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Biocontrol strategies of antibiotic-resistant, highly pathogenic bacteria and fungi with potential bioterrorism risks: Bacteriophage in focus

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ABSTRACT

There are many international attempts to control pathogenic antibiotic-resistant bacteria. This has been done in many ways, such as using chemical methods that rely on laboratory-created compounds or using natural methods. Natural techniques depend on vital sources derived from natural sources, such as microbes or plant extracts, or use of the same natural source as a parasitic microbe on pathogenic bacteria. The aim of the article was to focus on natural sources of antibiotic-resistant pathogenic bacteria and fungi. We studied antibiotic-resistant bacteria, such as *Escherichia coli, Salmonella* sp., *Shigella* sp., *Staphylococcus aureus, Mycobacterium tuberculosis*, *Pseudomonas aeruginosa, Listeria monocytogenes*, and highly pathogenic bacteria with potential bioterrorism risks, such as *Bacillus anthracis, Yersinia pestis, Francisella tularensis, Brucella* sp. and *Bulkholderia mallei*, in addition to other microbes. We also studied methods to biologically resist these antibiotic-resistant bacteria using extracts from natural sources or microbial parasites. Nonetheless, we focused on bacteriophage in particular as it has the potential of applications as bacteriophage and as alternatives to antibiotics for plants, animals, humans and useful microbes with the benefits of using bacteriophage in biocontrol. We conclude that the use of those stregies can be ecofriendly, non-toxic or hazardous to human beings.

1. Introduction

Multidrug-resistant microbes are on the spread these days and represent a major risk to humans' health and well being. Many bacteria strains with multiple genetic mutations, which eventually became resistant to most antibiotics, have been recorded by many international organizations. The US Centers for Disease Control and Prevention (CDC), the European Centre for Disease Prevention and Control (ECDC) and the World Health Organization (WHO) consider infections caused by multidrug-resistant (MDR) bacteria as an emergent global disease and a major public health problem (Roca and Akova, 2015). Antibiotic-resistant bacteria are among the most dangerous types of bacteria for public health and foodstuffs in terms of their speed of corruption and not being affected by any preventive factors in food processing; therefore, the food can carry the pathogens that cause many diseases, thus causing a loss of life and economic collapse due to the loss of manpower (Marshall and Levy, 2011).

Chemical biocontrol stregies have long focused on the the use of antibiotics Antibiotics have significantly contributed to the fight against and resistance to many diseases caused by microbes, but many health problems have begun to develop due to the intensive use of various antibiotics. Several antibiotic-resistant bacteria have emerged, which eventually led to difficulty in treating the resulting diseases, as well as the emergence of cancerous diseases due to the long-term intensive use of various antibiotics, such as colon and intestinal cancer (Jans et al., 2018). As such, it is time to end the use of antibiotics and begin the search for alternatives that are more effective at combating the spread and resistance of different bacterial species. These alternatives are natural and have several advantage over chemical methods including safety, cost-effectiveness and the presence of several bioactive compounds that act as natural antibiotics rather than using single antibiotic, to prevent any future resistance to bacteria as a result of adaptation (Tang et al., 2017; Jasovský et al., 2016). There are several natural biocontrol strategies that are presented and discussed here in that review. However, a special focus will be on the use of bacteriophage as biocontrol agents. Antimicrobial activity was assessed from plant extracts and phytochemicals with sensitive microorganisms and

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antimicrobial agents, and it was prevented by extracts of cloves, jambulans, pomegranates and thyme. This suppression was noted with unique extracts and, when used in reduced concentrations, with ineffectual antibiotics (Nascimento et al., 2000). Up to date, bacteriophage is the major biocontrol strategy as compared to other strategies as this will be thoroughly explained.

2. Bacteriophage

Bacteriophages are virus-only bacterial cells that have many potential applications as bacteriophage and as alternatives to antibiotics for plants, animals, humans and useful microbes (Kazi and Annapure, 2016; Jassim and Limoges, 2014; Ayman El-Shibiny and El-Sahhar, 2017). Bacteriophages have been suggested as natural preservatives for substances such as material samples for laboratory testing and food contaminated with pathogenic microbes (Bai et al., 2016). Evidence has shown that non-pathogenic *Staphylococcus aureus* has the potential for the production of antibacterial proteins that are effective against many of the causes of mastitis. (Bssssernhardt et al., 2001; Wongkattiya, 2008). Additionally, bacteriophages have a potential use as bacteriophage of the main pathogens of foodborne bacteria (*Salmonella* sp., *Escherichia coli O157: H7*). Moreover, the advantages and limitations of bacteriophages as a biological control agent in foods have a wide usage (Teng-Hern et al., 2014; Tssssomat et al., 2013).

Bacteriophage based on *Bacillus* sp. play a key role in the field of bio-pesticides. Many types of bacteria have proven to be effective against a wide range of plant pathogens. A plant growth activator, systemic resistance activator, has been used to produce a wide range of antimicrobial compounds (lipoprotein, antibiotics and enzymes) and is superior for growth factors with pathogenic microorganisms and other diseases acquired through colonialism (Shafi et al., 2017).

Bacteriophages have critical advantages over traditional methods of controlling pathogenic bacteria, such as host specificity, the ability to self-replicate, and the ability to evolve with their hosts. However, further research is needed to improve the parameters of bacteriophage applications, including the effect of environmental conditions on the efficiency of decomposition and contagion, and to significantly reduce the development of bacterial resistance to bacteriophages (Mark, 2016).

The filtration of bacteria and mildew from soil samples mixed with human saliva, as well as isolated types, has antimicrobial activity against some of the pathogenic microbes that cause skin diseases, such as *Staphylococcus aureus*, methicillin-resistant *Staphylococcus aureus* (MRSA) and *Aspergillus niger*. Bacterial filtration presents a sufficient antimicrobial effect against *Staphylococcus aureus* and methicillin-resistant *Staphylococcus aureus*, while a non-resistance effect was shown on pathogenic fungi. On the contrary, fungal filtration was hostile to the growth of the pathogenic fungi *Aspergillus niger* and did not show any resistant effect on pathogenic bacteria (Sheikh, 2010).

Laboratory activity testing is a critical assessment of any potential biological control factor. Isnansetyo et al. developed an eclectic medium to assess the quantitative activity of bacteriophage against pathogenic bacteria in aquaculture. Biological control sensitivity testing of nine antibiotics concluded that oxytetracycline resisted the growth of *Vibrio* spp., but it did not prevent the growth of the bacteria, which is a potential bacterial antibiotic in mariculture (Isnansetyo et al., 2011). Although Gram-positive bacteria were not well represented in the studies of biological control, their spore actions and industrial uses predict their biological control capabilities (Emmert and Handelsman, 1999).

Opportunistic bacteria require and eliminate other bacteria for food. It has been assumed that these bacteria are key to the development of new antibiotics, and now more than ever we need to investigate these applications in light of the high resistance to multiple drugs among medically important bacteria (Damron and Damron, 2013). *Trichoderma harzianum* extracts or launches an assortment of materials that stimulate topical or systemic reactions that reduce the pathogenicity of plants that presented antimicrobial activities in most of the experimented microorganisms; both bacteria and fungi can drive biocontrol through antagonism, competition and excessive intrusion (Leelavathi et al., 2014). *Simplicillium lamelicola* BCP strain has been developed as a biological control agent that effectively controls the evolution of several plant diseases that occur by pathogenic bacteria and fungi, during the antibacterial extraction called mannosyl (Dang et al., 2014). Top plants produce 100 to 1000 different chemical materials with their various biological vitalities. Antimicrobial materials that are produced by plants are activated against pathogenic microorganisms in plants and humans. Plant production with a purpose other than being used by antibiotics is expected to be effective against drug-sensitivity microbial pathogens (Desalegn, 2014).

Biocontrol can be using natural plant bioactive compounds such as essential oils. The different characteristics of essential oils (EO) provide the potential for safe, environmentally friendly, inexpensive, regenerate and easily absorbed substances (Pandey et al., 2017). EO and bacteriophage compounds have antimicrobial activity against *Staphylococcus aureus* and demonstrate superior growth suppression with other antimicrobial components (Ghosh, 2015). The most effective EO against the experimented bacteria was thyme oil, with a suppression size of 34.8 mm against *Ralstonia solanacearum* at a minimum dosage of 1 μl/ml, whereas this amount was greater than streptomycin resistance and erythromycin, as a control (Nezhad et al., 2012).

Many plant-extracted materials have a possibility in the biocontrol of pathogenic bacteria, especially the different impacts of plant materials on different maliciousness agents, which are important for diseases within the host. Moreover, plant-derived antimicrobials may have a possible effect against intestine microbiota (Upadhyay et al., 2014). The most powerful suppression of bacteria was noted with sage, cloves and thyme oil (Mikiciński et al., 2012). *Pimpinella anisum* has a high restraining effect on *Salmonella typhi, Enterococcus faecalis, Staphylococcus aureus, Escherichia coli* and *Micrococcus luteus*. Corn oil stops the growth of *Escherichia coli* and *Micrococcus luteus* at high concentrations. Streptomycin shows higher suppression with all pathogenic bacteria. Although, both of these have comparable impacts on *Enterococcus faecalis*, *Salmonella typhi* and *Micrococcus luteus* bacteria (Abdel-Reheema and Orabyb, 2015). *Punica granatum*; *Syzygium aromaticum*, *Zingiber officinale* and *Thymus vulgaris* extracts has superior abilities against the bacterial strains of *Bacillus cereus*, *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa* and *Salmonella typhi* (Mostafa et al., 2018). EOs have a possibility in the evolution of large-scale key components against a wide range of medicine-resistant pathogenic microbes (Swamy et al., 2016; Nazzaro et al., 2013). Propolis, royal jelly and bee venom have antibacterial activities against three Gram-positive bacteria (*Staphylococcus aureus*, *Bacillus subtilis* and *Listeria monocytogenes)* and two Gram-negative bacteria (*Escherichia coli* and *Salmonella enteritidis*); bee venom is the most effective, followed by propolis, then royal jelly (Attalla et al., 2007). Cinnamon oil has proven to be efficacious against two Gram-positive (*Staphylococcus aureus* and *Listeria innocua*) and two Gram-negative bacteria (*Pseudomonas aeruginosa* and *Salmonella typhi*), as well as two fungi (*Aspergillus niger* and *Candida albicans*) at a minimum concentration $\leq$1 μl/ml. Clove, fennel, anise, caraway, lemon grass, peppermint, at a minimum concentration $\leq$1 μl/ml, were successful with all the examined microorganisms, except *Pseudomonas aeruginosa*. Lavender oil showed antimicrobial activity against four strains (*Listeria innocua*, *Staphylococcus aureus*, *Candida albicans* and *Aspergillus niger)* at a minimum concentration

≤1 µl/ml, whereas geranium oil suppressed *Salmonella Typhi*, *Staphylococcus aureus*, *Candida albicans* and *Aspergillus niger* at a minimum concentration ≤1 µl/ml and *Listeria innocua* at a minimum concentration of approximately 2 µl/ml. However, the Gram-negative bacteria showed a high impedance to various EOs; exposure to cinnamon oil, even at the lowest concentration, was efficacious against impedance microorganisms (Tareka et al., 2014).

3. Bacteriophages

Bacteriophages are extremely effective and specific against their host, without an adverse effect on the gut microbiota. Phages are self-replicating, so when bacterial infection rises, a low concentricity of bacteriophages can reduce the required pathogen. Bacteriophage realisation is comparatively easy and is extremely preservation tolerant under various external status. The barriers to the use of bacteriophages for food storage involve a limited range of hosts, the hazard of developing mutant resistance and the possibility of transferring virulent personalities from one bacterial type to the other. However, this is simple to overcome. A bacteriophage mixture can be used when there are several strains of the host. It is unlikely that resistance mutant bacteriophages would spontaneously affect the effectiveness of treatment and dramatically overcome resistance to common complex phage mechanisms in bacteria through the examination of a host wide host and/or by using a mixture of phages (Hagens and Loessner, 2010). From another point of view, the *Escherichia coli O157: H7* phage resistant strain was observed to have a smaller cell, extra morphological of the coccoid cell, than the paternal type and it reverted back to being sensitive to the bacteriophage over several (up to 50) generations (O'Flynn et al., 2004). Similarly, *Salmonella enteritidis* phage resistant mutant strains lack a polysaccharide layer, which is necessary to absorb the phage and leads to avirulent bacteria (Santander and Robeson, 2007).

The nonlytic usage of genetically engineered bacteriophages enables the transfer of DNA encoding bacteriostatic proteins to selected pathogenic bacteria (Hagens, 2003; Westwater et al., 2003). The modified bacteriophage has been genetically manufactured to be highly efficient as a bactericide, while leaving structurally healthy cells intact. In several cases, the use of hybrid viral particles may boost some biosafety concerns by creating new genetic traits and spreading them among bacterial groups (Verheust et al., 2010). The determination of bacteriolytic peptides obtained from phages can revive attention as a new source of novel types of factors to fight multi-medicine resistant bacteria and provide steps for new curative factors that can surround such problems (Bernhardt et al., 2001; Bernhardt et al., 2001). The phages release lysins that cut off the links in the peptidoglycan chain in the bacterial cell wall, only before the launch of a generation and a series of lysine enzymes that kill bacteria in the laboratory within 5 s (Nelson et al., 2001; Schuch et al., 2002). Moreover, experiments with lysin enzymes may release an efficient bacteriocide and promote rapid diagnostic tools.

Overall, the advantages of using bacteriophages in biocontrol of multidrug-resistant pathogens include bactericidal agents, minimal disruption of normal flora, lack of cross-resistance with antibiotics, rapid detection, design and application versatility, biofilm clearance and possible transfer of phages between subjects (Loc-Carrillo and Abedon, 2011).

We list hereafter the case studies on using the bacteriophage against specific bacterial pathogens.

3.1. *Escherichia coli*

Many methods are used in the biological resistance of pathogenic bacteria, whether using plant or animal phages. These methods use the high-density liquid of the phage of each bacterial type to prevent the risk of bacterial or fungal infection, or to resist the actual infection of bacteria or pathogenic fungi. A mixture of three types of parasitical *Escherichia coli O157:H7* bacteriophages was considered acceptable by the FDA and FSIS for implementation in food in 2011. Various hopeful experiments have been conducted to control pathogenic bacteria, such as *Escherichia coli*, in which the CFU decreased by 100% in one hour with the addition of two types of bacteriophages (DT1 & DT6) to dairy milk with pending fermentation (Tomat et al., 2013). In another study, sprinkling of bacteriophages on spinach leaves led to a 4.5 log decrease of CFU two hours after the addition of the bacteriophage (Patel et al., 2011). No living cells could be detected on lettuce and spinach leaves 10 min after the addition of bacteriophages, along with a cinnamaldehyde treatment (Viazis et al., 2011). The CFU on cantaloupe and lettuce was also considerably decreased 2 days after being sprinkled with a bacteriophage mixture (ECP-100) (Sharma et al., 2009). In another infection, a bacteriophage mixture added to the surface of meat led to the annihilation of *Escherichia coli* in seven out of nine samples (Patel et al., 2011). Similar findings were noted in humans infected with *Escherichia coli* T4 phages from contaminated drinking water (Bruttin and Brussow, 2012). Persons with AIDS infections and non-infected donors have been vein vaccinated with purified bacteriophages without any visible side effects (Bssssueno et al., 2012; Atterbury, 2009). Bacteriophages have the possibility to treat animals suffering from bacterial diseases, specifically in the protection of broiler chickens against lethal *Escherichia coli* respiratory contagions (Huff et al., 2002; Huff et al., 2003; Loc-Carrillo et al., 2005). Spray aerosols and muscular injections produce the best results, compared to when provided orally through drinking water and/or feed or when directly managed by blood transfusion (Huff et al., 2003). This may be a consequence of the pH levels of the stomach, which protect against the reproduction of bacteriophages (Sillankorva et al., 2012). Virulent antigen-specific phages have been used in an attempt to control *Escherichia coli O157:H7* in batch cultures (Spits, 2009; Kudva et al., 1999; Sharma, 2013).

3.2. *Salmonella*

Lately, mixture of six *Salmonella* phages were classified as GRAS (generally recognised as safe) by the FDA in 2013 (Guenther et al., 2012). The addition of *Salmonella* phage (F01-E2) to chocolate milk and turkey meats led to a 5 log decrease of CFU, and 3 log decrease when added to sausages (Hooton et al., 2011). When the surface of meat was treated with a bacteriophage mixture, at a temperature of 4 °C for 96 h, the reduction in CFU was greater than 99% (Ye et al., 2010). A collective biological control of phage mixed with *Enterobacter asburiae* stopped the growth of pathogenic bacteria on alfa seeds and mung beans (Ye et al., 2009). When tomatoes were treated with a mix of bacteriophage and *Enterobacter asburiae*, infection by *Salmonella javiana* decreased; the main control was effective due to the antagonistic influence of *Enterobacter asburiae* (Bigwood et al., 2009). When exposed to bacteriophage P7, there was a 3 to 4 log decrease in CFU in thermally and non-thermally treated beef at 5 °C and a 6 log decrease in CFU at 24 °C (Leverentz et al., 2001). A bacteriophage mixture led to considerable decrease of CFU in fresh cantaloupes, but not in apples; the bacteriophages likely had no influence on apples because of the drop in pH on the surface of the apples (Modi et al., 2001). No survival was detectable after 89 days of heat treatment of cheeses with the addition of phage SJ2 (MOI 104) (Kim et al., 2014). However, this recorder/strain system does not require a substrate, and the recorder strain still needs to be examined. To evade this obstacle, a new strain of parasitical *Salmonella typhimurium* phage, involving a full part of the *luxABCDE* operon, was built

(Deresinski, 2009). This bacteriophage can reveal more than 20 CFU/ml of *Salmonella* in pure culture. Moreover, its dietary applications demonstrated that 22 CFU/g of *Salmonella* can be detected in ice lettuce, 37 CFU/g can be detected in pork slices and 700 CFU/g can be detected in milk (Clark and March, 2006). This recorder bacteriophage will be beneficial for the investigation and fast examination of *Salmonella typhimurium* in food samples, without a requirement to provide substrates or a recorder strain for examination.

3.3. Staphylococcus aureus

The first experiment using bacteriophages was a direct injection in six samples of staphylococcal furuncles in 1921; this led to the production of antibiotic resistant bacteria, and bacteriophage curing was used to control these suspicious bacteria in western Europe (Bueno et al., 2012). Ever since, bacteriophages have been utilised to treat different diseases that occur by bacterial contagion in eastern Europe. Bacteriophage mixtures added into heat-treated dairy contaminated with *Staphylococcus aureus* led to a decrease of *Staphylococcus aureus* to insignificant grades in fresh cheese after 6 h, and a continuous decrease in hard cheese. In buttermilk, a decrease of 4.64 log CFU per gram was gained, in comparison to the control sample (Tabla et al., 2012). The collection of high pressure processing (HPP) and bacteriophages led to the removal of *Staphylococcus aureus* in heat-treated dairy over 48 h, regardless of the level of contamination (1×10^6 or 1×10^4 CFU/ml) (Martınez et al., 2008). Bacteriophage mixed with nisin led to a reduction of *Staphylococcus aureus*; up to 1 log unit more than when using bacteriophages or nisin alone, for 24 h at 37 °C in heat-treated dairy (Gill et al., 2006). Lysis was suppressed when bacteriophage (K) was mixed with whey; this is probably a consequence of the adsorption of whey proteins on the surface of the *Staphylococcus aureus* cells, which suppressed bacteriophage tying (O'Flaherty et al., 2005). Adsorption of bacteriophage (K) was decreased in raw milk (Markoishvili et al., 2002). Recently, a medical product of bacteriophages has been produced under the name Phago Bio Derm; it consists of mixed bacteriophages with a biodegradable polymer, as well as an antibiotic, such as ciprofloxacin, to produce a plaster against the growth of resistant pathogenic bacteria, such as *Staphylococcus aureus* (Jikia et al., 2005). The CBD from *Staphylococcus aureus* endolysin plyV12 was used to focus the host cell via magnetic immunoassay isolation and explained that the beads coated with CBD could reveal more than 400 CFU of *Staphylococcus aureus* in polluted milk in 1.5 h (Yu et al., 2016).

3.4. Shigella

Singular bacteriophages or a bacteriophage mixture were used to treat meat polluted with any singular *Shigella* spp. (1×10^4 CFU/g) or a mixture of *Shigella* (*S. flexneri*, *S. dysenteriae*and *S. sonnei*, at a sum concentration of 3×10^4 CFU/g). Parasitism with the bacteriophage mixture was more efficient than exposure to a unique bacteriophage. Although, in all cases, the bacteriophage extracts led to a considerable decrease in viable counts, extending from 2 log units/g to annihilation (Zhang et al., 2013).

3.5. Pseudomonas aeruginosa

Recently, the presence of bacteriophages in aerosols was suggested for the treatment of pulmonary bacterial pathogens in patients with cystic fibrosis (Golshahi et al., 2008); it could also be sprinkled in the form of dried bacteriophage for inhalation (Matinkhoo et al., 2011). The first planned clinical experiment of therapeutic bacteriophage was conducted in 2009; it investigated their use as a preventive treatment for chronic ear infections with antibiotic-resistant *Pseudomonas aeruginosa* (Wright et al., 2009). After one year, in a study of using bacteriophages for chronic ear contagion in dogs, a topical application of a bacteriophage combination resulted in the lysis of the pathogenic bacteria *Pseudomonas aeruginosa* in the ear (otitis), without any effects of toxicity; as such, it can be used as an effective treatment against ear infections (otitis) caused by the pathogenic bacteria *Pseudomonas aeruginosa* (Hawkins et al., 2010).

3.6. Listeria monocytogenes

A combination of six bacteriophages against *Listeria monocytogenes* was confirmed by the FDA, USDA and FSIS for food applications in 2006, and readopted as GRAS by the FDA in 2014. Moreover, the FDA also classified Listex P100, a single bacteriophage with aims for *Listeria monocytogenes*, as GRAS in 2006. Oral toxicity did not appear in mice that were given bacteriophages against *Listeria monocytogenes* at a dose of 2×10^{12} PFU/kg BW/-day, nor did any effects of weight on a defect with respect to tissue changes, morbidity or mortality (Carlton et al., 2005). It led to a 2.5 log reduction of CFU at 30 °C in Ready-To-Eat (RTE) chicken; at 5 °C, regrowth was prevented over 21 days (Bigot et al., 2011). In red smear cheese, the application of bacteriophage A511 to the surface caused a 3 log reduction in CFU after 22 days; additionally, repeated application of A511 delayed re-growth (Guenther and Loessner, 2011). Moreover, bacteriophage P100 led to a decrease in the CFU on the surface of salmon and catfish fillets (Soni and Nannapaneni, 2010), as well as a 1 log and 2 log decrease of CFU on the surface of heated pork after 14– by 28 days (Holck and Berg, 2009). Cover washing with bacteriolphage P100 also led to the complete removal of CFU on red smear soft cheese (Carlton et al., 2005). Sprinkling pieces of watermelon with a bacteriophage mixture after a one-hour challenge with *Listeria* decreased the CFU by 6.8 units after 7 days of storage (Leverentz et al., 2004). A bacteriophage mixture caused a CFU decrease of 0.4 log in apples and 2.0–by 4.6 log in melons, whereas a combination of bacteriophage and nisin decreased the CFU by 2.3 log in apples and 5.7 log in melons (Leverentz et al., 2003). The bacteriophage and nisin mixture was efficient in soup, but not in beef (Dykes and Moorhead, 2002).

The C-terminal cell wall binding domain (CBD) can be used for the quick revelation and focus of specific foodborne diseases. For instance, CBD118 and CBD500 from *Listeria monocytogenes*, specifically endolysins Ply500 and Ply118, were covered by paramagnetic pills and the CBD-covered pills were evaluated for the concentration of bacterial cells in various *Listeria monocytogenes*-contaminated food samples (Kretzer et al., 2007). Using these beads, *Listeria monocytogenes* presented a recovery rate >90% in the case of the culture. Furthermore, these CBD-coated pills identified more than 1–100 CFU/g of *Listeria monocytogenes* in different samples of food involving dairy, lettuce, salmon, meats and turkey (Kretzer et al., 2007).

4. Microbial parasites as a source of antibacterials

Biological control of bovine mastitis caused by *S. uberis* is possible due to antibiotic therapy. Antibacterial bacteriocin, from a type of beneficial bacterium called *Macrococcus caseolyticus,* isolated from cow's milk, produced effective materials that were active against the genus *Streptococcus.* This specie was not known to produce bacteriocin However, additional work is needed to enhancethe production and purification of bacteriocins from *Macrococcus*. The special features of bacteriocins can help in the control of bovine mastitis. These bacteriocins are extremely particular to *Streptococci* and they have the possibility of being utilised under *in vivo* conditions because they are thermally stable and efficient over a broad range of pH values. Furthermore, bacteriocins are mostly regarded as safe to utilise as a natural food protectant because they have low toxicity and they are predigested by abundant proteolytic enzymes (Wongkattiya, 2008).

Bacillus species, such as *Bacillus subtilis* and *Bacillus cereus*, synthesise various types of lipopeptides, comprising bacillomycins, iturins, mycosubtilin and fengycins, or plipastatin or surfactins (Gong et al., 2015); based on specialised metabolic products against various plant pathogens that are of great importance in the agriculture, biotechnology and pharmaceutical industries. About 2428 antimicrobial peptides have been identified from different microorganisms, including 1819 from animals, 310 from plants, 12 from fungi, 7 from protists, 2 from archaea and 237 from bacteria. Between them, 756 of these different types of peptides have antifungal properties (Microbiology, 2016). A mixture of soil and saliva showed the highest antimicrobial activity; the same was noted for culture media of the bacterial- and fungal-free cell. Thus, the pathogenic organisms under study, such as *Staphylococcus aureus* bacteria, methicillin-resistant *Staphylococcus aureus* (*MRSA*) and *Aspergillus niger* fungi, showed higher sensitivity to the filtrates that resulted from mixing soil and saliva (Sheikh, 2010).

All examined bacterial strains of *Vibrio* spp. (*V. harveyi*, *V. parahaemolyticus* and *V. algosus*) were susceptible to streptomycin, kanamycin, sulphonamide and amoxicillin at 10 μg/disk, but various bacterial strains were susceptible to these antibiotics at 5 μg/disk. Two bacterial strains were susceptible to enrofloxacine and penicillin, either at 5 or 10 μg/disk. At the same concentration, chloramphenicol suppressed all bacterial strains except MIR2 and MIR3. Two bacterial biological controls and two pathogenic *Vibrio* bacteria were susceptible to novobiocin. All bacterial biological control was endured to oxytetracycline, either at 5 or 10 g/disk, although two strains of pathogenic *Vibrio* bacteria were susceptible to the same antibiotic at 10 g/disk. Additionally, oxytetracycline did not suppress the growth of all bacterial biological controls (Isnansetyo et al., 2011). Strains of *Bdellovibrio* are fierce bacteria that invade the periplasm of Gram-negative bacteria, multiply and finally break down the host cell (Sockett, 2009), whereas strains of *Micavibrio* victimise and control Gram-positive bacteria (Lambina et al., 1983). The concentration required inhibiting *Aspergillus fumigatus*; *Aspergillus flavus* and *Aspergillus candidus* was 100 μl/ml, while *Aspergillus niger*, *Fusarium graminearum*, *Fusarium semitectum*, *Aspergillus terreus* were suppressed by *Trichoderma harzianum* extract at 150 μl/ml, as well as by antibiotics effective against *Staphylococcus aureus* and *Escherichia coli* (Leelavathi et al., 2014). The *Simplicillium lamellicola* BCP strain was improved as a fungicide by producing verlamelin for the biological control of diverse plant pathogens, such as gray mould and bacterial wilt of tomatoes and rice blast (Choi et al., 2009; Choi et al., 2008; Kim et al., 2002), leading to the growth suppression of pathogenic bacteria; it was extremely efficacious against *Salmonella enteritidis*, *Staphylococcus aureus*, *Enterococcus faecium*, *Klebsiella pneumonia* and *Proteus vulgaris* (Leelavathi et al., 2014).

5. Natural extracts

Extracts of cloves and jambolan were the most effective, which were able to suppress 9 species at a percentage of 64.2% and 8 species at a percentage of 57.1% of microorganisms, respectively. Furthermore, they also had the highest effectives rate against antibiotic resistance bacteria (83.3%) (Nascimento et al., 2000). A small amount of *Ficus sycomorus* extract and *Eucalyptus camaldulensis* had strong activity against *Escherichia coli*; *Staphylococcus aureus* and *Pseudomonas aeruginosa* (Desalegn, 2014). *Cymbopogon citratus* essential oil completely prevented fungi such as *Aspergillus flavus, Neurospora sitophila* and *Penicillium digitatum* (Shukla, 2009; Sonker et al., 2015). Essential oils from *Nigella sativa*; *Cymbopogon citratus* and *Phyllocharis undulata* inhibited the growth of *Bacillus subtilis*, *Staphylococcus aureus*, *Pseudomonas aeruginosa* and *Escherichia coli* (Mali et al., 1998). The essential oils of *Acorus*; *Artemisia*, *Chenopodium* and others have clear characteristics as antimicrobials (Sonker et al., 2015; Pandey et al., 2012, 2013, 2014). Some essential oil components, such as citronol, eugenol, farnesol and nerol, can protect chili seeds and fruits from fungal diseases for over 6 months (Tripathi et al., 1984). Essential oils of *Ageratum conyzoides* succeeded in preventing tangerine rot by blue mould by increasing the validity duration of tangerines for a period of over 30 days (Dixit et al., 1995). *Cymbopogon nardus; Cymbopogon flexuosus* and *Ocimum basilicum* essential oils can prevent the lesions that cause the dark spots on bananas and increase the shelf life of bananas to over 21 days (Anthony et al., 2003). *Cymbopogon flexuosus* essential oil, at a concentration of 20 μl/ml, is able to protect fruits from *Mentzelia pumila* rot for over 3 weeks (Shahi et al., 2003). A smoke processing of essential oils from *Pinus roxburghii* was efficient against *Aspergillus flavus* and *Aspergillus niger* diseases, which infect pistachio through storage, boosting the longevity of pistachios to fungal damage to over 6 months (Tripathi and Kumar, 2007). Cymbopogon oil, used as the base for smoking, increased the life span of groundnut by 6–12 months (Shukla, 2009; Tripathi and Kumar, 2007), proving that it is more widely active than *Pinus roxburghii* essential oil. Thyme oil, at 0.1% and lemon oil, at 0.5%, decrease the occurrence of infection in papayas (Bosquez-Molina et al., 2010), whereas cinnamon oil increases the storage life of bananas by over 28 days and decreases the fungal diseases that occur in bananas (Maqbool et al., 2010). Smoking of *Ocimum Cannum* oil improved the shelf-life of *buchanania lanzan* (Singh et al., 2011). *Glycosmis pentaphylla* and *Chenopodium ambrosioides* oils, used as smoke in glass tanks and natural tarpaulin traps, were able to protect the seeds of peas from *Aspergillus terreus*, *Aspergillus ochraceus*, *Aspergillus niger* and *Aspergillus flavus* diseases for over 6 months (Pandey et al., 2013; Pandey et al., 2013). *Glycosmis pentaphylla* powder and *Chenopodium ambrosioides* oils were also capable of protecting pigeon pea seeds for over 6 months (Pandey et al., 2013). *Artemisia nilagirica* oil, as a smoke, enhanced the shelf life of grapes by 9 days (Sonker et al., 2015). Likewise, *Limnanthes alba* oil, used as an aerosol for processing in glass tanks, suppressed the spread of fungi and the production of aflatoxin in *Vigna radiate* and boosted its life span by over 6 months (Pandey et al., 2016). *Thymus vulgaris*; *Coriandrum sativum*, and *Cuminum cyminum* oils may have antibacterial characteristics against *Pectobacterium carotovorum*, *Ralstonia solanacearum* and *Escherichia coli* (Nezhad et al., 2012). *Pimpinella anisum* essential oil retains an obvious inhibitory influence on numerous vegetal and animal pathogens and nonpathogenic germs; there are no great differences between this oil and the inhibitory effect of streptomycin (Abdel-Reheema and Orabyb, 2015).

The chemical composition of various essential oils and their antibacterial, antifungal and antiviral activities against human pathogens are described in three tables (Attalla et al., 2007). *Staphylococcus aureus* seems to be the most sensitive (0.08 mg/ml for all bee venoms tested), followed by *Bacillus subtilis* (0.16 mg/ml), while Gram-negative bacteria seemed to be the least sensitive bacteria. Gram-positive bacteria were more affected by the tested venoms, compared to Gram-negative bacteria. Propolis was more potent with minimum lethal concentrations of 4, 4, 8, 8 and 16 mg/ml for *Staphylococcus aureus*, *Bacillus subtilis*, *Listeria monocytogenes*, *Salmonella Enteritidis*, and *Escherichia coli*, respectively. Finally, royal jelly seemed to be less active compared to bee venom or propolis (Attalla et al., 2007).

6. Conclusion

The success of biological control depends on the selection of effective microbial strains of pathogens, such as the production of microbial strains that have the ability to resist pathogenic microbes. It also depends on their ability to withstand various environmental conditions, in addition to their ability to produce secondary compounds that can be used in pure form to eliminate pathogenic microorganisms that are resistant to commercial extract.

In spite of this, bacteriophages are very beneficial and offer protections for food, but they are still not used widely because consumer culture needs to shift to realise the effectiveness of bacteriophages as natural food protective materials.

Plant and insect extracts have great potential because of consumer acceptance as many plants have been long consumed as food/herbs against microorganisms as antimicrobial compounds. Therefore, they should be used in the therapy of contagious diseases caused by microbial resistance.

However, natural alternatives exist for bacteriophage. They offer a different therapy type, as they are natural and have many advantages over chemical methods, including safety, economy and limited side effects, exemplified in the occurrence of slight disruption of normal flora. They are also effective against both antibiotic-sensitive and antibiotic-resistant bacteria. They cause potent disruption of bacterial biofilms and have low inherent toxicities. Moreover, the bioactive compounds in these natural remedies act as antibiotics and eliminate the possibility of any future resistance in pathogenic bacteria. Overall, the natural remedies offer a new defense line against pathogens and should be explored and further exploited.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Roca, I., Akova, M., et al., 2015. The global threat of antimicrobial resistance: science for intervention. New Microb. New Infect. 6, 22–29.
Marshall, B.M., Levy, S.B., 2011. Food animals and antimicrobials: impacts on human health. Clin. Microbiol. Rev. 24 (4), 718–733.
Jans, C., Sarno, E., Collineau, L., et al., 2018. Consumer exposure to antimicrobial resistant bacteria from food at swiss retail level. Front. Microbiol. 9. 362.
Tang, K.L., Caffrey, N.P., Nobrega, D.B., et al., 2017. Restricting the use of antibiotics in food-producing animals and its associations with antibiotic resistance in food-producing animals and human beings: a systematic review and meta-analysis. Lancet Planet Health 1 (8), e316–e327.
Jasovský, D., Littmann, J., Zorzet, A., Cars, O., 2016. Antimicrobial resistance—a threat to the world's sustainable development. Ups. J. Med. Sci. 121 (3), 159–164.
Kazi, M., Annapure, U.S., 2016. Bacteriophage biocontrol of foodborne pathogens. J. Food Sci. Technol. 53 (3), 1355–1362.
Jassim, S.A., Limoges, R.G., 2014. Natural solution to antibiotic resistance: bacteriophages 'The Living Drugs'. World J. Microbiol. Biotechnol. 30 (8), 2153–2170.
Ayman El-Shibiny, A., El-Sahhar, S., 2017. Bacteriophages: the possible solution to treat infections caused by pathogenic bacteria. Can. J. Microbiol. 63 (11), 865–879.
Bai, J., Kim, Y.T., Ryu, S., Lee, J.H., 2016. Biocontrol and rapid detection of food-borne pathogens using bacteriophages and endolysins. Front. Microbiol. 7, 474.
Bssssernhardt, T.G., Wang, I.N., Struck, D.K., Young, R., 2001. A protein antibiotic in the phage Qbeta virion: diversity in lysis targets. Science 292 (5525), 2326–2329.
Wongkattiya, N., 2008. Antibiotic resistance, characterization and biological control of bovine mastitis caused by Streptococcus uberis. RMIT University, Melbourne.
Teng-Hern, T.L., Kok-Gan, C., Han, L.L., 2014. Application of bacteriophage in biocontrol of major foodborne bacterial pathogens. J. Mol. Biol. Mol. Imag. 1 (1), 9.
Tssssomat, D., Mercanti, Q., Balague, C., Quiberoni, A., 2013. Phage biocontrol of enteropathogenic and Shiga toxin-producing escherichia coli during milk fermentation. Lett. Appl. Microbiol. 57, 3–10.
Shafi, J., Tian, H., Ji, M., 2017. Bacillus species as versatile weapons for plant pathogens: a review. Biotechnol. Biotechnol. Equip. 31, 446–459.
Mark, A., 2016. The Use of Bacteriophages as Natural Biocontrol Agents Against Bacterial Pathogens. Cranfield University, Cranfield.
Sheikh, H.M.A., 2010. Antimicrobial activity of certain bacteria and fungi isolated from soil mixed with human saliva against pathogenic microbes causing dermatological diseases. Saudi J. Biol. Sci. 17, 331–339.
Isnansetyo, A., Muhtadi, Istiqomah, I., Nitimulyo, K., Triyanto, 2011. Selective media for in vitro activity evaluation of bacterial biocontrol against pathogenic vibrio. Hayati J. Biosci. 3, 129–134.
Emmert, E.A.B., Handelsman, J., 1999. Biocontrol of plant disease: a (Gram) positive perspective. FEMS Microbiol. Lett. 171 (1), 1–9.
Nascimento, G.G.F., Locatelli, J., Freitas, P.C., Silva, G.L., 2000. Antibacterial activity of plant extracts and phytochemicals on antibiotic-resistant bacteria. Braz. J. Microbiol. 31, 24–56.
Damron, H.F., Damron, Barbier M., 2013. Predatory bacteria: living antibiotics, biocontrol agents, or probiotics? J. Postdoc. Res. 1 (12). 10–5.
Leelavathi, M.S., Vani, L., Reena, P., 2014. Antimicrobial activity of Trichoderma harzianum against bacteria and fungi. Int. J. Curr. Microbiol. Appl. Sci. 3 (1), 96–103.
Dang, Q.L., Shin, T.S., Park, M.S., 2014. Antimicrobial activities of novel mannosyl lipids isolated from the biocontrol fungus Simplicillium lamellicola BCP against phytopathogenic bacteria. J. Agric. Food Chem. 62 (15), 3363–3370.
Desalegn, A., 2014. Antimicrobial activity of medicinal plant extracts and their synergistic effect on some selected pathogens. Am. J. Ethnomed. 1 (1), 018–029.
Pandey, A.K., Kumar, P., Singh, P., 2017. Essential oils: sources of antimicrobials and food preservatives. Front. Microbiol 7, 2161.
Ghosh, A., 2015. Application of Essential Oil Compounds and Bacteriophage to Control Staphylococcus aureus. University of Arkansas, Fayeteville.
Nezhad, M.H., Alamshahi, L., Panjehkeh, N., 2012. Biocontrol efficiency of medicinal plants against pectobacterium carotovorum ralstonia solanacearum and *Escherichia coli*. Open Conf. Proc. J. 3 (Suppl 1–M8), 46–51.
Upadhyay, A., Upadhyaya, I., Kollanoor-Johny, A., Venkitanarayanan, K., 2014. Combating pathogenic microorganisms using plant-derived antimicrobials: a minireview of the mechanistic basis. Biomed. Res. Int. 761741.
Mikiciński, A., Sobiczewski, P., Berczyński, S., 2012. Efficacy of fungicides and essential oils against bacterial diseases of fruit trees. J. Plant Prot. Res. 52 (4), 467–471.
Abdel-Reheema, M.A.T., Orabyb, M.M., 2015. Anti-microbial, cytotoxicity, and necrotic ripostes of Pimpinella anisum essential. Ann. Agric. Sci. 60 (2), 335–340.
Mostafa, A., Al-Askar, A., Almaary, K., Dawoud, T., Sholkamy, E., Bakri, M., 2018. Antimicrobial activity of some plant extracts against bacterial strains causing food poisoning diseases. Saudi. J. Biol. Sci. 25, 361–366.
Swamy, M.K., Akhtar, M.S., Sinniah, U.R., 2016. Antimicrobial properties of plant essential oils against human pathogens and their mode of action: an updated review. Evid. Based Complemen. Alternat. Med 21.
Nazzaro, F., Fratianni, F., De Martino, L., Coppola, R., De Feo, V., 2013. Effect of essential oils on pathogenic bacteria. Pharmaceuticals 6 (12), 1451–1474.
Attalla, K.M., Owayss, A.A., Mohanny, K.M., 2007. Antibacterial activities of bee venom, propolis, and royal jelly produced by three honey bee, Apismellifera L., hybrids reared in the same environmental conditions. Ann. Agric. Sci. Moshtohor 45 (2), 895–902.
Tareka, N., Hossam, H.M.B., Abdel Ghan, S.M.M., 2014. Comparative chemical and antimicrobial study of nine essential oils obtained from medicinal plants growing in Egypt Beni-Suef University. J. Basic Appl. Sci. 3 (2), 149–156.
Hagens, S., Loessner, M.J., 2010. Bacteriophage for biocontrol of foodborne pathogens: calculations and considerations. Curr. Pharm. Biotechnol. 11 (1), 58–68.
O'Flynn, G., Ross, R.P., Fitzgerald, G.F., Coffey, A., 2004. Evaluation of a cocktail of three bacteriophages for biocontrol of Escherichia coli O157: H7. Appl. Environ. Microbiol. 70 (6), 3417–3424.
Santander, J., Robeson, J., 2007. Phage-resistance of Salmonella enterica serovar Enteritidis and pathogenesis in Caenorhabditis elegans is mediated by the lipopolysaccharide. Electron J. Biotechnol. 10, 627–632.
Hagens, S., Bla¨si, U., 2003. Genetically modified filamentous phage as bactericidal agents: a pilot study. Lett. Appl. Microbiol. 37 (4), 318–323.
Westwater, C., Kasman, L.M., Schofield, D.A., Werner, P.A., 2003. Use of genetically engineered phage to deliver antimicrobial agents to bacteria: an alternative therapy for treatment of bacterial infections. Antimicrob. Agents Chemother. 47 (4), 1301–1307.
Verheust, C., Pauwels, K., Mahillon, J., Helinski, D.R., Herman, P., 2010. Contained use of bacteriophages: risk assessment and biosafety recommendations. Appl. Biosaf. 15 (1), 32–44.
Bernhardt, T.G., Struck, D.K., Young, R., 2001. The lysis protein E of phi X174 is a specific inhibitor of the MraY-catalyzed step in peptidoglycan synthesis. J. Biol. Chem. 276, 6093–6097.

Bernhardt, T.G., Wang, I.-N., Struck, D.K., Young, R., 2001. A protein antibiotic in the phage Qbeta virion: diversity in lysis targets. Science 292 (5525), 2326–2329.
Nelson, D., Loomis, L., Fischetti, V.A., 2001. Prevention and elimination of upper respiratory colonization of mice by group A streptococci by using a bacteriophage lytic enzyme. Proc. Natl. Acad. Sci. U.S.A. 8 (7), 4107–4112.
Schuch, R., Nelson, D., Fischetti, V.A., 2002. A bacteriolytic agent that detects and kills Bacillus anthracis. Nature 418 (6900), 884–889.
Tomat, D., Mercanti, Q., Balague, C., Quiberoni, A., 2013. Phage biocontrol of enteropathogenic and Shiga toxin-producing *escherichia coli* during milk fermentation. Lett. Appl. Microbiol. 57, 3–10.
Patel, J., Sharma, M., Millner, P., Calaway, T., Singh, M., 2011. Inactivation of Escherichia coli O157:H7 attached to spinach harvester blade using bacteriophage. Foodborne Pathog. Dis. 8 (4), 541–546.
Viazis, S., Akhtar, M., Feirtag, J., Diez-Gonzalez, F., 2011. Reduction of Escherichia coliO157:H7 viability on hard surfaces by treatment with a bacteriophage mixture. Int. J. Food Microbiol. 145 (1), 37–42.
Sharma, M., Patel, J.R., Conway, W.S., Ferguson, S., Sulakvelidze, A., 2009. Effectiveness of bacteriophages in reducing *Escherichia coli* O157: H7 on fresh-cut cantaloupes and lettuce. J. Food. Prot. 72 (7), 1481–1485.
Bruttin, A., Brussow, H., 2012. Human volunteers receiving Escherichia coli phage T4 orally: a safety test of phage therapy. Am. Soc. Microbiol. 49, 2874–2878.
Bssssueno, E., Garcıa, P., Martınez, B., Rodrıguez, A., 2012. Phage inactivation of Staphylococcus aureus in fresh and hard-type cheeses. Int. J. Food Microbiol. 158 (1), 23–27.
Atterbury, R.J., 2009. Bacteriophage biocontrol in animals and meat products. Microb. Biotechnol. 2, 601–612.
Huff, W.E., Huff, G.R., Rath, N.C., Balog, J.M., Donoghue, A.M., 2002. Prevention of *Escherichia coli* infection in broiler chickens with a bacteriophage aerosol spray. Poult. Sci. 81 (10), 1486–1491.
Huff, W.E., Huff, G.R., Rath, N.C., Balog, J.M., Donoghue, A.M., 2003. Evaluation of aerosol spray and intramuscular injection of bacteriophage to treat an Escherichia coli respiratory infection. Poult. Sci. 82 (7), 1108–1112.
Huff, W.E., Huff, G.R., Rath, N.C., Balog, J.M., Donoghue, A.M., 2003. Bacteriophage treatment of a severe Escherichia coli respiratory infection in broiler chickens. Avian Dis. 47, 1399–1405.
Sillankorva, S.M., Oliveira, H., Azeredo, J., 2012. Bacteriophages and their role in food safety. Int. J. Microbiol. Article ID 863945.
Spits, H.B., 2009. Bacteriophages for improvement of intestinal health in pigs and poultry. University of Utrecht.
Kudva, I.T., Jelacic, S., Tarr, P.I., Youderian, P., Hovde, C.J., 1999. Biocontrol of *Escherichia coli* O157 with O157-specific bacteriophages. Appl. Environ. Microbiol. 65, 3767–3773.
Loc-Carrillo, C., Atterbury, R.J., El-Shibiny, A., Connerton, P.L., 2005. Bacteriophage therapy to reduce Campylobacter jejuni colonization of broiler chickens. Appl. Environ. Microbiol. 71 (11), 6554–6563.
Sharma, M., 2013. Lytic bacteriophages: potential interventions against enteric bacterial pathogens on produce. Bacteriophage 3 (2). e25518.
Guenther, S., Herzig, O., Fieseler, L., Klumpp, J., 2012. Loessner MJ "Biocontrol of salmonella typhimurium in RTE foods with the virulent bacteriophage FO1-E2". Int. J. Food Microbiol. 154 (1–2), 66–72.
Hooton, S.P.T., Atterbury, R.J., Connerton, I.F., 2011. Application of a bacteriophage cocktail to reduce salmonella typhimurium U288 contamination on pig skin. Int. J. Food Microbiol. 151 (2), 157–163.
Ye, J., Kostrzynska, M., Dunfield, K., Warriner, K., 2010. Control of salmonella on sprouting mung bean and alfalfa seeds by using a biocontrol preparation based on antagonistic bacteria and lytic bacteriophages. J. Food Prot. 73 (1), 9–17.
Ye, J., Kostrzynska, M., Dunfield, K., Warriner, K., 2009. Evaluation of a biocontrol preparation consisting of enterobacterasburiae JX1 and a lytic bacteriophage cocktail to suppress the growth of salmonella javiana associated with tomatoes. J. Food Prot. 72 (11), 2284–2292.
Bigwood, T., Hudson, J.A., Billington, C., 2009. Influence of host and bacteriophage concentrations on the inactivation of food-borne pathogenic bacteria by two phages. FEMS Microbiol. Lett. 291, 59–64.
Leverentz, B., Conway, W.S., Alavidze, Z., 2001. Examination of bacteriophage as a biocontrol method for salmonella on fresh-cut fruit: a model study. J. Food Prot. 64 (8), 1116–1121.
Modi, R., Hirvi, Y., Hill, A., Griffiths, M.W., 2001. Effect of phage on survival of salmonella enteritidis during manufacture and storage of cheddar cheese made from raw and pasteurized milk. J. Food Prot. 64 (7), 927–933.
Kim, S., Kim, M., Ryu, S., 2014. Development of an engineered bioluminescent reporter phage for the sensitive detection of viable Salmonella Typhimurium. Anal. Chem. 86, 5858–5864.
Deresinski, S., 2009. Bacteriophage therapy: exploiting smaller fleas. Clin. Infect. Dis. 48, 1096–1101.
Clark, J.R., March, J.B., 2006. Bacteriophages and biotechnology: vaccines, gene therapy and antibacterials. Trends Biotechnol. 24, 212–218.
Bueno, E., Garcıa, P., Martınez, B., Rodrıguez, A., 2012. Phage inactivation of *Staphylococcus aureus* in fresh and hard-type cheeses. Int. J. Food Microbiol. 158 (1), 23–27.
Tabla, R., Martínez, B., Rebollo, J.E., González, J., Ramírez, M.R., Roa, I., Rodríguez, A., García, P., 2012. Bacteriophage performance against staphylococcus aureus in milk is improved by high hydrostatic pressure treatments. Int. J. Food Microbiol. 156 (3), 209–213.
Martınez, B., Obeso, J.M., Rodrıguez, A., Garcıa, P., 2008. Nisin-bacteriophage cross resistance in *Staphylococcus aureus*. Int. J. Food Microbiol. 122 (3), 253–258.
Gill, J., Sabour, P.M., Leslie, K.E., Griffiths, M.W., 2006. Bovine whey proteins inhibit the interaction of staphylococcus aureus and bacteriophage. K. J. Appl. Microbiol. 101 (2), 377–386.
O'Flaherty, S., Coffey, A., Meaney, W.J., Fitzgerald, G.F., Ross, R.P., 2005. Inhibition of bacteriophage K proliferation on staphylococcus aureus in raw bovine milk. Lett. Appl. Microbiol. 41 (3), 274–279.
Markoishvili, K., Tsitlanadze, G., Katsarava, R., Morris Jr, J.G., Sulakvelidze, A., 2002. A novel sustained-release matrix based on biodegradable poly(ester amide)s and impregnated with bacteriophages and an antibiotic shows promise in management of infected venous stasis ulcers and other poorly healing wounds. Int. J. Dermatol. 41, 453–458.
Jikia, D., Chkhaidze, N., Imedashvili, E., Mgaloblishvili, I., Tsitlanadze, G., Katsarava, R., Glenn, M.J., Sulakvelidze, A., 2005. The use of a novel biodegradable preparation capable of the sustained release of bacteriophages and ciprofloxacin, in the complex treatment of multidrug-resistant Staphylococcus aureus-infected local radiation injuries caused by exposure to Sr90. Clin. Exp. Dermatol. 30, 23–26.
Yu, J.P., Zhang, Y., Zhang, Y., Li, H., Yang, H., Wei, H.P., 2016. Sensitive and rapid detection of Staphylococcus aureus in milk via cell binding domain of lysin. Biosens. Bioelectron 77, 366–371.
Zhang, H., Wang, R., Bao, H., 2013. Phage inactivation of foodborne Shigella on ready- to-eat spiced chicken. Poult. Sci. 92, 211–217.
Golshahi, L., Seed, K.D., Dennis, J.J., Finlay, W.H., 2008. Toward modern inhalational bacteriophage therapy: nebulization of bacteriophages of Burkholderia cepacia. J. Aerosol Med. Pulm. Drug Deliv. 21 (4), 351–360.
Matinkhoo, S., Lynch, K.H., Dennis, J.J., Finla, W.H., Vehring, R., 2011. Spray-dried respirable powders containing bacteriophages for the treatment of pulmonary infections. J. Pharm. Sci. 100 (12), 5197–5205.
Wright, A., Hawkins, C.H., Anggaård, E.E., Harper, D.R., 2009. A controlled clinical trial of a therapeutic bacteriophage preparation in chronic otitis due to antibiotic-resistant *Pseudomonas aeruginosa*; a preliminary report of efficacy. Clin. Otolaryngol. 34 (4), 349–357.
Hawkins, C., Harper, D., Burch, D., Anggaård, E., Soothill, J., 2010. Topical treatment of Pseudomonas aeruginosa otitis of dogs with a bacteriophage mixture: a before/after clinical trial. Vet. Microbiol. 146 (3–4), 309–313.
Carlton, R.M., Noordman, W.H., Biswas, B., de Meester, E.D., Loessner, M.J., 2005. Bacteriophage P100 for control of Listeria monocytogenes in foods: genome sequence, bioinformatic analyses, oral toxicity study and application. Regul. Toxicol. Pharmacol. 43 (3), 301–312.
Bigot, B., Lee, W.J., McIntyre, L., Wilson, T., Hudson, J.A., Billington, C., Heinemann, J. A., 2011. Control of Listeria monocytogenes growth in a ready-to-eat poultry product using a bacteriophage. Food Microbiol. 28 (8), 1448–1452.
Guenther, S., Loessner, M.J., 2011. Bacteriophage biocontrol of Listeria monocytogenes on soft ripened white mold and red- smear cheeses. Bacteriophage 1 (2), 94–100.
Soni, A., Nannapaneni, R., 2010. Hagens S "Reduction of Listeria monocytogenes on the surface of fresh channel catfish fillets by bacteriophage listex p100". Foodborne Pathog. Dis. 7 (4), 427–434.
Holck, A., Berg, J., 2009. Inhibition of Listeria monocytogenes in cooked ham by virulent bacteriophages and protective cultures. Appl. Environ. Microbiol. 75 (21), 6944–6946.
Leverentz, B., Conway, W.S., Janisiewicz, W., Camp, M.J., 2004. Optimizing concentration and timing of a phage spray application to reduce Listeria monocytogenes on honeydew melon tissue. J. Food Prot. 67 (8), 1682–1686.
Leverentz, B., Conway, W.S., Camp, M.J., 2003. Biocontrol of Listeria monocytogenes on fresh-cut produce by treatment with lytic bacteriophages and a bacteriocin. Appl. Environ. Microbiol. 69 (8), 4519–4526.
Dykes, G.A., Moorhead, S.M., 2002. Combined antimicrobial effect of nisin and a listeriophage against Listeria monocytogenes in broth but not in buffer or on raw beef. Int. J. Food Microbiol. 73 (1), 71–81.
Kretzer, J.W., Lehmann, R., Schmelcher, M., Banz, M., Kim, K.P., Korn, C., 2007. Use of high-affinity cell wall-binding domains of bacteriophage endolysins for immobilization and separation of bacterial cells. Appl. Environ. Microbiol. 73, 1992–2000.
Gong, A.D., Li, H.P., Yuan, Q.S., Yuan, Q.S., Song, X.S., Yao, W., He, W.J., Zhang, J.B., Liao, Y.C., 2015. Antagonistic Mechanism of Iturin A and Plipastatin A from Bacillus amyloliquefaciens S76–3 from Wheat Spikes against Fusarium graminearum. PLoS One 10 (2). e0116871.
Microbiology UDoPa. AntimicrobPept database. 18 April 2016. Available from: http://aps.unmc.edu/AP/main.php.
Sockett, R.E., 2009. Predatory lifestyle of Bdellovibrio bacteriovorus. Annu. Rev. Microbiol. 63, 523–539.
Lambina, V.A., Afinogenova, A.V., Romay Penobad, Z., Konovalova, S.M., Andreev, L. V., 1983. New species of exoparasitic bacteria of the genus Micavibrio infecting gram-positive bacteria. Mikrobiologiia 52, 777–780.
Choi, G.J., Kim, J.-C., Jang, K.S., Nam, M.H., Lee, S.W., Kim, H.T., 2009. Biocontrol activity of Acremoniumstrictum BCP against Botrytis diseases. Plant Pathol. J. 25, 165–171.
Choi, G.J., Kim, J.C., Jang, K.S., Cho, K.Y., Kim, H.T., 2008. Mycoparasitism of Acremonium strictum BCP on Botrytis cinerea, the gray mold pathogen. J. Microbiol. Biotechnol. 18, 167–170.
Kim, J.-C., Choi, G.J., Kim, H.J., Kim, H.T., Ahn, J.W., Cho, K.Y., 2002. Verlamelin, an antifungal compound produced by mycoparasite Acremoniumstrictum. Plant Pathol. J. 18, 102–105.

Shukla, A.C., 2009. Volatile oil of Cymbopogon pendulus as an effective fumigant pesticide for the management of storage-pests of food commodities. Nat. Acad. Sci. Lett. 32, 51–59.
Sonker, N., Pandey, A.K., Singh, P., 2015. Efficiency of Artemisia nilagirica (Clarke) Pamp essential oil as a mycotoxicant against postharvest mycobiota of table grapes. J. Sci. Food Agric. 95, 1932–1939.
Mali, E.K., Ahmed, H.H., Mohammed, A.H., Yahia, A.S., Yeb, E.T., Ali, A.A., 1998. Antibacterial properties of essential oils from Nigella sativa seeds, Cymbopogon citratus leaves and Pulicaria undulata aerial parts. Fitoterapia 69, 7–12.
Pandey, A.K., Singh, P., Palni, U.T., Tripathi, N.N., 2012. In-vitro antibacterial activity of essential oils of aromatic plants against Erwinia herbicola (Lohnis) and Pseudomonas putida (Krish Hamilton). J. Serb. Chem. Soc. 77, 313–323.
Pandey, A.K., Singh, P., Palni, U.T., Tripathi, N.N., 2013. Application of Chenopodium ambrosioides Linn. essential oil as botanical fungicide for the management of fungal deterioration in pulses. Biol. Agric. Hortic. 29, 197–208.
Pandey, A.K., Singh, P., Palni, U.T., Tripathi, N.N., 2014. In vivo evaluation of two essential oil based botanical formulations (EOBBF) for the use against stored product pests, Aspergillus and Callosobruchus (Coleoptera: Bruchidae) species. J. Stored Prod. Res. 59, 285–291.
Tripathi, N.N., Asthana, A., Dixit, S.N., 1984. Toxicity of some terpenoids against fungi infesting fruits and seeds of Capsicum annuum L. during storage. J. Phytopathol. 110, 328–335.
Dixit, S.N., Chandra, H., Tiwari, R., Dixit, V., 1995. Development of botanical fungicide against blue mould of mandarins. J. Stored Prod. Res. 31, 165–172.
Anthony, S., Abeywickrama, K., Wijeratnam, S.W., 2003. The effect of spraying essential oils Cymbopogonnardus, C. flexuosus and Ocimumbasilicum on post-harvest diseases and storage life of Embul banana. J. Hort. Sci. Biotech. 78 (6), 780–785.
Shahi, S.K., Patra, M., Shukla, A.C., Dikshit, A., 2003. Use of essential oil as botanical-pesticide against post harvest spoilage in Malus pumilo fruit. Bio. Control 48, 223–232.
Tripathi, N.N., Kumar, N., 2007. Putranjiva roxburghii oil—A potential herbal preservative for peanuts during storage. J. Stored Prod. 43, 435–442.
Bosquez-Molina, E., Jesus, E.R., Bautista-Banos, S., Verde-Calvo, J.R., Morales-Lopez, J., 2010. Inhibitory effect of essential oils against Colletotrichum gloeosporioides and Rhizopus stolonifer in stored papaya fruit and their possible application in coatings. Postharvest Biol. Technol. 57, 132–137.
Maqbool, M., Ali, A., Alderson, P.G., 2010. Effect of cinnamon oil on incidence of anthracnose disease and post-harvest quality of bananas during storage. Int. J. Agric. Biol. 12, 516–520.
Singh, P., Pandey, A.K., Sonker, N., Tripathi, N.N., 2011. Preservation of Buchanania lanzan Spreng. Seeds by Ocimum canum Sims essential oil. Annals Plant Protec. Sci. 19 (2), 407–410.
Pandey, A.K., Palni, U.T., Tripathi, N.N., 2013. Evaluation of Clausena pentaphylla (Roxb.) DC oil as a fungitoxicant against storage mycoflora of pigeon pea seeds. J. Sci. Food Agric. 93 (7), 1680–1686.
Pandey, A.K., Sonker, N., Singh, P., 2016. Efficacy of some essential oils against *Aspergillus flavus* with special reference to Lippia alba oil an inhibitor of fungal proliferation and aflatoxin b1 production in green gram seeds during storage. J. Food Sci. 81, 928–934.
Loc-Carrillo, C., Abedon, S.T., 2011. Pros and cons of phage therapy. Bacteriophage 1 (2), 111–114.