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REVIEW ARTICLE

A Comprehensive Review: Exploring the Potential of Bacteriophages in Agriculture and Environment

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Abstract

Bacteriophages, viruses that infect and replicate within bacterial hosts, offer versatile solutions across various fields, including biotechnology, medicine, and agriculture. This comprehensive review explores the intricate life cycle of bacteriophages, encompassing both lytic and lysogenic phases, and highlights their role in shaping microbial communities and influencing bacterial evolution. In Biotechnology, bacteriophages are instrumental tools in molecular biology research, drug discovery, and environmental remediation. In agriculture, phage-based biopesticides provide sustainable solutions for controlling bacterial pathogens in crops, livestock, and aquaculture. The robust, targeted solutions bacteriophages offer for addressing societal and environmental challenges necessitate continued research and innovation in phage-based technologies, particularly in understanding their influence on microbial communities.

Introduction

Bacteriophages are viruses that infect and replicate within bacterial cells. Since they were discovered over a century ago, bacteriophages have attracted increasing attention in various scientific disciplines due to their unique biological properties and versatile applications (Panwar et al., 2020). Bacteriophages were utilized in multiple fields, such as biotechnology, medicine, agriculture, environmental science, and nanotechnology. Bacteriophages are vital in forming microbial communities and controlling the bacterial population in ecological conditions (Naureen et al., 2020). Their interactions with bacterial hosts influence ecosystem dynamics and nutrient cycling processes.

Bacteriophages are essential indicators of microbial community structure and function in various environments, including aquatic systems and wastewater treatment plants (Bayat et al., 2021). In agricultural settings, bacteriophages have emerged as potential biocontrol agents for managing bacterial diseases in crops and livestock. Bacteriophages provide a targeted method for disease management by specifically attacking pathogenic bacteria while preserving non-pathogenic strains. This precision minimizes environmental consequences and decreases dependence on chemical treatments [53]. Bacteriophage therapy, or phage therapy, involves using lytic bacteriophages to specifically target and kill pathogenic bacteria [15]. Bacteriophages have demonstrated potential in diagnostic applications, especially in creating bacteriophage-based biosensors for the rapid and specific detection of bacterial pathogens. These biosensors utilize the host specificity of bacteriophages to selectively identify and target bacteria, facilitating sensitive and rapid detection in clinical, food, and environmental samples. Although the potential application of bacteriophage holds significant promise for various applications, several challenges persist. These challenges encompass concerns

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regarding phage stability, formulation, and commercialization [21].

Additionally, understanding the complex interaction between bacteriophages and their bacterial host is essential for enhancing their application in diverse fields while minimizing potential risks, including the development of phage-resistant bacteria [48]. This review aims to provide an overview of the diverse applications of bacteriophages in different fields, including environmental science, agriculture, and nanotechnology. Furthermore, it provides the emerging trends and technologies in bacteriophage research, as well as challenges and opportunities for future development and transformation to real-world applications.

Applications of Phage-Based Bacterial Control in the Environment

Bacteriophages are predominantly used in the treatment of wastewater. Wastewater treatment is critical for safeguarding public health and preserving environmental integrity. Bacteria are present in every water supply stage in urban and rural areas. Depending on the concentration and location, bacteria can be beneficial or harmful [41]. Bacteriophages, with their unique characteristics and interactions with bacterial hosts, have emerged as valuable tools for enhancing the efficiency and sustainability of wastewater treatment processes. Also, it is used to identify beneficial and harmful bacteria in the water [59]. Bacteriophages play multifaceted roles in wastewater ecosystems, significantly influencing microbial interactions and the cycling of nutrients. Bacteriophages are essential regulators of bacterial populations, playing an important role in maintaining microbial diversity and stability in wastewater treatment systems [46]. Their predation on bacterial hosts is essential for controlling the bacterial population, which subsequently affects the structure and function of microbial communities (Fig. 1). Bacteriophages play a significant role in biogeochemical processes by influencing nutrient cycling and the breakdown of organic matter, thus enhancing the overall efficiency of wastewater treatment processes (Chen et al., 2021). Besides their ecological roles, bacteriophages have significant technological applications in wastewater treatment (Table 1). The critical application of phage is they are used as indicators of membrane

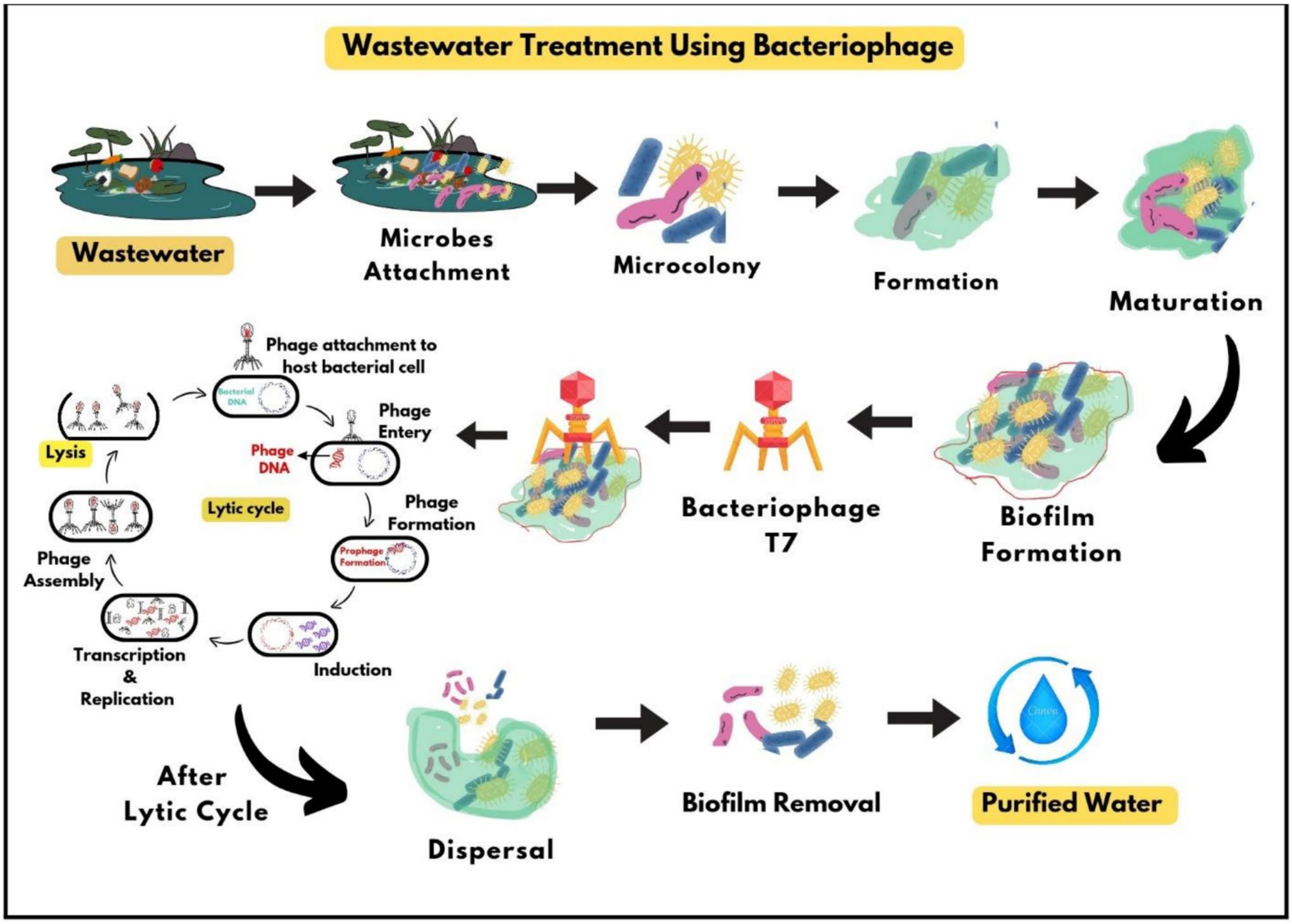

Fig. 1 Role of bacteriophage in wastewater treatment [3]

Table 1 Application of bacteriophage in wastewater treatment

Bacteriophage Variants	Wastewater Application	Description	Reference
MS2, Qβ	Indicators of faecal contamination and viral water pollution	Somatic coliphages are used as indicators due to their presence in human and animal feces, making them reliable markers for detecting faecal contamination in water	Ballesté et al., [6]
T4, T2	Control of pathogenic bacteria in sewage and biofilm formation on membranes	These phages target and lyse specific pathogenic bacteria, reducing their population in sewage and preventing biofilm formation on treatment membranes	Runa et al., [50]
Ma-LMM01, S-PM2	Control of bloom-forming cyanobacteria in wastewater systems	Phages infect cyanobacteria, which are responsible for harmful algal blooms, thus helping to control and reduce these blooms in wastewater systems	de Oliveira et al., [14]
Pseudomonas phage LUZ19	Control of *Pseudomonas aeruginosa* in wastewater	These phages specifically target *Pseudomonas aeruginosa*, a common pathogen in wastewater, helping to reduce its presence and associated risks	Abedon et al., [2]
E. coli phage T4, *E. coli phage* T7	Control of *E. coli* in wastewater systems	These phages are effective in lysing *E. coli*, a common indicator of faecal contamination, thereby improving water quality	Sillankorva et al., [56]
phiIPLA-RODI, phiIPLA-C1C	Control of *Staphylococcus aureus*	Lyses staphylococcal biofilms, improving the efficiency of wastewater treatment systems	Gutiérrez et al., [25]

performance within membrane bioreactors (MBRs) [52]. Bacteriophages serve as indicators for monitoring membrane integrity and assessing the efficiency of MBRs in removing pathogens and contaminants from wastewater. Monitoring the abundance and diversity of bacteriophages enables wastewater treatment operators to evaluate the efficacy of membrane filtration processes and optimize treatment protocols as needed. Membrane fouling represents a common challenge in wastewater treatment that can affect the effectiveness and durability of membrane-based filtration systems. Bacteriophages provide a potential solution to reduce membrane fouling by explicitly targeting and lysing the bacterial biofilm that adheres to membrane surfaces [9]. Through their lytic action, Bacteriophages interfere with biofilm development and inhibit the accumulation of foulants, enhancing the membrane permeability and reducing the fouling potential. Bacteriophages can be engineered or selected for their specificity towards essential biofilm-forming bacteria, facilitating the specific interventions to prevent membrane fouling in wastewater treatment plants [3].

Several case studies have demonstrated the efficacy of bacteriophages in improving wastewater treatment processes [8]. Incorporating specific bacteriophages can enhance the removal of pathogenic bacteria and reduce the membrane fouling in MBRs. In addition, field trials have evaluated the feasibility of introducing bacteriophage-based interventions in full-scale wastewater treatment plants. The excellent findings of these investigations demonstrate the promise of bacteriophages as low-cost, environmentally friendly solutions to wastewater treatment problems [8, 37, 54]. Future research investigations should overcome these challenges while exploring novel strategies to utilize the bacteriophages in wastewater treatment.

Application of Bacteriophages in Agriculture

Agriculture is the backbone of worldwide food production, and it is encountering challenges such as crop and pest diseases that significantly affect yield and quality. Bacteriophages possess the unique capability to selectively target and destroy bacterial pathogens, presenting a viable and sustainable solution to mitigate these agricultural issues. Bacterial infections constitute significant risks to crop health, resulting in large production losses and adverse financial impacts. Since they can specifically infect and lyse the bacterial species that cause illnesses, including bacterial blight, bacterial wilt, and soft rot, bacteriophages provide an alternative method to fight against these pathogens [32]. Bacteriophages present a precise and eco-friendly substitute for chemical pesticides by specifically targeting harmful bacteria while preserving beneficial microorganisms (Fig. 2).

In agricultural contexts, they utilize two primary mechanisms to manage bacterial pathogens: the lytic and lysogenic cycles [11, 31]. The rapid destruction of bacterial populations can significantly reduce disease severity and restrict the spread of pathogens in crop fields. Alternatively, bacteriophages can incorporate their genetic material into the bacterial chromosomes during the lysogenic cycle, where they remain inactive until specific environmental conditions prompt their activation [11]. This prophylactic strategy allows the bacteriophage to confer resistance to bacterial pathogens for prolonged periods, thereby ensuring long-term protection of crops (Fig. 3).

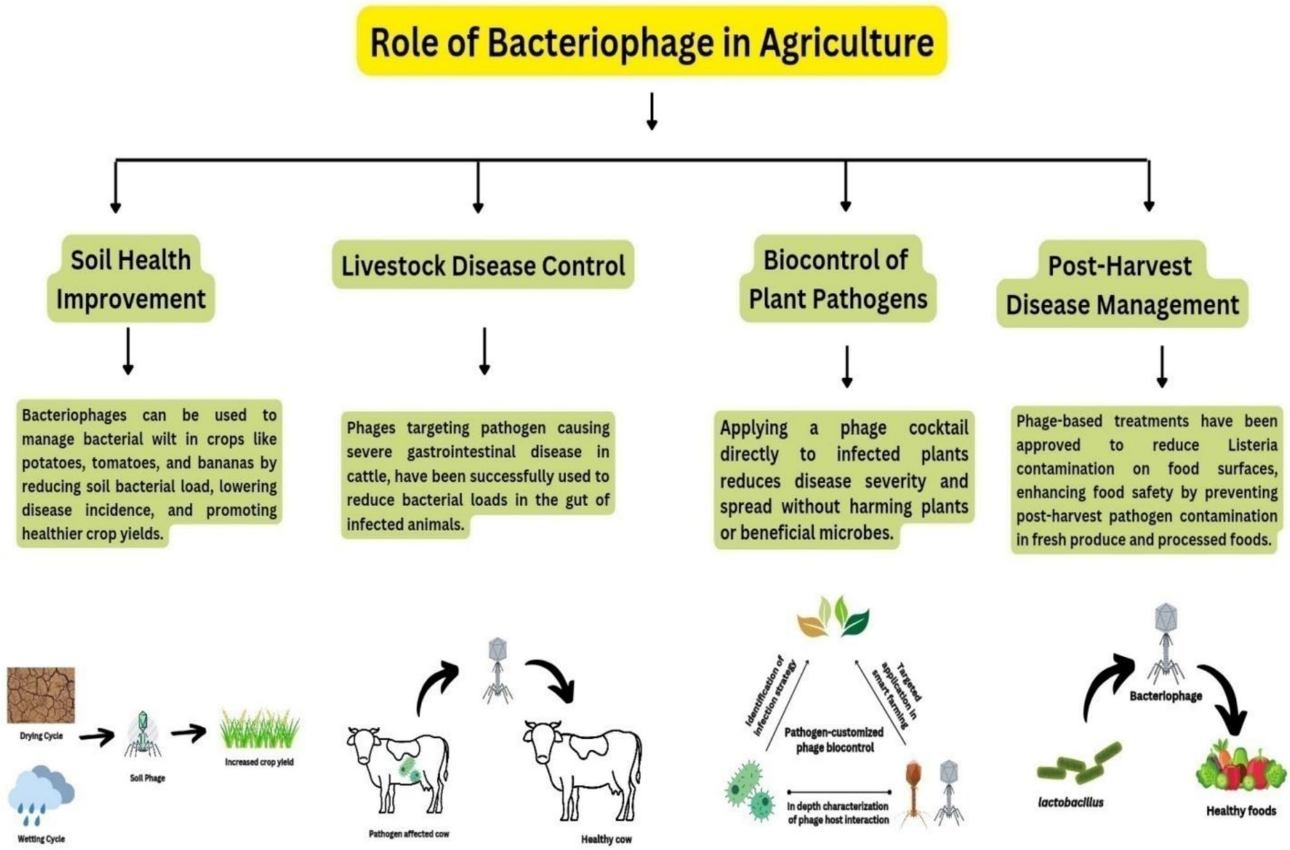

Fig. 2 Role of bacteriophage in Agriculture [11, 32]

Several studies have shown the efficacy of bacteriophage in controlling bacterial disease in various crops such as potatoes, tomatoes, and citrus fruits (Table 2) [26].Bacteriophage-based biocontrol formulations have been developed and commercialized for agriculture, influencing farmers to make a sustainable and eco-friendly alternative to chemical pesticides [26]. These formulations can be helpful via foliar sprays, soil drenches, or seed treatments, providing flexible possibilities for integrated pest management strategies.

In some studies, the virus's genetic material is inserted into the bacterial host and transmitted from parent to daughter cells of the bacterial host. Phage therapy has been used since 1960 to till now to control the plant pathogens such as *Pseudomonas sp., Erwinia sp., Streptomyces sp., Xanthomonas sp.,* etc. (Enebe and Erasmus et al., 2023). Czajkowski et al., [12] reported that the bacterium *Dickeya-solani* cause soft rot disease in potato tubers is controlled using ΦD5 lytic phage. This phage reduced the infection in potatoes by about 50% in phage-treated plants. These phages can survive in soil and on the surface of the tubers for about 24 days. The phage isolated from the rhizosphere of tomato plant has the efficacy as the biocontrol agent against the bacteria *Xanthomonas sp*., and also, when the phage is applied into the soil, can inhibit the growth of bacterial pathogens including *Pectobacterium atrosepticum* and *Pectobacterium carotovorum* [33, 65]. Ramírez et al. (2020) investigated that banana and plantain plants are affected by moko disease by *Ralstonia solanacearum*. The researcher used the phage cocktail to treat this disease. These phage cocktails inhibit the pathogenic bacterium growth in soil and also inhibit plant disease. This study confirms that single phage usage showed symptoms of diseases compared to the plant treated with a cocktail of phages, which showed no symptoms.

In another study, the tomato seeds were soaked and coated with phage particles before plantation. This inhibits the *R. solanacearum* colonization at the root part of the plant. These phage particles were found within the shoot system and provided intracellular protection against the plant pathogen (Askora et al., 2021) [18]. Wang et al. [61] reported that the 80% decrease in the disease caused by plant pathogen *R. solanacearum* was due to the treatment of plants with phage cocktails. The bacteriophage isolated from the Kiwi fruit planted soil was able to degrade the *Pseudomonas syringaepv. Actinidiae* that cause disease in kiwi plant. Phages isolated from apple plant-growing soil were used to treat the plant disease caused by *Erwinia amylovora*[24].

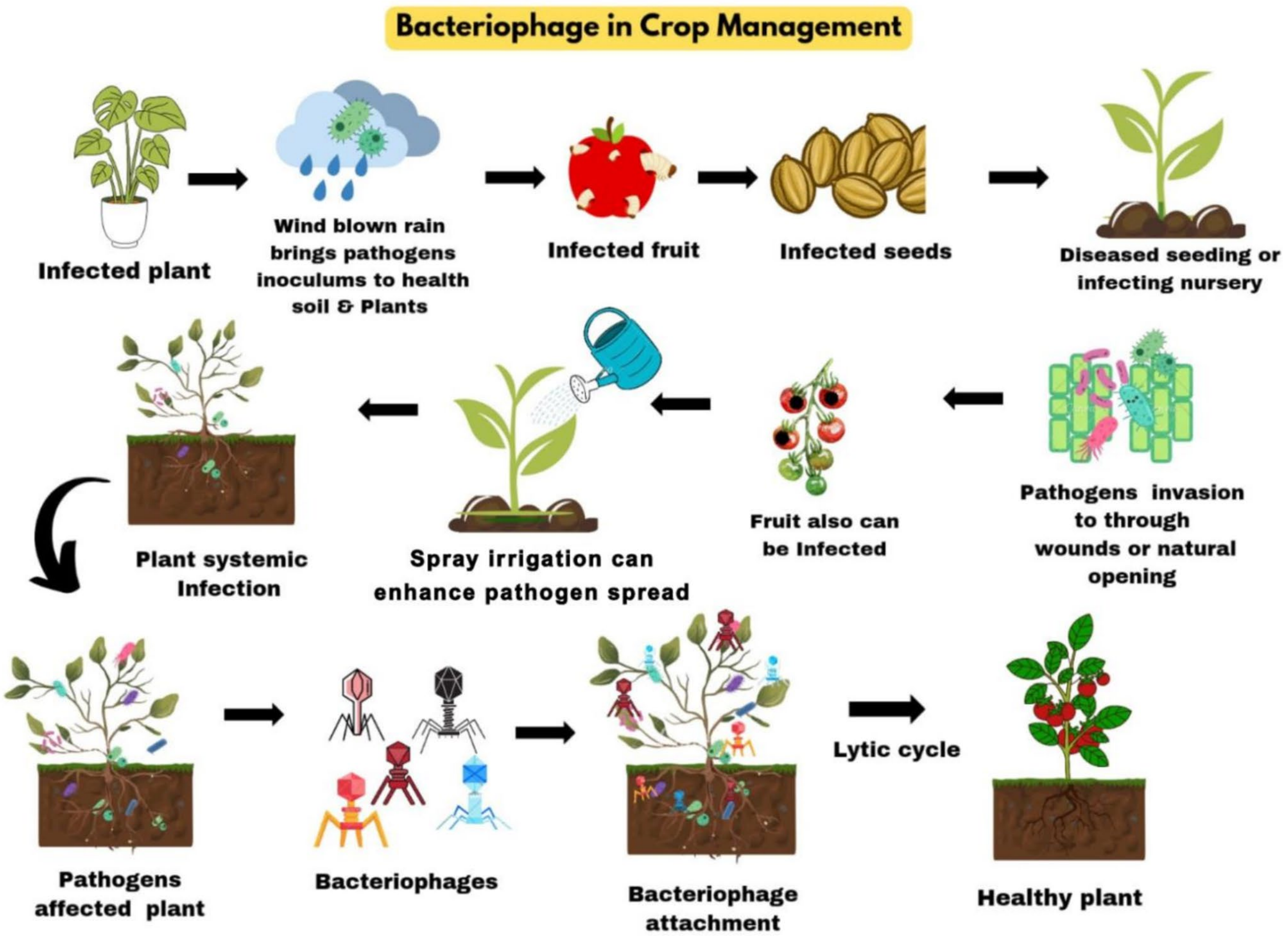

Fig. 3 Role of bacteriophage in controlling the crop disease

Despite their potential benefits, the widespread approval of bacteriophage-based biocontrol aspects has several challenges. It is essential to understand the comprehensive interactions between bacteriophages, bacterial pathogens, and plant hosts within agricultural ecosystems [31, 57]. Furthermore, problems that include bacteriophage stability, formulation, optimization, and monitoring approval processes require further research and development to facilitate the effective integration of bacteriophage-based biocontrol into conventional agricultural practices. This includes investigating the ecological impacts of bacteriophage applications on non-target organisms, optimizing formulation and delivery methods to maximize efficacy and minimize environmental impact, and developing strategies to mitigate the emergence of bacterial resistance to bacteriophages [31, 57].

Emerging Technologies in Bacteriophage Research

In recent years, advancements in biotechnology have paved the way for developing innovative strategies connecting the potential of bacteriophages in various applications. These emerging technologies are used to understand the challenges and create the scope of bacteriophage research beyond the traditional restrictions. Phage display technology aids in appearing foreign peptides or proteins on the surface of bacteriophage capsids, producing phage libraries that display various peptide sequences (Jaroszewicz et al., 2022). This technology has altered the fields of protein engineering, drug discovery, and vaccine development by aiding in the high-throughput screening of peptides or ligands for target molecules. Phage display libraries provide a wide range of potential binding agents for applications that include targeted administration of drugs for biomarker detection through the utilization of the inherent diversity of bacteriophage genomes [49]. Genome engineering and synthetic biology developments have made it easier to modify and alter

Table 2 Application of bacteriophage in Agriculture

Bacteriophage Variants	Agricultural application	Description	Reference
ΦX174	Pathogen Control in Crops	Targets and eliminates *Xanthomonas campestris*, a pathogen causing bacterial spot in tomatoes and peppers	Fernández et al., [20]
T4	Compost Treatment	Reduces harmful *Escherichia coli* in compost, enhancing the safety of organic fertilizers	Carlon et al., (2023)
P100	Animal Health	Treats *Listeria monocytogenes* infections in livestock, reducing the reliance on antibiotics	Svircev et al., [58]
Φ29	Soil Health Improvement	Enhances soil health by targeting and reducing *Pseudomonas syringae*, a bacterium harmful to plant roots	Jones et al., [31]
Φ6	Post-Harvest Disease Control	Reduces *Erwinia amylovora*, the causative agent of fire blight in apples and pears, during post-harvest storage	Korniienko et al., (2022)
ΦRSM3	Plant Growth Promotion	Enhances plant growth by targeting and reducingsoil-borne pathogen*Ralstonia solanacearum*	Yamada et al., [64],Askora et al., (2021)

bacteriophage genomes for specific applications (Lenneman et al., 2021). Researchers can precisely engineer bacteriophage genomes through techniques such as CRISPR-Cas-based genome editing to enhance their specificity, efficacy, and safety profiles. This enables the development of customized bacteriophage therapeutics with improved pharmacokinetic properties and reduced immunogenicity. Synthetic biology approaches allow synthetic bacteriophage design with novel functionalities, such as enhanced host range or biofilm-disrupting capabilities, expanding the therapeutic potential of bacteriophage-based interventions [45]. Biocontrol techniques can be enhanced more precisely by using engineered bacteriophages designed as biocontrol agents to target specific bacterial infections by minimizing the effect on beneficial microorganisms. It enables the development of novel formulation and delivery systems to optimize the efficiency and stability of phage-based products in various environmental conditions [30, 62].

The convergence of nanotechnology and bacteriophage research has led to the development of bacteriophage-based nanomaterials with unique properties and applications (Ahmed, 2024). The bacteriophage-based nanomaterials exhibit specific physicochemical properties and can be utilized for various applications, including biosensing, imaging, and drug delivery [62]. Bacteriophage-based nanomaterials have advantages such as biocompatibility, stability, and specificity, making them promising candidates for biomedical and environmental applications [62]. Although bacteriophage research and applications can be significantly improved by developing technology, many challenges including technical challenges associated with phage display library construction, optimizing genome editing techniques for specific phage engineering, and confirming the scalability and reproducibility of bacteriophage-based nanomaterial synthesis [17]. Additionally, interdisciplinary collaborations between biologists, engineers, and materials scientists are essential for utilizing emerging technologies in bacteriophage research and transformation into real-world solutions.

Bacteriophage-Based Biosensors

Bacteriophage-based biosensors have emerged as powerful tools for the rapid and specific detection of bacterial pathogens in various environments. Bacteriophage-based biosensors work on the principle of bacteriophage-mediated recognition and collection of target bacteria [54]. Typically, these biosensors consist of immobilized bacteriophages on a solid support, such as a sensor surface or membrane, coupled with a signal transduction mechanism to detect bacterial binding measures. The bacteriophages especially attach to their specific receptors on the surface of the target bacteria once they come into contact, causing signal generation or amplification [54]. This signal can be quantitatively measured and correlated with the concentration of target bacteria present in the sample, enabling rapid and sensitive detection. Bacteriophage-based biosensors have been utilized for the detection of a wide range of bacterial pathogens, including *Escherichia coli, Salmonella spp., Listeria monocytogenes*, and *Staphylococcus aureus*, in various sample conditions [4, 61]. These biosensors offer several advantages, including high specificity, rapid response times, low detection limits, and compatibility with complex sample matrices. In clinical situations, bacteriophage-based biosensors have been used for the rapid diagnosis of infectious diseases, monitoring of microbial contamination in food and water, and observation of antibiotic-resistant bacteria in healthcare situations [61].

Bacteriophage-based biosensors can detect the disease because of their portability, ease of use, and potential for integration with reduced detection conditions. Recent advances in bacteriophage-based biosensor technology have led to the development of next-generation biosensors with enhanced sensitivity, specificity, and multiplexing capabilities [27, 51]. The incorporation of advanced signal transduction mechanisms, such as electrochemical, optical, or microfluidic-based detection platforms, enables real-time and label-free detection of bacterial pathogens [27, 51]. Developing portable and smartphone-based biosensor systems shows the potential for various environmental applications. Bacteriophage-based biosensors to be widely used in clinical and industrial environments, testing methods must be standardized, and integration into current regulatory structures must be integrated. Future research studies should focus on these challenges and the development of bacteriophage-based biosensor technology for various applications such as disease diagnostics, food safety, environmental monitoring, and biosecurity.

Bacteriophages in Poultry Farming

The occurrence of diseases in poultry farming is a widespread and harmful factor. The poultry farm is contaminated due to the unhygienic conditions. Diseases such as salmonellosis, botulism, and fowl pox reduce the growth factors in the chicken. Therefore, bacteriophages play a significant role in stimulating the growth promotors (Fig. 4).

Necrotic enteritis in chickens is the primary cause of weight loss in the chicken [28]. The cocktail of phage infusion in poultry feeding will control the pathogenic enteritis in chickens and assist in regaining their original weight. The chicken infected with *Campylobacter jejuni* was treated orally with a phage cocktail, including *Campylobacter* phage. These decreased the prevalence of *Campylobacter jejuni* but did not decrease the microbiota (Steffan, 2022; [47]). The effectiveness of bacteriophage was observed by the simultaneous administration of phages with *Salmonella typhimurium* to chickens. During the trial process, the bacteriophage decreased the viability of *Salmonella* sp. in a bird's gut small intestine (Lorenzo-Rebenaqueetal., 2021). Another study was conducted on pigs with a cocktail of bacteriophages and other growth supplements. The tremendous healthy weight gain and disease-resistant capacity were noticed, and in conclusion, the beneficial bacteria were improved, and other harmful pathogens in the pig's feces were reduced [13].

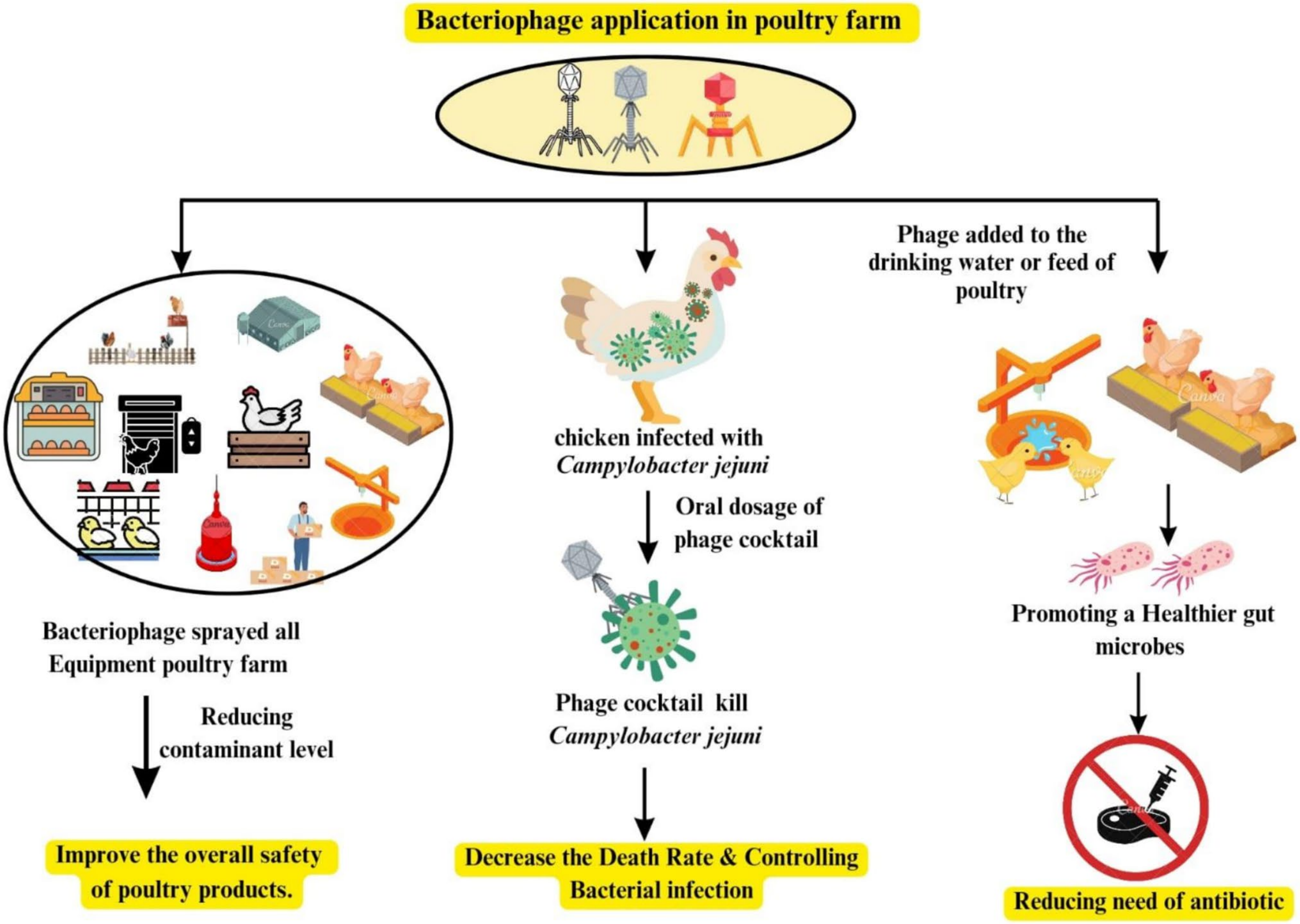

Fig. 4 Role of bacteriophage in poultry farming (Steffan, 2022) [47]

Table 3 Phages engineered for delivery of Biological compounds using carrier molecule

Phage	Carrier Molecule	Application	Reference
M13	Gold nanorods	Lysis pf *P. aeruginosa* biofilm and controlled phage therapy by photothermal method	Peng et al., [44]
T7	Fluorescent protein	Counting mRNA by naked eye by the fluorescent protein present in phage	Wisuthiphaet, [63]
M13	Exogenous protein	Delivery of functional protein and enzyme to target Prostrate cancer cells	Chang et al., [10]
Lambda	Mammalian expression cassette which encode luciferase enzyme	It is used for gene delivery and expression through integral binding protein in phage	Aanei et al., [1]
MS2 capsid	Cu 2 + Radiolabelled capsid in phage	Anti – EGFR antibody targeting breast cancer cells by PET/CT imaging of tumour xenografts	Si et. al., [55]

Genetically Engineered Phage as a Delivery system

Phage act as a nanocarrier to deliver the nucleic acids such as DNA and RNA. The processes of virion production, survival, and attachment to host cells are subject to selective pressures that facilitate phage propagation. These characteristics along with phage production in bacterial culture, make phages to be used as delivery system for the biomedical applications (Dąbrowska, 2019). Phage therapy focus the attention of various researchers due to the growing problem of antibiotic- resistance infections. For instance, Phages of *Staphylococcus aureus* transfer their antibiotic resistance gene among hosts. Phages that carries CTXϕ virulence factors gene, transmits the toxic gene reduces the effect of *Vibrio cholerae* to humans. Additionally, phage particles also contribute to the pathogenic infections. For example, Pf4 phage virions form liquid crystalline biofilm around the *Pseudomonas aeruginosa* cells and increases the tolerance to antibiotics (Tarafder et. al., 2020). Because of presence of wide variety of phages, their characteristics are undetermined and their negative effects are difficult to predict. Some phages are used as delivery system to deliver certain molecules to cure the diseases particularly cancer cells. For instances, The targeting peptides from biological interactions such as antibodies or random peptides from library by invitro selection against the reception by phage display method. The carrier molecules such as nucleic acids, peptides, nanomaterials, drugs, etc. are attached to the capsid protein through physical or chemical conjugation (Tarafder et. al., 2020). The examples of phages and their carrier molecule and application are shown in Table 3.

Application of Bacteriophage in Food Industry

In the food industry, physical methods including steam, dry heat and chemical methods such as antimicrobial agents and preservatives were used for controlling and protecting the food borne pathogens. The quality of the food was affected by these two treatment methods for preventing food borne pathogens [22]. Instead of this thermal sterilization technique is also followed, in this, the colour and flavour of the food is affected and the nutritional value also reduced. Chemical sanitizer also used for reducing the bacterial contamination in fruits and vegetables. It will damage the food processing and also pollute the environment [22].

Currently, Bacteriophage therapy is gaining more interest due to the emergence of antimicrobial resistance pathogens. The FDA (Food and Drug Administration) has approved certain phages to use on crops to reduce the crop disease by microorganisms. For instance, bacterial blight disease in soybean was treated with certain phages to reduce the antibiotic resistant bacteria [19]. Nabil et al., (2018) reported that the use of phage cocktail in the form of microencapsulated feed reduces the colonization of *Salmonella* sp., in broiler chicken and pigs. The bacteriophage cocktail LPSTLL, LPST94, and LPST153 reduces the *Salmonella* inoculum on chicken breast and milk [29].

Bacteriophage has also been used as a faecal indicator and water quality indicator as an early warning of contamination in sewage and it is used as an efficient marker in wastewater treatment [48].

Positive and Negative Impacts of Bacteriophage

The utilization of phage in various fields exhibit pros and cons. Phage therapy is used in treating various human and animal diseases and in medical treatment. It is used as an alternative for antibiotics. Phages are used to reduce the illness caused by microorganisms such as *Staphylococcus, Salmonella* and *Pseudomonas sp.,* The phages were used effectively against cystic fibrosis treatment and also against resistant bacterial infections [36]. It is not only used in medicinal application,it is also used in the treatment of wastewater by reducing the biofilm formation in wastewater to determine the quality of the water. Susceptible assessment of bacteria is important for specific bacteriophage before it is used in any therapy. Due to the lack of diagnostic screening test, against the cocktail of bacteriophage, the bacterial lysis will occur and cause the release of endotoxin that will cause sepsis [16].

Phages also used to increase the food quality especially in case of animal foods. Phages are used in food processing industry in order to increase the food quality especially in animal-based foods. Several phage-based food products are approved by FDA includes, LISTEX is used in the control of *L. monocytogenes*, Eco Shield for reducing the growth of *E. coli* O157:H7. It is also used at decontaminating the livestock that lowers the risk of diseases that enters the food supply and raised in use of human consumption [34, 38]. Phage – based sensor received more interest due to their high specificity, simplicity and sensitivity. Phages are immobilized on electrode surface and it can infect only specific bacterial strains. Whole phage probe, phage display peptides, receptor binding protein, nucleic acid-based probe are used in order to detect the infection on the biosensor surfaces [42]. Surface plasmon resonance and Raman spectroscopy transducer are widely used in the development of phage based bacterial detection and for the development of biosensor-based phages. Phage based therapy are also used in the detection and selection of antibodies against coronavirus [5].

There are some limitations are also there in the utilization of phage-based therapy because IT release peptidoglycans, lipopolysaccharides, and other inflammatory molecules that will create crude phage preparation. These crude phages can be purified by various techniques includes column chromatography, density gradient centrifugation which are cost effective and also it reduces the problem due to contamination [35, 40]. In food industry, the phage contamination was observed in dairy industry. The challenges of phage resistance are crucial for ensuring the long-term effectiveness and sustainability of phage-based applications.

Conclusion

In conclusion, bacteriophage with their unique specificity and self-replicating nature, offer many solutions for controlling microbial population in diverse fields including wastewater treatment, agriculture, food and poultry farming. In wastewater treatment, phage therapy provides a precise method to solve challenges such as foaming, bulking and biofilm formation decrease dependence on chemical treatments and assist in environmental sustainability. In the field of agriculture, phages are effectively combat bacterial infections in plants, providing a naturally and eco-friendly alternative to chemical pesticides. Similarly, in poultry farming, phages provides an alternative to antibiotics, directed to significant importance given the global concern regarding antibiotic resistance. In food industry, bacteriophages are used to enhance food safety, increased shelf life of foods and reduces the reliance on chemical preservatives. With increasing regulatory support and consumer demand for cleaner products, phages are becoming a valuable tool for safe food production and preservation.

Despite, these advantages, phage therapy faces several future challenges. It also limited host- range restricts broad spectrum use and the development of resistance against target bacteria reduces it effectiveness for longer period. Furthermore, systematic challenges related to formulation sustainability and delivery methods require further investigation. Advances in synthetic biology and genomic technologies could help to deal with these challenges by developing phage cocktails that are either capable of infecting a wide range of hosts or personalized to meet specific needs. The full potential of phage-based solution requires interdisciplinary collaboration, extensive research field and establish supportive regulatory policies. Through ongoing innovation, bacteriophage have the potential to significantly impact microbial management in various agricultural, food and environmental system.

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Declarations

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Research Involving Human Participants and/or Animals Not applicable.

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