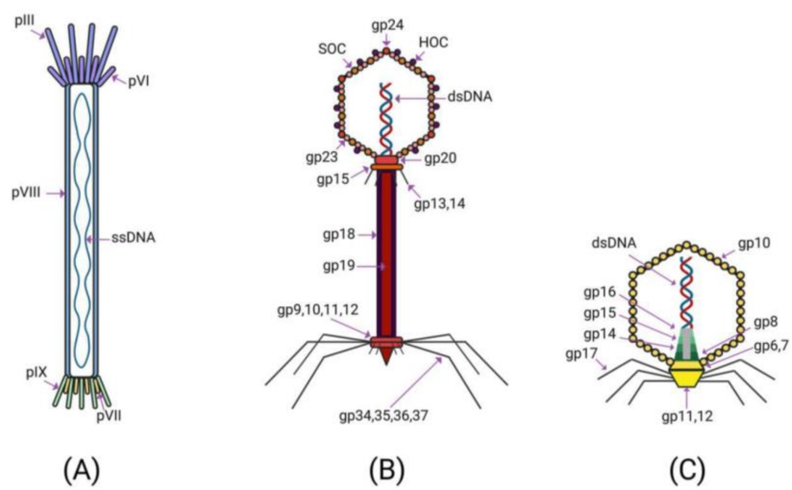

Figure 1. Structures of (A) M13 phage, (B) T4 phage, and (C) T7 phage (Petrov et al.,2022).

Beyond their ecological significance in regulating microbial populations and nutrient cycles, bacteriophages have broad applications in medicine and industry. They are considered a promising alternative to antibiotics for combating antimicrobial resistance (AMR), treating infections in humans and animals, controlling diseases in aquaculture, and ensuring food safety. Phages can effectively target and eliminate pathogens such as *Salmonella*, *Listeria*, and *E. coli* without disrupting beneficial microbiota or compromising food quality (Azam et al., 2021).

Antibacterial mechanism of lytic bacteriophages

During infection and cell lysis, phages produce a suite of enzymes, including virion-associated lysins (VALs), holins, pinholins, and endolysins, which ultimately leads to genetic material injection, degradation, and lysis of the bacterial cell wall (Guliy & Evstigneeva, 2025). Specifically, endolysins target bacterial hosts by cleaving peptidoglycan bonds and can lyse biofilms on surfaces within the food industry, irrespective of the host's metabolic phase (Guliy & Evstigneeva, 2025). The lytic phase of bacteriophage infection, which is most relevant for biotechnological applications, involves the initial takeover of the host's biosynthetic machinery. Subsequently, the release of new virions is executed by the activation of holin and endolysin enzymes, leading to degradation of the bacterial cell wall. Holins form pores that facilitate the access of endolysins to the peptidoglycan layer by penetrating the inner membrane, resulting in bacterial cell wall rupture and lysis (**Fig. 2B**) (Harshitha et al., 2022). Phage enzymes, recognized as the most critical functional molecules driving lytic activity, are highly efficient in promoting viral progeny release (Choi et al., 2025a). VAPGHs, a phage-encoded structural protein (Mtimka et al.,2024), create a small aperture in the cell envelope, thereby allowing the injection of the viral genome to commence the infection process (**Fig. 2B**) (Kashani et al., 2017).

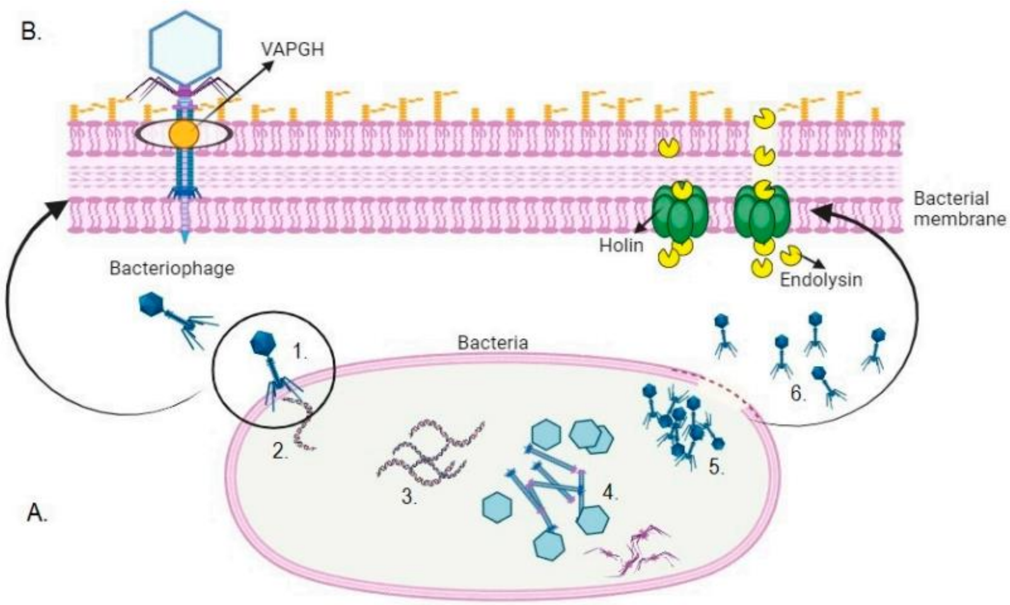

Figure 2. (**A**) Lytic cycle: (1) phage attachment to the bacterium, (2) injection of genetic material, (3) replication of the phage genome, (4) production of phage protein structures, (5) phage assembly, and (6) lysis and release of virions. (**B**) Activity of VAPGH, endolysins, and holins (Soto Lopez et al., 2025).

Holins are small hydrophobic enzymes embedded in the cytoplasmic membrane that initiate cell lysis by forming a channel through which lysins traverse to reach the peptidoglycan matrix (**Fig. 2B**) (Guliy & Evstigneeva, 2025). In scenarios where the direct passage of lysins is restricted by space limitations, ion permeation occurs, altering membrane function and subsequently activating lysins. An alternative phage-encoded holin, the pinholin, forms nanometer-sized pores (less than 2 nm in diameter) that permit the non-specific passage of folded proteins into the cytoplasm. Consequently, for bacterial lysis to proceed, pinholins require SAR endolysins, whose transport is facilitated by a membrane-bound, inactive form of the endolysin (Khan et al., 2023).

Endolysins (or lysins) are phage-encoded enzymes produced within the bacterial cytoplasm towards the termination of the infection cycle. Endolysins cleave peptidoglycan from the cell wall, a process essential for rapid and efficient bacteriolysis (Shen et al., 2022). This cleavage induces an osmotic imbalance owing to the high internal pressure of the bacterium, leading to rupture of the cell membrane layer, extrusion of cytoplasmic contents, and subsequent lysis of the host cell, along with the release of newly replicated phages (Li et al., 2022). As significant functional enzymes in the bacteriophage lysis process, endolysins cannot autonomously reach the bacterial cell wall in an active state; thus, the activity of other phage enzymes, holins and pinholins, which act directly on the cytoplasmic membrane, is necessary to achieve this goal (Gontijo et al., 2021).

Efficacy of bacteriophages on reducing microbial load in food products

In recent years, efforts to improve consumer dietary habits and the search for novel health-promoting products have led to an increased interest in minimally processed foods (Agriopoulou et al., 2020). These products are preserved using non-thermal techniques, resulting in minimal changes in the food texture. This approach also allows for the retention of bioactive food components, such as vitamins, provitamins, and phytochemicals, which are naturally present in high amounts in plant-based, minimally processed foods (Zhang et al., 2019b). The use of physical methods in the food industry does not always ensure the production of food products with satisfactory sensory attributes and microbiological properties. Biological approaches, which can serve as alternatives to physicochemical methods, have gained increasing importance in the preservation of minimally processed foods with high microbial contamination risks, such as fresh juices, sprouts, and salad mixes (Gientka et al., 2021). The findings indicate that minimally processed plant-based foods can be heavily contaminated by saprophytic bacteria, whose numbers may increase by 2 to 3 log units during refrigerated storage compared to their initial levels upon entering the system, ultimately leading to a decline in product quality.

The use of bacteriophages can satisfy consumer expectations for minimally processed foods by extending their shelf life without adversely affecting their physical properties. Bacteriophages are viruses that typically infect only a single species or a limited number of bacterial species. Unlike antibiotics, they do not disrupt the natural gut microbiota of humans. Research has shown that phages are generally resilient to many stress conditions encountered during food processing, including a wide range of temperatures and pH levels, with their pH stability increasing at lower temperatures (Jayamanne & Foddai, 2025).

Bacteriophages can be applied in three main areas of the food industry during primary production, primarily to prevent biofilm formation on equipment surfaces; in hygiene and sanitation, mainly for disinfection in food processing facilities; and as biological preservatives to extend the shelf life of products by targeting pathogenic bacteria responsible for food spoilage Given the antimicrobial potential of bacteriophages demonstrated in numerous previous studies, various investigations have been conducted to evaluate the feasibility of harnessing this potential in the food industry. These studies have yielded notable results both *in vitro* against problematic foodborne pathogenic bacteria and in experiments involving the contamination of food products. Although diverse bacteriophages targeting bacteria derived from various food sources have been isolated in prior research, the present study focused on examining the functional effects of bacteriophages on different food matrices and their capacity to reduce microbial contamination by foodborne pathogens. This review systematically discusses key studies in the field and summarizes their findings on phage applications in food safety.

Efficacy of bacteriophages against *Salmonella* in food products

A polyvalent phage solution, designated PS5, in Japan, exhibits strong antibacterial activity against *S. enteritidis*, *S. enterica ser.* Typhimurium, and *E. coli* O157:H7, was evaluated for its antibacterial properties both *in vitro* within bacterial populations and directly on poultry meat. Phage PS5, demonstrated a short latent period, a large burst size, and high stability in different environmental conditions. Genomic analysis revealed the absence of antibiotic resistance, toxin-associated, and virulence factor genes. This phage was able to reduce bacterial counts in liquid media for all three bacterial hosts by more than 1.3 $\log_{10}$ CFU/mL compared to control groups after two hours of incubation at both 4 °C and 24 °C. Five types of food products, raw chicken skin, raw beef slices, fresh lettuce, pasteurized whole milk, and eggs, were tested for their effects on food matrices. In these food samples, a significant reduction in bacterial counts was observed for all three target bacteria compared to controls under the tested temperature conditions (Duc et al., 2020). Comprising four *Salmonella* phages with the morphology of *Myoviruses* and *Siphoviruses*, was performed on raw chicken meat contaminated with different strains of *S.* Typhimurium and *S. enteritidis*. The phages exhibited latent periods ranging from 5 to 30 min and demonstrated similar stability with respect to temperature and pH. When contaminated chicken meat samples were treated with the phage cocktail at 4 °C for seven days, bacterial counts were significantly reduced, with results showing statistical significance (Kim et al., 2020). Regarding *Salmonella* contamination in ground beef (both finely and coarsely ground), the application of a bacteriophage cocktail containing four phages resulted in a reduction in *Salmonella* across all stages of meat preparation. *Salmonella* counts decreased by approximately 1 log_{10} CFU/g when bacteriophage concentrations of 10^9 and 10^8 PFU/g were added to ground beef. In contrast, a 1.6 log_{10} CFU/g reduction was observed using larger meat pieces. The grinding process produces smaller meat particles, thereby increasing the surface area available for the phage to contact. In spite of highlighting the potential of bacteriophage application for reducing *Salmonella* contamination in bovine meat products, it has been suggested that higher phage concentrations are required to achieve statistically significant reductions in *Salmonella* contamination in ground beef (Shebs et al., 2021). Also, a bacteriophage was isolated from milk samples against *Salmonella* with morphology of *Siphoviruses,* exhibited high stability under temperature and pH conditions relevant to the milk preservation chain. After three hours of incubation at 37 °C, the phage reduced *Salmonella* growth in milk by approximately 1000-fold. The results showed not only the biocontrol potential of the phage but also its strong ability to extend the shelf life of milk (Abdelsattar et al., 2021). The efficacy of a commercial bacteriophage preparation, Salmo Fresh, consisting of six bacteriophage strains, against *Salmonella* contamination in romaine lettuce, mung bean sprouts, and mung bean seeds was compared with that of chlorinated water in reducing *Salmonella* contamination. The combined effect of chlorinated water and phage preparations was also assessed. Immersion of food samples in the phage solution produced stronger antimicrobial activity than spraying, achieving approximately a 2.5 log_{10} CFU/mL reduction in *Salmonella* contamination. However, due to *Salmonella* growth within mung bean seeds during sprouting, the phage cocktail showed no effect on larger sprouted seeds. The combined use of chlorinated water and the phage mixture was reported as the most effective treatment for reducing *Salmonella* contamination in mung beans and lettuce (Zhang et al., 2019a). Therefore, investigating different parameters is important for the biocontrol application of bacteriophages in the food industry. Antibacterial activity of the phage mixture was demonstrated against three *Salmonella* species, S. Typhimurium, *S. kentucky*, and *S. enteritidis*, in turkey meat at 37 °C, while no antibacterial effect was observed against *Salmonella* Heidelberg contamination (Sharma et al., 2015). A five-phage cocktail was employed to control seven strains of *Salmonella enterica* from four different serovars; romaine lettuce and cantaloupe leaves were challenged with various *Salmonella* strains. In some cases, reductions in contamination levels reached up to 3 log units, suggesting the efficacy of bacteriophages for biocontrol against *Salmonella* in cantaloupe and lettuce tissues, although the degree of efficacy varied depending on the target *Salmonella* strain (Wong et al., 2020).

Efficacy of bacteriophages against *Shigella* in food products

Phages against *Shigella* in food have been successfully studied. The strategic combination of two phages, S2_01 (with prolonged antibacterial activity) and S2_02 (with rapid bactericidal action), provides an innovative approach to combat *Shigella* biofilms, which represent a major challenge in the food industry (Choi et al., 2025b). Lee et al. (2016) reported that phage HY01, active against *S. flexneri*, exhibited strong resistance to acidic conditions, indicating its suitability for food applications. Phage AShi was isolated from *S. flexneri* in Argentina and demonstrated the highest resistance to all tested preservatives and biocides. AShi particles were detected in most assays up to the longest incubation time. Finding these phages can be very helpful in the food industry, which requires special conditions (Tomat et al., 2025). Furthermore, host–phage interaction studies using specific receptor molecules in *Shigella* revealed that phage Sfin-2 could interact with both the LPS-O antigen and protein components, whereas Sfin-6 interacted exclusively with the LPS-O antigen of the host cell's outer membrane. Subsequent investigations of the activity of Sfin-2 and Sfin-6 in raw chicken meat contaminated with *Shigella*, either individually or in combination, confirmed the potential of both phages to reduce MDR *Shigella* counts in meat samples (Ahamed et al., 2023).

Efficacy of bacteriophages against *E. coli* in food products

Bacteriophages as potent antibacterial agents showed acceptable results in food experiments. In Turkey, a bacteriophage with the morphology of *Myovirus*, isolated from wastewater of local slaughterhouses. It showed broad-spectrum lytic activity against most strains of *E. coli* O157:H7. Using various concentrations of phages indicated a significant reduction of more than 2 $\log_{10}$ CFU/g in bacterial counts within the first five hours of treatment. Moreover, the extent of bacterial reduction increased with increasing phage concentration. From an application perspective, the addition of bacteriophages to complex traditional food formulations, such as Turkish meatballs, could serve as an important method for eliminating contamination by *E. coli* O157:H7. The findings of this study demonstrated the practical potential of bacteriophages in ready-to-eat foods for biocontrol of pathogenic bacteria (Gencay et al., 2016). Efficacy of a commercial phage product, EcoShield™, containing three bacteriophages specific to *E. coli* O157:H7, reduced bacterial counts in beef (more than 94%) and lettuce (greater than 87%) within the first five minutes after contamination. However, protection against recontamination was not achieved after a single application of the phage solution, and post-processing contamination was not reduced. Interestingly, reductions in microbial load remained highly promising, ranging from 94% to 98%, even after beef samples were stored for varying durations from 10 minutes to 22 hours at 4 °C. Furthermore, when beef was refrigerated for seven days, similar reductions of 94–98% were recorded, owing to the absence or minimal growth of *E. coli* at this temperature. These observations may have important practical implications for designing effective biocontrol strategies using bacteriophages in facilities associated with industrial food processing facilities (Carter et al., 2012).

The effectiveness of another phage cocktail in reducing contamination caused by seven STEC strains was evaluated using food matrices, including mung bean sprouts, mung bean seeds, and lettuce (Ding et al., 2023). The efficacy of this phage mixture was also tested on romaine and iceberg lettuces. Additionally, the combined effect of chlorinated water and the phage cocktail was investigated, showing that this combined treatment reduced STEC contamination on lettuce and mung bean sprouts by 1.2 and 2.2 $\log_{10}$ CFU/g, respectively. Application of the cocktail against four other *E. coli* strains in lettuce resulted in reductions ranging from 2.3 to 2.6 $\log_{10}$ CFU/g. Notably, the phage mixture demonstrated the greatest reduction in bacterial load after 72 h at 2 °C and 10 °C. However, in the case of mung bean seeds, the phage cocktail did not reduce contamination by toxigenic *E. coli*, which may be related to the structural characteristics of the food matrix. These findings represent an important step toward understanding the practical applications of phages in enhancing food safety in fresh leafy produce. Based on the promising results of this study, phage cocktails could potentially be commercialized as a post-harvest decontamination treatment in the fresh and minimally processed food industry (Ding et al., 2023).

Efficacy of bacteriophages against other membranes of *Enterobacteriaceae* in food products

Studies on the antibacterial activity of phages against other members of *Enterobacteriaceae* are limited, but isolated lytic phages have shown efficacy in reducing *Enterobacter cloacae* complex contamination on fresh produce under food-relevant conditions and in controlling MDR *Enterobacter* growth in dairy matrices (Nasr-Eldin et al., 2023). Additionally, phage biocontrol against a broader saprophytic and opportunistic microflora, including *Citrobacter* and *Enterobacter* isolates, has been reported in minimally processed plant-based foods, suggesting that phages may serve as complementary biocontrol agents beyond classical pathogens (Mizuno et al., 2020). Despite these promising findings, further studies are needed to characterize the host range, environmental stability, and regulatory pathways of phage applications targeting these understudied members of *Enterobacteriaceae* in food systems.

Commercial bacteriophage products against *Enterobacteriaceae* bacteria in food

The successful use of bacteriophages as antimicrobial agents has led to the development of several commercial products in the fields of food, agriculture, biomedicine and clinical applications. ListShield, the first commercial phage product to receive FDA approval, holds a prominent position in the application of phages for food safety (Vikram et al., 2021). In a study, SalmoLyse®, a six-phage cocktail effective against multiple *Salmonella* serotypes, was evaluated for its efficacy in raw pet food ingredients and safety in dogs and cats. This study, along with previous investigations on dry pet food, demonstrated an average 0.91 log reduction in *Salmonella* and showed no observable adverse effects in animals (Soffer et al, 2016).

The commercial product SalmoFresh™, a six-phage cocktail, was shown in one study to effectively reduce *Salmonella* contamination on lettuce and mung bean sprouts. Immersion in the phage solution resulted in a reduction of 2.1–2.43 $\log_{10}$ CFU, whereas spraying was less effective. The product demonstrated limited efficacy on seeds; therefore, the most effective approach was the combined use of chlorinated washing and phage application (Zhang et al., 2019a). Bafasal™ (PhageTech, Poland) is a combination of four bacteriophages (PCM F/00069, PCM F/00070, PCM F/00071, and PCM F/00097) that has been approved by the European Food Safety Authority and acts against *S. enterica* ser. Gallinarum is the causative agent of fowl typhoid in poultry (EFSA FEEDAP Panel et al., 2023). SalmoFree® (developed at the University of Andes, Bogotá, Colombia; patent pending) contains six lytic bacteriophages that target *Salmonella*. Supplementation of drinking water with this phage mixture at a concentration of 10^8 PFU/mL protected poultry against infection with *S.* Typhimurium (Clavijo et al., 2019).

To reduce the population of STEC O157:H7 in beef, the commercial formulation PhageGuard E™, containing two bacteriophages, EP75 and EP335, was developed by MICREOS Food Safety (Wageningen, the Netherlands). Phage EP75 is classified as a virus of the genus *Vi1virus*, order *Caudovirales*, family *Ackermannviridae*, and subfamily *Cvivirinae*, while phage EP335 belongs to the genus *Phieco32virus*, order *Caudovirales*, family *Podoviridae*. These phages reduced the growth of *E.* Coli strains ATCC® 35,150™, ATCC® 43,895™, ATCC® 43,894™, and NCTC 13128 by approximately 98.3%, 97.2%, 96.7%, and 98.3%, respectively (Shebs et al., 2020). Researchers developed the lytic phage cocktail EcoShield PX, which specifically targets *E.* Coli O157:H7. This phage was tested on eight food products, including beef, chicken, salmon, cheese, cantaloupe, and lettuce, resulting in a significant reduction in bacterial load of up to 97% and a decrease in the prevalence of STEC at low bacterial levels of up to 80% (Vikram et al., 2020).

ShigaShield™, a phage preparation composed of five lytic bacteriophages specifically targeting pathogenic *Shigella* species present in contaminated water and food, was evaluated. The efficacy of different doses of this product (9×10^5 to 9×10^7 PFU/g) in eliminating inoculated *Shigella* in smoked salmon, cooked chicken, lettuce, cantaloupe, and yogurt was assessed. The highest applied doses (2×10^7 or 9×10^7 PFU/g) resulted in at least a 1-log (90%) reduction in *Shigella* across all food types. Significant reductions in bacterial populations ($P < 0.01$) were observed in all phage-treated foods compared to untreated controls; however, the lowest phage dose (9×10^5 PFU/g) on cantaloupe only achieved approximately 45% reduction (0.25 log). The genomes of each phage in this cocktail were fully sequenced and analyzed, revealing no undesirable genes, including those listed in the United States Code of Federal Regulations (40 CFR Ch1). These results indicate that ShigaShield™ and similar phage-based products with strong lytic activity against *Shigella* spp. can serve as a safe and effective approach for reducing *Shigella* levels in a wide range of potentially contaminated foods (Soffer et al., 2017).

Advantages and challenges of using bacteriophages in food

Bacteriophages have garnered considerable attention as biological control agents in food safety.

These viruses are classified into two categories based on their host interactions: lysogenic and lytic. Lytic phages are considered a suitable option for antimicrobial applications in the food industry because of their direct bacterial lysis capability (Vikram et al., 2021). Phages exhibit high specificity, targeting pathogenic bacteria without disrupting beneficial microbiota. Given their natural ubiquity, they pose no adverse effects on human health or food quality. The approval of multiple phage formulations for food applications underscores their safety and efficacy (Alomari et al., 2021). Phages can be applied individually, as phage cocktails, or in combination with antibiotics and disinfectants to broaden their spectrum of activity and achieve more effective infection control. The synergistic effect between phages and antibiotics (Phage-Antibiotic Synergy, PAS) is also well documented. These characteristics align with the "One Health" concept of reducing foodborne diseases and facilitating the implementation of phages across various stages of the agricultural supply chain. The emergence of AMR and increasing restrictions on antibiotic use in livestock have further amplified the interest in phages as a natural and safe alternative (Brives et al., 2020).

However, significant regulatory, industrial, and implementation challenges must be addressed to effectively scale up this process. Regulatory frameworks and approval processes for phages as food additives, biocontrol agents, or components of packaging materials necessitate clear guidelines concerning their safety, efficacy, impact on food quality, and environmental footprint. Large-scale phage production for food safety applications must be economically viable and capable of meeting the food industry's high-volume demands. For active food packaging, phage incorporation must be cost-effective while retaining phage viability and efficacy in real-world conditions. Direct application to food introduces additional complexities, including the need to maintain phage stability during transportation, storage, and application, particularly for perishable items. Implementation barriers are equally significant, with consumer acceptance being a critical issue. Educating consumers and food producers about the safety, natural ubiquity, and efficacy of phages is essential to overcome these barriers. This requires careful coordination among food producers, packaging companies, and regulators to develop solutions that are both effective and practical on an industrial scale (Braz et al., 2025).

Conclusion and future perspectives

Despite advancements in food safety protocols, the persistent issue of contaminated additives in fresh produce remains a significant threat, compromising product quality through the proliferation of pathogenic and spoilage bacteria, which substantially contributes to food loss. Current microbiological research robustly supports the efficacy of bacteriophages in controlling harmful bacterial growth on fresh produce, including lettuce. Phages demonstrate utility across the entire food production continuum, pre-harvest, harvest, and post-harvest, positioning them as a crucial tool for mitigating foodborne infections, particularly in vulnerable cohorts such as children, the elderly, and pregnant women. Phages function as potent, self-replicating antagonists of bacterial species, offering substantial value in disease reduction, surface disinfection in agricultural settings and food preservation. Well-formulated phage cocktails exhibit significant lytic activity against MDR bacterial strains and can be synergistically combined with safe antimicrobials, such as bacteriocins, to enhance overall efficacy and specificity.

Bacteriophages are integral ecological components that play a decisive role in bacterial evolutionary dynamics. Their deployment as biocontrol agents aligns closely with the objectives of the United Nations Sustainable Development Goals by enhancing food safety and sustainability of the food supply. Regulatory acceptance is growing, as evidenced by the Generally Recognized as Safe status granted by the U.S. Food and Drug Administration for food applications, simultaneously satisfying both organic and regulatory compliance standards. Furthermore, phage-based interventions have been successfully applied as food preservatives in numerous jurisdictions, including the United States, Canada, Israel, Switzerland, Australia and New Zealand (Zia et al., 2023).

Given the inherent challenges in scaling phage technology, as previously detailed, extensive further studies are warranted to integrate bacteriophages as a routine biocontrol method on an industrial scale. A critical requirement is the establishment of a coherent and consistent regulatory framework that explicitly addresses key parameters, such as optimal dosage, phage stability under industrial conditions, and mitigation of resistance development. Significant hurdles remain in achieving industrial scalability, whether through direct application or novel integration into packaging systems. Future research should rigorously refine application methodologies, ensure consistent performance across diverse food matrices, and conduct long-term impact assessments. Critical areas for subsequent investigation include elucidating the interactions between applied phages and non-targeted commensal microbiota, confirming the absence of unintended ecological disruptions, and maximizing reproducibility through optimized combination strategies with orthogonal decontamination methods, including precise temporal sequencing of applications (Braz et al., 2025).

Conflicts of interest

Authors declare that they have no conflicts of interest.

Disclaimer

Authors declare that no generative AI was used to create or analyze the scientific content.

References

Abdelsattar, A. S., Safwat, A., Nofal, R., Elsayed, A., Makky, S., & El-Shibiny, A. (2021). Isolation and characterization of bacteriophage ZCSE6 against *Salmonella* spp.: Phage application in milk. *Biologics*, *1*(2), 164–176. https://doi.org/10.3390/biologics1020010

Agriopoulou, S., Stamatelopoulou, E., Sachadyn-Król, M., & Varzakas, T. (2020). Lactic acid bacteria as antibacterial agents to extend the shelf life of fresh and minimally processed fruits and vegetables: Quality and safety aspects. *Microorganisms, 8*(6), 952. https://doi.org/10.3390/microorganisms8060952

Ahamed, S. K. T., Rai, S., Guin, C., Jameela, R. M., Dam, S., Muthuirulandi Sethuvel, D. P., … Giri, N. (2023). Characterizations of novel broad-spectrum lytic bacteriophages Sfin-2 and Sfin-6 infecting MDR *Shigella* spp. with their application on raw chicken to reduce the *Shigella* load. *Frontiers in Microbiology, 14*, 1240570. https://doi.org/10.3389/fmicb.2023.1240570

Alomari, M. M. M., Dec, M., & Urban-Chmiel, R. (2021). Bacteriophages as an alternative method for control of zoonotic and foodborne pathogens. *Viruses, 13*(12), 2348. https://doi.org/10.3390/v13122348

Azam, A. H., Tan, X. E., Veeranarayanan, S., Kiga, K., & Cui, L. (2021). Bacteriophage technology and modern medicine. *Antibiotics*, *10*(8), 999. https://doi.org/10.3390/antibiotics10080999

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T., & Bartram, J. (2014). Fecal contamination of drinking-water in low- and middle-income countries: A systematic review and meta-analysis. *PLOS Medicine, 11*(5), e1001644. https://doi.org/10.1371/journal.pmed.1001644

EFSA FEEDAP Panel (EFSA Panel on Additives and Products or Substances used in Animal Feed), Bampidis, V, Azimonti, G., Bastos, M.L., Christensen, H., Dusemund, B., … Brozzi R (2023). Scientific Opinion on the safety and efficacy of a feed additive consisting of the bacteriophages PCM F/00069, PCM F/00070, PCM F/00071 and PCM F/00097 (Bafasal®) for all avian species (Proteon Pharmaceuticals S.A.). *EFSA Journal, 21*(3), e07861. https://doi.org/10.2903/j.efsa.2023.7861

Bensid, A., El Abed, N., Houicher, A., Regenstein, J. M., & Özogul, F. (2020). Antioxidant and antimicrobial preservatives: Properties, mechanism of action and applications in food – a review. *Critical Reviews in Food Science and Nutrition, 62*(11), 2985–3001. https://doi.org/10.1080/10408398.2020.1862046

Bhardwaj, N., Bhardwaj, S. K., Deep, A., Dahiya, S., & Kapoor, S. (2015). Lytic bacteriophages as biocontrol agents of foodborne pathogens. *Asian Journal of Animal and Veterinary Advances, 10*(11), 708–723. https://doi.org/10.3923/ajava.2015.708.723

Braz, M., Pereira, C., Freire, C. S. R., & Almeida, A. (2025). A review on recent trends in bacteriophages for post-harvest food decontamination. Microorganisms, 13(3), 515. https://doi.org/10.3390/microorganisms13030515

Brives, C., & Pourraz, J. (2020). Phage therapy as a potential solution in the fight against AMR: Obstacles and possible futures. *Humanities and Social Sciences Communications, 6*, 100. https://doi.org/10.1057/s41599-020-0478-4

Carstens, C. K., Salazar, J. K., & Darkoh, C. (2019). Multistate outbreaks of foodborne illness in the United States associated with fresh produce from 2010 to 2017. *Frontiers in Microbiology, 10*, 2667. https://doi.org/10.3389/fmicb.2019.02667

Carter, C. D., Parks, A., Abuladze, T., Li, M., Woolston, J., Magnone, J., … Sulakvelidze, A. (2012). Bacteriophage cocktail significantly reduces *Escherichia coli* O157:H7 contamination of lettuce and beef, but does not protect against recontamination. *Bacteriophage, 2*(3), 178–185. https://doi.org/10.4161/bact.22825

Choi, D., Ryu, S., & Kong, M. (2025a). Phage-derived proteins: Advancing food safety through biocontrol and detection of foodborne pathogens. *Comprehensive Reviews in Food Science and Food Safety*, *24*, e70124. https://doi.org/10.1111/1541-4337.70124

Choi, J., Park, S., & Chang, Y. (2025b). Development and application of a bacteriophage cocktail for *Shigella flexneri* biofilm inhibition on the stainless-steel surface. *Food Microbiology, 125*, 104641. https://doi.org/10.1016/j.fm.2024.104641

Clavijo, V., Baquero, D., Hernandez, S., Farfan, J. C., Arias, J., Arévalo, A., … Vives-Flores, M. (2019). Phage cocktail SalmoFREE® reduces *Salmonella* on a commercial broiler farm. *Poultry Science, 98*(10), 5054–5063. https://doi.org/10.3382/ps/pez251

Ding, Y., Nan, Y., Qiu, Y., Niu, D., Stanford, K., Holley, R., … McAllister, T. A. (2023). Use of a phage cocktail to reduce the numbers of seven *Escherichia coli* strains belonging to different STEC serogroups applied to fresh produce and seeds. *Journal of Food Safety, 43*(4), e13044. https://doi.org/10.1111/jfs.13044

Duc, H. M., Son, H. M., Yi, H. P. S., Sato, J., Ngan, P. H., Masuda, Y., … Miyamoto, T. (2020). Isolation, characterization and application of a polyvalent phage capable of controlling *Salmonella* and *Escherichia coli* O157:H7 in different food matrices. *Food Research International, 131*, 108977. https://doi.org/10.1016/j.foodres.2020.108977

Endersen, L., & Coffey, A. (2020). The use of bacteriophages for food safety. *Current Opinion in Food Science, 36*, 1–8. https://doi.org/10.1016/j.cofs.2020.10.006

Gencay, Y. E., Ayaz, N. D., Copuroglu, G., & Erol, I. (2016). Biocontrol of Shiga toxigenic *Escherichia coli* O157:H7 in Turkish raw meatball by bacteriophage. *Journal of Food Safety, 36*(1), 120–131. https://doi.org/10.1111/jfs.12219

Gientka, I., Wójcicki, M., Żuwalski, A. W., & Błażejak, S. (2021). Use of phage cocktail for improving the overall microbiological quality of sprouts—Two methods of application. *Applied Microbiology, 1*(2), 289–303. https://doi.org/10.3390/applmicrobiol1020021

Gontijo, M. T. P., Jorge, G. P., & Brocchi, M. (2021). Current status of endolysin-based treatments against Gram-negative bacteria. *Antibiotics*, *10*(10), 1143. https://doi.org/10.3390/antibiotics10101143

Guliy, O. I., & Evstigneeva, S. S. (2025). Bacteria- and phage-derived proteins in phage infection. *Frontiers in Bioscience*, *30*(2): 24478 https://doi.org/10.31083/FBL24478

Harshitha, N., Rajasekhar, A., Saurabh, S., Sonalkar, R., Tejashwini, M., & Mitra, S. D. (2022). Bacteriophages: Potential biocontrol agents and treatment options for bacterial pathogens. *Clinical Microbiology Newsletter*, *44*(5), 41–50. https://doi.org/10.1016/j.clinmicnews.2022.02.002

Hintz, T., Matthews, K. K., & Di, R. (2015). The use of plant antimicrobial compounds for food preservation. *BioMed Research International, 2015*, 246264. https://doi.org/10.1155/2015/246264

Huang, C., Virk, S.M., Shi, J.; Zhou, Y., Willias, S.P., Morsy, M.K., … Li, J. (2018). Isolation, characterization, and application of bacteriophage LPSE1 against *Salmonella enterica* in ready to rat (RTE) foods. *Frontiers in Microbiology, 9*, 1046. https://doi.org/10.3389/fmicb.2018.01046

Igbinosa, E. O., & Beshiru, A. (2019). Antimicrobial resistance, virulence determinants, and biofilm formation of *Enterococcus* species from ready-to-eat seafood. *Frontiers in Microbiology*, *10*, 728. https://doi.org/10.3389/fmicb.2019.00728

Islam, F., Saeed, F., Afzaal, M., Ahmad, A., Hussain, M., Khalid, M. A., … Khashroum, A. O. (2022). Applications of green technologies-based approaches for food safety enhancement: A comprehensive review. *Food Science & Nutrition*, *10*(9), 2855–2867. https://doi.org/10.1002/fsn3.2915

Islam, M., Zhou, Y., Liang, L., Nime, I., Liu, K., Yan, T., … Li, J. (2019). Application of a phage cocktail for control of *Salmonella* in foods and reducing biofilms. *Viruses*, *11*(9), 841; https://doi.org/10.3390/v11090841

Jayamanne, M. N., & Foddai, A. C. G. (2025). Use of bacteriophages for biocontrol of pathogens in food and food-contact surfaces: A systematic review of the literature. *Sustainable Microbiology, 2*(1), qvaf005. https://doi.org/10.1093/sumbio/qvaf005

Kashani, H. H., Schmelcher, M., Sabzalipoor, H., Seyed Hosseini, E., & Moniri, R. (2017). Recombinant endolysins as potential therapeutics against antibiotic-resistant *Staphylococcus aureus*: Current status of research and novel delivery strategies. *Clinical Microbiology Reviews*, *31*(1), 1101–1134. https://doi.org/10.1128/cmr.00071-17

Khan, F. M., Chen, J. H., Zhang, R., & Liu, B. (2023). A comprehensive review of the applications of bacteriophage-derived endolysins for foodborne bacterial pathogens and food safety: Recent advances, challenges, and future perspective. *Frontiers in Microbiology, 14,* 1259210. https://doi.org/10.3389/fmicb.2023.1259210

Kim, J. H., Jung, S. J., Mizan, M. F. R., Park, S. H., & Ha, S. D. (2020). Characterization of *Salmonella* spp.–specific bacteriophages and their biocontrol application in chicken breast meat. *Journal of Food Science, 85*(3), 526–534. https://doi.org/10.1111/1750-3841.15042

Lee, H., Ku, H. J., Lee, D. H., Kim, Y. T., Shin, H., Ryu, S., & Lee, J. H. (2016). Characterization and genomic study of the novel bacteriophage HY01 infecting both *Escherichia coli* O157:H7 and *Shigella flexneri*: Potential as a biocontrol agent in food. *PLOS ONE*, *11*(12), e0168985. https://doi.org/10.1371/journal.pone.0168985

Li, J., Zhao, F., Zhan, W., Li, Z., Zou, L., & Zhao, Q. (2022). Challenges for the application of bacteriophages as effective antibacterial agents in the food industry. *Journal of the Science of Food and Agriculture*, *102*(2), 461–471. https://doi.org/10.1002/jsfa.11505

Lukman, C., Yonathan, C., Magdalena, S., & Waturangi, D. (2020). Isolation and characterization of pathogenic *Escherichia coli* bacteriophages from chicken and beef offal. *BMC Research Notes*, *13*(8). https://doi.org/10.1186/s13104-019-4859-y

Mahajan, P. V., Caleb, O. J., Singh, Z., Watkins, C. B., & Geyer, M. (2014). Postharvest treatments of fresh produce. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372*, 20130309. https://doi.org/10.1098/rsta.2013.0309

McCallin, S., Sarker, S. A., Barretto, C., Sultana, S., Berger, B., Huq, S., … Reuteler, G. (2013). Safety analysis of a Russian phage cocktail: From metagenomic analysis to oral application in healthy human subjects. *Virology, 443*(2), 187–196. https://doi.org/10.1016/j.virol.2013.05.022

Mizuno, C. M., Luong, T., Cederstrom, R., Krupovic, M., Debarbieux, L., & Roach, D. R. (2020). Isolation and characterization of bacteriophages that infect *Citrobacter rodentium*, a model pathogen for intestinal diseases. *Viruses*, *12*(7), 737. https://doi.org/10.3390/v12070737

Moye, Z. D., Woolston, J., & Sulakvelidze, A. (2018). Bacteriophage applications for food production and processing. *Viruses, 10*(4), 205. https://doi.org/10.3390/v10040205

Mtimka, S., Pillay, P., Kwezi, L., Pooe, O. J., & Tsekoa, T. L. (2024). An exploratory review of the potential of lytic proteins and bacteriophages for the treatment of tuberculosis. *Microorganisms*, *12*(3), 570. https://doi.org/10.3390/microorganisms12030570

Murray, K., Wu, F., Shi, J., Jun Xue, S., & Warriner, K. (2017). Challenges in the microbiological food safety of fresh produce: Limitations of post-harvest washing and the need for alternative interventions. *Food Quality and Safety, 1*(4), 289–301. https://doi.org/10.1093/fqsafe/fyx027

Nasr-Eldin, M., Gamal, E., Hazza, M., Abo-Elmaaty, S. A. (2023). Isolation, characterization, and application of lytic bacteriophages for controlling *Enterobacter cloacae* complex (ECC) in pasteurized milk and yogurt. *Folia Microbiologica*, *68*, 911–924. https://doi.org/10.1007/s12223-023-01059-7

Papoula-Pereira, R., Alvseike, O., Cenci-Goga, B. T., Grispoldi, L., Nagel-Alne, G. E., Ros-Lis, J. V., & Thomas, L. F. (2025). Economic evidence for the control of *Salmonella* in animal-derived food systems: A scoping review. *Food Control, 175*, 111275. https://doi.org/10.1016/j.foodcont.2025.111275

Petrov, G., Dymova, M., & Richter, V. (2022). Bacteriophage-mediated cancer gene therapy. *International Journal of Molecular Sciences, 23*(22), 14245. https://doi.org/10.3390/ijms232214245

Ramos-Vivas, J., Tapia, O., Elexpuru-Zabaleta, M., Tutusaus Pifarre, K., Armas Diaz, Y., Battino, M., & Giampieri, F. (2022). The molecular weaponry produced by the bacterium *Hafnia alvei* in foods. *Molecules*, *27*(17), 5585. https://doi.org/10.3390/molecules27175585

Rashida, H., Sean, B., Douglas, N., Carlota, M., Alida, S., Jessica, L., … Gieraltowski, L. (2019). Multistate outbreak of Salmonella infections linked to raw turkey products — United States, 2017–2019*. MMWR Morbidity and Mortality Weekly Report*, *68*(46), 1045–1049. https://doi.org/10.15585/mmwr.mm6846a1

Sarno, E., Pezzutto, D., Rossi, M., Liebana, E., & Rizzi, V. (2021). A review of significant European foodborne outbreaks in the last decade*. Journal of Food Protection, 84*(12), 2059–2070. https://doi.org/10.4315/JFP-21-096

Scallan, E., Hoekstra, R. M., Angulo, F. J., Tauxe, R. V., Widdowson, M. A., Roy, S. L., … Griffin, P. M. (2011). Foodborne illness acquired in the United States—major pathogens. *Emerging Infectious Diseases, 17*(1), 7–15. https://doi.org/10.3201/eid1701.P11101

Shahin, K., Barazandeh, M., Zhang, L., Hedayatkhah, A., He, T., Bao, H., … Wang, R. (2021). Biodiversity of new lytic bacteriophages infecting *Shigella* spp. in freshwater environment. *Frontiers in Microbiology,* *12*, 619323. https://doi.org/10.3389/fmicb.2021.619323

Shahin, K., Bouzari, M., Komijani, M., & Wang, R. (2020). A new phage cocktail against multidrug, ESBL-producer isolates of *Shigella sonnei* and *Shigella flexneri* with highly efficient bacteriolytic activity. *Microbial Drug Resistance, 26*(7), 831–841. https://doi.org/10.1089/mdr.2019.0235

Shang, Y. T., Sun, Q. F., Chen, H. F., Wu, Q. P., Chen, M. T., Yang, S. H., … Zhang, J. (2021). Isolation and characterization of a novel Salmonella phage vB_SalP_TR2. *Frontiers in Microbiology, 12*, 664810. https://doi.org/10.3389/fmicb.2021.664810

Sharma, C. S., Dhakal, J., & Nannapaneni, R. (2015). Efficacy of lytic bacteriophage preparation in reducing *Salmonella* in vitro, on turkey breast cutlets, and on ground turkey. *Journal of Food Protection, 78*(7), 1357–1362. https://doi.org/10.4315/0362-028X.JFP-14-585

Shebs, E. L., Lukov, M. J., Giotto, F. M., Torres, E. S., & de Mello, A. S. (2020). Efficacy of bacteriophage and organic acids in decreasing STEC O157:H7 populations in beef kept under vacuum and aerobic conditions: A simulated High Event Period scenario. *Meat Science,* *162*, 108023. https://doi.org/10.1016/j.meatsci.2019.108023

Shebs-Maurine, E. L., Giotto, F. M., Laidler, S. T., & de Mello, A. S. (2021). Effects of bacteriophages and peroxyacetic acid applications on beef contaminated with *Salmonella* during different grinding stages. *Meat Science, 173*, 108407. https://doi.org/10.1016/j.meatsci.2020.108407

Shen, K. S., Shu, M., Tang, M. X., Yang, W. Y., Wang, S. C., Zhong, C., & Wu, G. P. (2022). Molecular cloning, expression and characterization of a bacteriophage JN01 endolysin and its antibacterial activity against *E. coli* O157:H7. *LWT-Food Science and Technology*, *165*, 113705. https://doi.org/10.1016/j.lwt.2022.113705

Sillankorva, S. M., Oliveira, H., & Azeredo, J. (2012). Bacteriophages and their role in food safety. *International Journal of Microbiology, 2012*, 863945. https://doi.org/10.1155/2012/863945

Soffer, N., Abuladze, T., Woolston, J., Li, M., Hanna, L. F., Heyse, S., … Sulakvelidze, A. (2016). Bacteriophages safely reduce *Salmonella* contamination in pet food and raw pet food ingredients. *Bacteriophage,* *6*(3), e1220347. https://doi.org/10.1080/21597081.2016.1220347

Soffer, N., Woolston, J., Li, M., Das, C., & Sulakvelidze, A. (2017). Bacteriophage preparation lytic for *Shigella* significantly reduces *Shigella sonnei* contamination in various foods. *PLOS ONE, 12*(3), e0175256. https://doi.org/10.1371/journal.pone.0175256

Soto Lopez, M. E., Mendoza-Corvis, F., Salgado-Behaine, J. J., Hernandez-Arteaga, A. M., González-Peña, V., Burgos-Rivero, A. M., … Pérez-Sierra, O. (2025). Phage endolysins as an alternative biocontrol strategy for pathogenic and spoilage microorganisms in the food industry. *Viruses*, *17*(4), 564. https://doi.org/10.3390/v17040564

Tomat, D., Casabonne, C., Aquili, V., & Quiberoni, A. (2025). Evaluation of food-grade additives on the viability of ten *Shigella flexneri* phages in food to improve safety in agricultural products. *Viruses, 17*(4), 47. https://doi.org/10.3390/v17040474

Vikram, A., Tokman, J. I., Woolston, J., & Sulakvelidze, A. (2020). Phage biocontrol improves food safety by significantly reducing the level and prevalence of *Escherichia coli* O157:H7 in various foods. *Journal of Food Protection, 83*(4), 668–676. https://doi.org/10.4315/0362-028X.JFP-19-433

Vikram, A., Woolston, J., & Sulakvelidze, A. (2021). Phage biocontrol applications in food production and processing. *Current Issues in Molecular Biology, 40*, 267–302. https://doi.org/10.21775/cimb.040.267

Wagh, R. V., Priyadarshi, R., & Rhim, J. W. (2023). Novel bacteriophage-based food packaging: An innovative food safety approach, *Coatings*, *13*(3), 609. https://doi.org/10.3390/coatings13030609

Wong, C. W. Y., Delaquis, P., Goodridge, L., Lévesque, R. C., Fong, K., & Wang, S. (2020). Inactivation of Salmonella enterica on post-harvest cantaloupe and lettuce by a lytic bacteriophage cocktail. *Current Research in Food Science, 2*, 25–32. https://doi.org/10.1016/j.crfs.2019.11.004

Żaczek, M., Weber-Dąbrowska, B., & Górski, A. (2015). Phages in the global fruit and vegetable industry. *Journal of Applied Microbiology, 118*(3), 537–556. https://doi.org/10.1111/jam.12700

Zhang, H. Z., Shu, M., Yang, W. Y., Pan, H., Tang, M. X., Zhao, Y. Y., … Wu, G.P. (2023). Isolation and characterization of a novel Salmonella bacteriophage JNwz02 capable of lysing Escherichia coli O157:H7 and its antibacterial application in foods. *LWT – Food Science and Technology, 173,* 14251. https://doi.org/10.1016/j.lwt.2022.114251

Zhang, X., Niu, Y. D., Nan, Y., Stanford, K., Holley, R., McAllister, T., & Narváez-Bravo, C. (2019a). SalmoFresh™ effectiveness in controlling Salmonella on romaine lettuce, mung bean sprouts and seeds. *International Journal of Food Microbiology, 305,* 108250. https://doi.org/10.1016/j.ijfoodmicro.2019.108250

Zhang, Z. H., Wang, L. H., Zeng, X. A., Han, Z., & Brennan, C. S. (2019b). Non-thermal technologies and its current and future application in the food industry: A review. *International Journal of Food Science & Technology, 54*(1), 1–13. https://doi.org/10.1111/ijfs.13903

Zia, S., & Alkheraije, K. A. (2023). Recent trends in the use of bacteriophages as replacement of antimicrobials against food-animal pathogen. *Frontiers in Veterinary Science*, *10*, 1162465. https://doi.org/10.3389/fvets.2023.1162465