

POTENTIAL OF ANTIMICROBIALS DERIVED FROM MICROORGANISMS- A REVIEW

Sukhmanvir Kaur¹, Rahul Mehra², Poonam Baniwal³, Harish Kumar⁴, Akash Kumar⁵, Shiv Kumar^{5*}

Address(es):

- ¹ Department of Food Technology, Eternal University, Baru Sahib, Sirmour-173101, Himachal Pradesh, India.
- ² University Centre for Research & Development, Chandigarh University, Gharuan, Mohali, Punjab, 140413, India.
- ³ Food Corporation of India, New Delhi-110001, India.
- ⁴ Shri Vishwakarma Skill University Palwal Haryana-121102, India.
- ⁵ Food Science and Technology, (MMICT&BM HM) Maharishi Markandeshwar, Mullana, 133207, Ambala, Haryana, India.

*Corresponding author: shivk1999@gmail.com

<https://doi.org/10.55251/jmbfs.9097>

ARTICLE INFO

Received 9. 6. 2022
Revised 31. 7. 2025
Accepted 8. 12. 2025
Published 1. 2. 2026

Review



ABSTRACT

Antimicrobial compounds, such as antibiotics, are produced by microbes and eventually restrict the growth and proliferation of harmful microorganisms. The majority of antimicrobials generated by microorganisms are considered secondary metabolites. Because of the ongoing worldwide concern about antibiotic resistance, scientific discussions are needed to examine breakthroughs in the production of antimicrobial agents and their alternatives that may limit the development of antibiotic-resistant strains among bacterial infections. Bacteriophages have been employed in the food industry in a variety of ways, depending on their intended function. The use of bacteriophages to regulate bacterial cells in raw materials from fields, abattoirs, and ready-to-eat food products is known as biocontrol. The development of low-cost and convenient model organisms, as well as cutting-edge molecular biology, has aided in the bioprospecting of new antimicrobial medications and the discovery of new therapeutic targets. Antimicrobial compounds isolated from microorganisms, such as bacteriophages, lysin, lactic acid, nisin, probiotics, natamycin, reuterin, and other antimicrobial compounds isolated from marine microbes, are summarized in this review, along with their mode of action, potential applications in food and human health, and future scope.

Keywords: Antimicrobial, Antibiotic, Bacteriophages, Nisin, Reuterin

INTRODUCTION

Food security is currently an emerging and immensely supervised issue. Approximately 13 percent of the food produced and harvest food is wasted or lost (United Nation, 2023). There are numerous reasons for this food loss across the world, which are different in both evolved and evolving nations. Poor handling during harvesting, transportation, and processing contributes to food loss. The loss varies with categories of food such as root crops (40-50%), fruits and vegetables (35%), fish and seafood (30%), cereals, oilseed, dairy and meat (each 20%) (Emilie Wieben, 2017). However, microbial contamination is the primary factor responsible for undesirable food loss (Saeed et al., 2019). Some food spoilage microbes threaten humans who are consuming the same products. There are certain metabolites produced by microbes by which human health is impaired, such as mycotoxins produced by fungi (Goessens et al., 2024).

To gain confidence in this alarming issue, numerous techniques have been employed. These techniques vary with country and include preservatives (natural and synthetic), thermal treatments, and hurdle technology along with advanced packaging technology. These treatments are given at different stages of contamination. The widely accepted method for preservation is either chemical preservatives or natural preservatives, although natural antimicrobial compounds derived from microbes have room for further research. Chemical preservatives such as sulfites, nitrites, benzoic acid, sodium benzoate, potassium sorbate and sodium sorbate are less preferred due to growing awareness in the community regarding health issues (Rathee et al., 2023). Natural preservatives are those that are sound and of authentic natural origin, and synthetic chemicals are not incorporated into them. Its origin may be plants; insects, such as honey from bees; or microbes, such as lactic acid from LAB. Table 1 lists several microbial-derived antimicrobial agents and their potential applications.

Table 1 Potential of microbe-derived antimicrobial agents

Antimicrobials	Target microbe	Application	Reference
Bacteriophage	<i>Salmonella</i> spp. and <i>Campylobacter</i> spp.	Raw meat (beef)	(Hooton et al., 2011)
In combination with Nisin	<i>Staphylococcus aureus</i> <i>Listeria monocytogenes</i>	Soft and hard cheese, pasteurized milk	(Tabla et al., 2012)
Lactic acid bacteria	Food borne pathogens: <i>Escherichia coli</i> O157:H7 <i>L. monocytogenes</i> <i>Listeria innocua</i>	Apples and melons Bakery products	(Leverentz et al., 2001) (Yang et al., 2012)
LAB as source of bacteriocin (Nisin)	<i>L. lactis subsp lactis</i>	Cheese, fermented sausages	(McAuliffe et al., 1998)
LAB as probiotic	<i>Campylobacter</i> spp	Raw poultry products	(Mignacca et al., 2017)
Natamycin (antibiotic)	<i>Saccharomyces cerevisiae</i> <i>Aspergillus flavus</i> <i>Penicillium expansum</i> , <i>Fusarium culmorum</i> , <i>Lactobacillus helveticus</i> , and <i>Listeria ivanovi</i>	Liquid cheese whey Olives Ripened cheese	(Titone et al., 2025)
Reuterin	<i>L. monocytogenes</i> and <i>E. coli</i>	Milk and cottage cheese	
In combination with lactic acid	<i>E. coli</i> O157:H7 and <i>L. monocytogenes</i>	Meat	(El-Ziney et al., 1999)

Microorganisms produce certain compounds, namely, secondary metabolites and antimicrobial peptides, or themselves act as antagonists (Rani et al., 2021). Bacteriophages are potent antimicrobial agents that act as agents against microbes (Zalewska-Piątek & Piątek, 2021). However, some examples have shown that the compounds produced by these microbes act against spoilage microbes, such as nisin, the bacteriocin produced by lactic acid bacteria (Perez et al., 2022), and natamycin, the antibiotic produced by the microbe *Streptomyces natalensis* (Shen et al., 2024). Natural preservatives of microbial origin have no harmful effects on human life and are quite convenient for use in the food industry. The concept of including these compounds in food has been proven to be correct since the shelf life of the products is enhanced without causing any unfavorable organoleptic changes in the product (Abdulmumeen et al., 2012). Due to the potential advantages of these microorganisms as antimicrobial agents, consumer attention needs to be given to this topic. The methods of action, possible applications, and future scopes of antimicrobial chemicals derived from microbes are summarized in this review.

Bacteriophages

Bacteriophages are viruses that specifically invade bacterial cells without causing any harm to animals or plants. These bacteria use bacterial resources for their replication and are consequently regarded as obligate parasites of bacteria (Monk et al., 2010). Phages are categorized into two categories, namely, lytic and lysogenic. The former are considered virulent, whereas the latter are considered temperate (Ackermann and Prangishvili, 2012). Lytic phages cause lysis of bacterial cells (especially *E. coli*), and temperate phages result in infection and hardly cause lysis (Kutter and Sulakvelidze, 2004). In food, lytic phages have been used to inhibit the metabolism of host bacterial cells. Because they are used as biocontrol agents, the amount of bacteriophages taken for the destruction of bacteria is the main concern or point of attention (Hagens and Loessner, 2010). This is because while used in food, there is less bacterial contamination due to high hygiene practices at the place, and diffusion and mixing are slow due to the use of selected solid food rather than liquid food (Hagens and Loessner, 2010). The complete eradication of the food matrix contamination can be achieved by adding high amount of bacteriophages (Hagens and Loessner, 2010). The mechanism by which a bacteriophage infects a bacterial cell to replicate its genome and lyse the host cell is illustrated in Figure 1. Bacteriophages have been used in the food sector in different ways according to their application. The biocontrol of bacteria in raw material from fields, slaughterhouses, and ready-to-eat food products is the major area covered by bacteriophages. The contamination of finished products, namely, milk and milk products, is controlled via phage treatment under biopreservation (Kazi and Annappure, 2016). *Listeria* was successfully removed from the surface of stainless steel using different bacteriophages and hence proved to be useful for disinfecting surfaces (biosanitation). Phage therapy is another way for bacteriophages to reduce diseases in livestock (Kazi and Annappure, 2016).

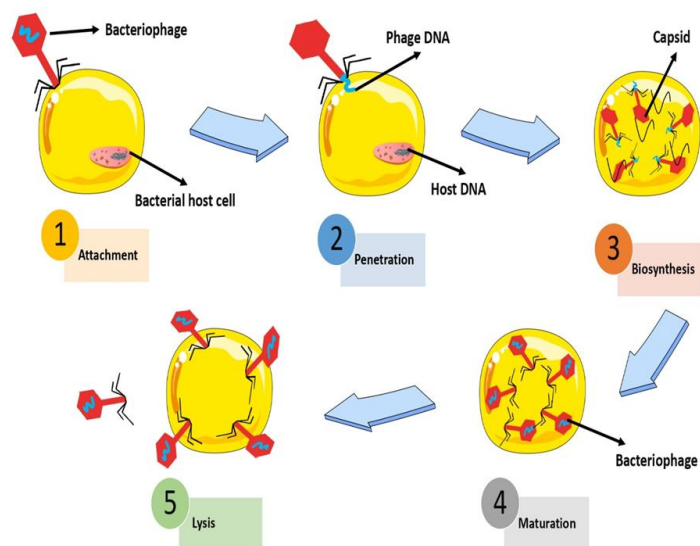


Figure 1 Mechanistic action of Bacteriophages

Enormous success has been achieved in controlling food pathogens using bacteriophages. The *E. coli* phage can eliminate host cells only when a host is undergoing metabolism, that is, when the host is active (O'flynn et al., 2004). *Salmonella* and *Campylobacter* contamination in raw meat and in raw and cooked beef has been reported to be reduced to a greater extent (Thames, & Theradiyil, 2020). *Staphylococcus aureus* inactivation has been achieved using a phage cocktail in both soft and hard cheese (Weng et al., 2021). A study showed that incorporation of A511 bacteriophage into a whey protein isolate based coating reduced the count of *Listeria monocytogenes* in cheese. Additionally this coating

have positive impact on springness, color, and hardness (García-Anaya et al., 2023). The combined effect of combined pressure and high static pressure has resulted in a decrease in *Staphylococcus* spp. contamination in pasteurized milk (Martinez et al., 2008). Phage treatment was also applied to the plants before harvest. The main reason behind this preharvest treatment is to avoid human contamination in food products. Although these phages are harmless to healthy humans, they are inactivated using fertilizers (Kazi and Annappure, 2016).

Lysin: A Bacteriophage Enzyme

Lytic phages produce enzymes called lysins, which play a key role in the degradation of the bacterial cell wall or release of phage cells into the body (Borysowski et al., 2006). These compounds attack peptidoglycan in the cell wall and hence are more lethal to gram-positive bacteria and thereby improve food safety when added externally (Fischetti, 2008). Lysins are highly specific to the host cell and consequently have narrow-spectrum activity (Shah et al., 2023), with the exception of the enterococcal phage lysin (Yoong et al., 2004). The primary benefit of using lysins is that bacterial cells are not resistant to these enzymes (Fischetti, 2008). There are numerous methodologies by which lysins can be incorporated into food. First, they may be directly put on as proteins in purified form into the food product pasteurized milk (Obeso et al., 2008). Second, recombinant bacteria, which secrete lysin, are added to food products (Xu, 2021). In addition, lysin production is expensive, and these enzymes are highly prone to proteolysis, making them unstable proteins and thereby reducing their usage in certain food products (Coffey et al., 2010).

First, phages are exceptionally limited for use in food products since they do not affect the human body. All the verifications have shown that oral consumption of these compounds in the diet is harmless to healthy humans. Bacteriophages are extremely active and specific, allowing them to be used in specific food products. Additionally, they have a versatile nature, covering biocontrol, biopreservation, biosanitation and phage therapy. Additionally, bacteriophages are strong antimicrobial agents (Kazi and Annappure, 2016). The use of chemicals as biocontrol measures seems to have decreased their effective use in the food sector after the exponential growth of bacteriophages as effective biocontrol measures (Garcia et al., 2008). In the future, more attention needs to be given to safety and technical issues related to the antimicrobial skills of these materials. To understand the proper mechanism of phage resistance, further research is needed (Kazi and Annappure, 2016). Moreover, the emergence of phage-resistant progenies has been reported by my authors; however, no evidence has been shown to affect phage trials (Kazi and Annappure, 2016). The company Intralyx, Inc., has released two phage preparations, namely, EcoShield™ (target *E. coli*) and ListShield™ (target *Listeria monocytogenes*). Mircro is another company that releases phage products against *Listeria* spp. and *Salmonella* spp. (Listex™ and Salmonlex™, respectively). The main challenge for bacteriophages to be used in food is their acceptance by consumers because of their different advantages (Ge et al., 2022).

Lactic acid bacteria

Taxonomically, Lactic acid bacteria (LAB) belong to various groups that include both rod-shaped (*Lactobacillus*) and coccus-shaped (*Lactococcus*) bacteria. LAB are gram-positive (+), sternly nonsporulating, producing either lactic acid alone (Homofermentation) or a mixture of carbon dioxide, acetic acid and ethanol (Heterofermentation) as a final product of glucose metabolism, and they are aerotolerant (Kuipers et al., 2000). Different species, including *Oenococcus*, *Lactobacillus*, *Carnobacterium*, *Tetragenococcus*, *Pediococcus*, *Streptococcus*, *Lactococcus*, *Lactosphaera*, *Melissococcus*, *Enterococcus* and *Leuconostoc*, are the genera that fall under LAB (Holzapfel et al., 2001). Several LAB produce antimicrobial peptides commonly referred to as “bacteriocins”, which inhibit the growth of food spoilage microbes. Lactic acid is the result of fermentation, which also protects food from spoilage. Moreover, lactic acid serves as an antimicrobial agent and is extravagantly used in different food sectors, including fermentation and baking (Perez et al., 2022). Lactic acid interferes with the homeostasis of target cells by lowering the pH. Many strains of lactic acid bacteria function as probiotics, thereby improving the intestinal biota by killing harmful microorganisms.

Lactic acid bacteria work as antimicrobial agents by producing several compounds that act against microbes during their metabolism. Lactic acid, hydrogen peroxide (H₂O₂), carbon dioxide (CO₂), bacteriocins and diacetyl are the primary antimicrobial compounds produced by LAB (Mobolaji and Wuraola, 2011). Mobolaji and Wuraola (2011) reported that lactic acid interrupts the cell membrane potential, hinders active transport, decreases the cellular pH and affects other metabolic functions; thus, lactic acid has antimicrobial effects. The cultural composition, growing environment and strain used are the determinants for producing lactic acid and decreasing the pH. Gram-negative bacteria show greater sensitivity to diacetyl, and the latter reacts with arginine-binding proteins, therefore affecting the utilization of arginine and in turn inhibiting gram-negative bacterial growth (Ammor et al., 2006). Similarly, H₂O₂ oxidizes the sulfhydryl groups of enzymes, resulting in the denaturation of enzymes and the production of bacterial free radicals that damage DNA (Sunil and Narayana, 2008). There are several main factors that have contributed to the success of LAB as antimicrobial agents.

The subsequent production of lactic acid or acetic acid during the metabolism of glucose decreases the pH. These bacteria release certain organic acids that have antimicrobial properties and therefore inhibit the growth of microbes during food production (Reis et al., 2012). For example, in sauerkraut LAB are responsible for

fermentation and preservation. The different strains that are effective against food spoilage bacteria are presented in Table 2.

Table 2 Different strains that are effective against food spoilage bacteria

LAB strain	Target microorganisms	References
<i>Lactobacillus curvatus</i>	Food borne pathogens: <i>Escherichia coli</i> O157:H7	(Brillet et al., 2005)
<i>Carnobacterium divergens</i>	<i>L. monocytogenes</i>	(Yang et al., 2012)
<i>Enterococcus faecium, Lactococcus lactis</i>	<i>Listeria innocua</i>	

Lactic acid bacteria produce certain bactericidal peptides during their growth, known as bacteriocins, which have antimicrobial effects on many foodborne microbes (*Listeria monocytogenes*) and spoilage microbes (*Staphylococcus aureus*) (Ricke, 2015). Bacteriocins are different from antibiotics in many ways. The major difference lies in the spectrum of action; bacteriocins are specific and work against microbes that closely resemble the producing species, whereas antibiotics have broad-spectrum activity. Antibiotics are secondary metabolites that are not used by producing species directly; however, bacteriocins are polypeptides that work in favor of the producing microbe (Ricke, 2015). Class-I bacteriocins are also known as antibiotics due to the presence of dehydroalanine, methylanthionine, lanthionine, and 2-aminoisobutyric acid. These polypeptides work against target

microbes due to their antimicrobial properties. Nisin is a major class that represents this class (Rodriguez et al., 2003). Like active peptides, class 2 bacteriocins are called nonlantibiotics because they do not contain lanthionine amino acids in their membrane. These compounds are relatively heat stable and small in size (<10 kDa). Lactacin F and lactacin G are the main bacteriocins in this category. Compared with other bacteriocins, class 3 bacteriocins are heat labile and generally larger (>30 kDa). Enterolysin bacteriocin belongs to this class, and further exploration within this category is ongoing (Dimitrov Todorov and Dicks, 2005; Ross et al., 2002). The different classifications of bacteriocins produced by LAB are presented in Table 3.

Table 3 Classification of bacteriocins produced by LAB

Classification	Bacteriocin	Bacteriocin producing strain	References
Class 1	Nisin	<i>Lactococcus lactis</i>	
Class 2	Lactacin F Lactocin G	<i>L. johnsonii</i> spp. <i>L. lactis</i> spp.	(Daw and Falkiner, 1996; Ross et al., 2002; Todorov and Dicks, 2004)
Class 3	Helveticin I Enterolysin	<i>Lactobacillus helveticus</i> <i>Enterococcus faecium</i>	

Lactic acid bacteria as probiotics

According to the Food and Agriculture Organization and World Health Organization, probiotics are live microorganisms that, when administered in adequate amounts, confer health benefits to the host (Bajagai et al., 2016). Probiotics have been extensively used during animal food production to enhance overall health and the immune system. Different species, including *Enterococcus*, *Lactobacillus*, *Propionibacterium*, *Bacillus*, and *Bifidobacterium*, are widely used as probiotic species (Buntyn et al., 2016). *Lactobacilli*, *Streptococci*, *Enterococci* and *Lactococci* are lactic acid-producing bacteria that have been utilized as direct-fed microbes or probiotics (Bajagai et al., 2016). There are many factors that contribute to the success of these strains as probiotics. These cells can produce enzymes and organic acids that have antimicrobial properties (Saarela et al., 2002). They are stable in bile and other gastric juices, and they have antagonistic effects on specific microbes. Additionally, they have not shown any interference with the host body (Saarela et al., 2002). It has been reported that when *Lactobacillus* spp. are utilized as probiotics, there is a decrease in *Campylobacter* spp. in raw poultry products (Mignacca et al., 2017). The most commonly used probiotics are *Lactobacillus* spp. (Bajagai et al., 2016; Buntyn et al., 2016), and the use of nisin as a bacteriocin can be replaced by the use of *L. casei* to reduce *Mycobacterium avium* ssp. *Paratuberculosis*. These probiotics from naturally occurring bacteria have several advantages, such as being potentially more competent against ecologically similar taxa, and they have high chances for approval from regulatory agencies to be utilized during food and animal production (Seal et al., 2013). Various other nontoxic anaerobic bacteria produced from indigenous species, mainly gram-positive, spore-forming *Clostridium* spp., have been reported to aid in fostering anti-inflammatory immune responses, especially inside the gut of mammals, since T-regulatory cells are activated. Notably, these bacterial strains constitute a large proportion of the intestinal microflora of many monogastric animals (Atarashi et al., 2011). As a result, several species of *Clostridium* live in the gastrointestinal tract, which is pathogenic; however, these can be used as probiotics (Cartman, 2011). The identification and isolation of potential probiotics from unrestricted species might be valuable for their use in commercial food and animal production due to their history of minimal discovery (Dec et al., 2014). Research on the isolation of novel probiotic bacteria from the feces of Canadian geese (*Branta canadensis*) is ongoing, and these bacteria could be consumed as probiotics in poultry. Consequently, many anaerobic and aerobic, gram-positive and gram-negative bacteria, which are thought to possess probiotic properties, have been isolated (Volokhov et al., 2012). As a result of several types of research, many other microbes have been identified to have potential probiotic properties, and now interest has shifted to *Clostridia* to be used as probiotics. Probiotics help to improve gut health and have already been available on the market (Kumar et al., 2024). A study demonstrated that bacteriophage CPQ1 effectively controlled

Clostridium perfringens in chicken meat and milk thus used as a potential method to prevent foodborne diseases (Mohammadi et al., 2022).

The lactic acid bacteria used in food preservation are considered natural and are more preferred than chemical antimicrobials because they are linked with fermented products as probiotics (Das and Goyal, 2012). There are products containing yeast, bacteria and fungi that are already commercialized worldwide. LAB probiotic strains have contributed significantly to interactions in the human intestine (Das and Goyal, 2012). The addition of bacteriocins to fermented sausages used to make cheese has resulted in overall improvements in food quality and food safety. Natural microbial antioxidants are experiencing significant future demand due to their inherent safety and cost-effectiveness compared to synthetic alternatives.

Nisin

Nisin, a polycyclic peptide that is a member of the lantibiotic class of bacteriocins, is produced by *Lactococcus lactis*. This bacteriocin is routinely used by manufacturers because of its antimicrobial properties (Rodriguez et al., 2003). It also exhibits broad-spectrum activity and is active against food spoilage microorganisms, including *L. monocytogenes* and *S. aureus* (Egan et al., 2016). Nisin was first discovered when it caused a problem for cheese making and hindered the activity of starter culture. Since 1988, it has been marketed in America as a food preservative and is regarded as safe for consumption. Nisin has been reported to have the potential to work against *Clostridium* infections in humans because it inhibits spore germination (Le Lay et al., 2016). The underlying mechanism of nisin is that it binds to the cell membrane of the targeted cell. It passes through the cell wall and reaches lipid-II, which is a membrane-attached cell wall precursor important for the synthesis of the cell wall. Nisin does one thing from the following after reaching the cell wall. Either it attaches to lipid II and hampers the peptidoglycan network or binds to a carbohydrate-pyrophosphate moiety of lipid II in an N-terminal pattern so that a pore can be formed, as illustrated in Figure 2.

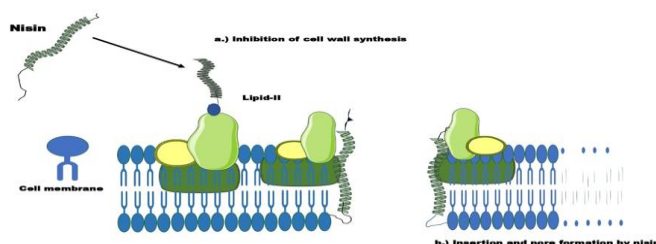


Figure 2 Nisin-induced pore formation mechanism

This results in decreasing membrane potential because the increased permeability of the cell membrane results in leakage of ions, amino acids and nucleotides from cells. This eventually results in cell death, as damaged cells can produce energy (Egan et al., 2016; Pol et al., 2000; Rodriguez et al., 2003). Bacteriocins have been widely used for food preservation, especially in dairy, egg meat and vegetable products. Nisin is the only bacteriocin that is regarded as safe for utilization and is effective against many spoilage and food poisoning microbes (Deegan et al., 2006). Bacteriocins have been combined with other techniques so that it becomes easy to dissolve the membrane of pathogenic microbes (Daw and Falkner, 1996). Another application of bacteriocins is in packaging, referred to as bioactive packaging. This may be achieved by incorporating bacteriocins in sachets and placing these sachets in packed products. This would ensure the activity of antimicrobial peptides (Ross et al., 2002).

Natamycin

Antibiotics are secondary bioactive metabolites produced naturally by microorganisms that stop growth and kill a wide range of other competing microbes. Unfortunately, numerous of these competing microbes develop resistance against these metabolites (Clardy and Walsh, 2004). Additionally, antibiotics act indiscriminately against pathogenic bacteria as well as good bacteria in food, which in turn highlights the importance of the development of alternative antibacterial agents with selective targets so that potentially beneficial microbes can be saved (Clardy and Walsh, 2004). The use of antibiotics has gained global interest due to their resistance to bacterial pathogens that put human and animal health in danger. These issues were first discussed at the "Alternatives To Antibiotics" (ATA) conference at the World Organization for Animal Health (OIE) in Paris in September 2012 (Seal et al., 2013). Antibiotics may serve as antibacterial or antifungal agents. Antifungal antibiotics, as the name suggests, work against fungal infection. There are many techniques employed to hinder the fungal growth of raw agricultural produce and finished food products. These methods include the application of fungicides, disinfectants and advanced packaging techniques for raw produce (Rojas-Graü et al., 2009). For processed food products, many procedures are followed, including Hazard analysis and critical control points (HACCP), Good Hygiene Practices, the use of hurdle technology and other thermal techniques (Dijksterhuis et al., 2013). Moreover, the use of preservatives is quite common (Silva and Lidon, 2016). However, natural preservatives are preferred over chemical or synthetic preservatives because of their origin and effects. The structure of natamycin is presented in Figure 3.

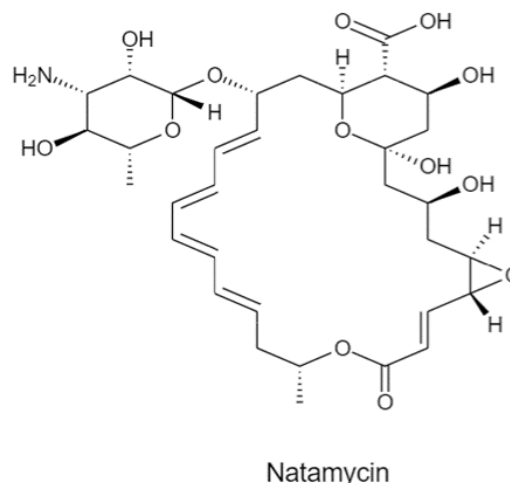


Figure 3 Structure of natamycin (Image is produced by PubChem)

Natamycin is the only antifungal compound that has a natural microbial origin and is permitted to be used in the food industry as a preservative. Surprisingly, competing microbes are unable to develop resistance to natamycin, which has broad-spectrum activity (TeWelscher et al., 2008). The E number given to natamycin by the European Union and the European Free Trade Association is E235. The natamycin-producing microbe is *Streptomyces nataliensis* (Shen et al., 2024). Surface treatment using natamycin on cheese and uncured meats has been approved in many countries. Natamycin is different from other food preservatives because it remains on the surface of food products (dairy products, meat and others) without penetrating them (Davidson and Doan, 2020). An evident reduction in the *Saccharomyces cerevisiae* population occurred when liquid cheese whey was treated with natamycin at a concentration of 12.5 mg/L. It has been found to be effective against *Aspergillus flavus* in fresh-packed and seasoned table olives (Davidson and Doan, 2020). In addition, natamycin is also used in packaging films in addition to nisin for the inhibition of *Penicillium expansum*, *Listeria ivanovi*, *Fusarium culmorum* and *Lactobacillus helveticus* when applied to ripened cheese surfaces. It serves as a biocontrol agent for fungal pathogens on plant produce without causing any harm to nontarget organisms. In combination with oxygen, natamycin has been reported to improve button mushroom excellence and improve shelf life (Davidson and Doan, 2020). There are different levels or doses of natamycin used and permitted for different food products. There are many different ways in which natamycin has been utilized for food products. These include direct addition, spraying onto the product surface, immersion in the liquid and coating emulsions (Stark, 2003). The permitted levels of natamycin in different food products are presented in Table 4.

Table 4 Permitted level of natamycin in different food products

Products	Natamycin permitted level (mg/kg)	References
Cheese	1250-2000	(Sreerama, et al., 20221)
Meat products	1250-2000	(Delves-Broughton and Weber, 2011)
Bakery products	1250-2000	(Debonne, 2020)
Yogurt	5-10	(Sara et al., 2014)
Fruit juices	2.5-10	(Siricururata et al., 2013)
Tomato paste	7.0-7.5	(Sreerama, et al., 20221)

TeWelscher et al., (2008) conducted a study that demonstrated the mechanism behind the action of natamycin. This antibiotic works by binding to the ergosterol present in yeast cells. Ergosterol is a sterol present in yeast and protozoal cell membranes that maintains the integrity of the cell. Thus, interference with the state of the cell membrane obstructs growth and reproduction in target cells. This study demonstrated that yeast is killed by natamycin via specific irreversible binding to ergosterol without permeating the plasma membrane. As a result of this mechanism, natamycin is different from all other polyene antibiotics examined thus far. Ergosterol binds with an evident affinity of approximately 10 μM, specifically to ergosterol, at a stoichiometry of approximately 1:1 or 1:2, as determined by whether sterol is present to interact with both the outer or both leaflets' membranes. Recently, natamycin was shown to block yeast and fungal cell growth by instantaneously stopping the active transport of amino acids and glucose through the plasma membrane, which is reversible hindrance of membrane transport proteins (Davidson and Doan, 2020). Polyene antibiotics cause membrane permeability and oxidative damage to the membrane structure. In yeast cells, natamycin interacts with the crucial functions of ergosterol. It is evident that sterols are present in sterol-rich domains in membranes and perform functions such as endocytosis, exocytosis and vascular fusion (Takeda and Chang, 2005; Wachtler and Balasubramanian, 2006). Therefore, after binding to ergosterol, natamycin inhibits these activities. Natamycin has been shown to have

antimicrobial effects on almost all molds and yeast. It is widely used in different processing sectors, including juices, meat, dairy and bakery.

Reuterin

Reuterin is an antimicrobial compound that is produced by *Lactobacillus reuteri* bacteria during the anaerobic breakdown of glycerol (Greifová et al., 2017). This compound offers a wide range of antimicrobial activities and inhibits gram-negative bacteria (Cleusix et al., 2007). Moreover, its activity has expanded to include gram-positive bacteria, molds, yeasts, bacterial spores and protozoa. Reuterin is a water-soluble mixture of monomeric, hydrated and cyclic dimers in the form of 3-hydroxypropionaldehyde (Figure 4).

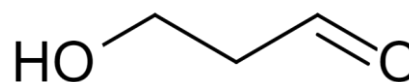


Figure 4 Structure of Reuterin (Image is produced by PubChem)

These compounds are synthesized by coenzyme B12-dependent or glycerol dehydratase-mediated reactions (Chen and Chen, 2013). 3-hydroxypropionaldehyde (3-HPA) is spontaneously converted into acrolein (a cytotoxic electrophile), on which its antimicrobial activity relies (Engels et al., 2016). These microbial compounds were effectively proven to be proteolytic and lipolytic enzymes. This property favors reuterin, which can be utilized to preserve different meat products (Mishra et al., 2012). Reuterin can decrease the number of *E. coli* and *L. monocytogenes* in milk and cottage cheese under cold conditions at 7 °C. At different concentrations, it has different effects. A study reported that at a lower concentration (1.38 mM), reuterin had a fungistatic effect, and at a concentration of 6.9 mM, a fungicidal effect was observed in yogurt. Nisin bacteriocin has advantages over nisin bacteriocin due to its poor binding properties, uneven distribution on the surface of the meat and its products, and poor solubility (Gharsallaoui et al., 2016).

Reuterin is linked to DNA synthesis, but this has not been fully elucidated because of the complexity of HPA-system chemistry (Vollenweider and Lacroix, 2004). These compounds have the potential to stop the activity of ribonucleotide reductase, which catalyzes the initial step of DNA synthesis by competing with ribonucleotides for binding sites for HPA dimers. It has been assumed that reuterin may stop the activity of an enzyme (ribonucleotide reductase) that catalyzes the first step in DNA synthesis by competing (HPAdimer) with ribonucleotides for binding sites (Dobrogosz, 1989). The broad-spectrum activity could be explained by the mechanism behind the inhibition of the conversion of ribonucleotides to deoxyribonucleotides (Dobrogosz, 1989). It has been proposed by scientists that the activity of reuterin can be increased by the addition of lactic acid to meat even under low-temperature (78°C) and short-term (15 s) treatments against *L. monocytogenes* and *E. coli* O157:H7 (El-Ziney and Devere, 1998). Furthermore, the undesirable changes at the meat surface could be overcome by using lower concentrations of lactic acid and reuterin. In summary, this antimicrobial compound can be used as both an antibacterial and antifungal preservative (Cleusix et al., 2007).

Antimicrobial compounds from marine microbes, especially for the preservative of cosmetics

Microbes are known to attack cosmetic products, and to avoid microbial contamination, preservatives are added, which also help to retard microbial contamination (Corinaldesi et al., 2017). For the protection of food and cosmetic products, parabens, such as 4-hydroxybenzoate alkyl esters, have been widely employed. These esters were isolated from the marine bacterial strain A4B-17, a strain that belongs to the genus *Microbulbifer*, which is potentially effective against yeasts, molds and bacteria (Peng et al., 2006). Particularly for cosmeceuticals and cosmetic products, chitosan is an extensively used antimicrobial compound. Chitosan is a basic polysaccharide mainly made from partial deacetylation of chitin (Younes and Rinaudo, 2015). Chitin is an abundantly found natural polysaccharide that is part of the exoskeleton of fungi and many marine arthropods (Tharanathan and Kittur, 2003). Chitosan is considered to have excessive antimicrobial and wide-spectrum activity against bacteria, viruses and fungi (Friedman and Juneja, 2010). Favorably, chitosan has lower toxicity in humans.

The possible nature of the action of these antimicrobial compounds derived from marine microbes has been proposed since the actual mechanism has not yet been fully recognized (Nadarajah et al., 2001). Depending on the molecular weight of chitosan, two methods are being proposed. Low-molecular-weight chitosan is thought to integrate with DNA-inhibiting transcription after entering the bacterial cell wall (Friedman and Juneja, 2010; Ruocco et al., 2016), and high-molecular-weight chitosan is believed to change the permeability of cells, hindering the transport of essential solutes into the cell by interacting with the cell surface (Eaton et al., 2008). Chitosan can act against fungi by either directly interfering with the growth of fungal cells or activating defense processes. Fungi, particularly *Zygomycetes*, *Chytridiomycetes*, *Ascomycetes* and *Basidiomycetes*, are the richest sources of chitin and chitosan (Ghormade et al., 2017), and chitin contributes 22% to 44% of the fungal cell wall, and the amount depends on the life stage, morphology and taxa (Abdel-Mohsen et al., 2016). Fungal chitin and chitosan lack protein, which is expected to cause allergic reactions (Friedman and Juneja, 2010). Interestingly, advancements in fermentation technology have suggested that cultivation of certain fungi is easier, less time consuming and less expensive than cultivation of other fungal sources (Corinaldesi et al., 2017). Carotenoids, particularly astaxanthin, are also known to have antimicrobial properties (Vichez et al., 2011). It prevents swelling under the eyes, wrinkles and acne (Ambati et al., 2014).

CONCLUSION

Effective preservation methods are crucial to minimize food loss throughout the entire supply chain. This necessitates exploring the naturally occurring antimicrobial compounds from microbial origin. Recently, bacteriophages are gaining attraction for various purposes. Lactic acid bacteria (LAB) are used as antimicrobial agents due to their probiotic and production of antimicrobial compounds. The presence of bacteriocins produced by LAB has demonstrably enhanced safety and

quality in cheese production. Additionally, natamycin which is considered as a Generally Recognized as Safe (GRAS) category compound has antifungal activity and can be used in medical therapies. Similarly, reuterin exhibits antimicrobial activity against both bacteria and fungi, thus increase the shelf life of various products including meat, yogurt, and cheese. However, future researches should be prioritizing safety and address technical challenges associated with antimicrobial agents, also consider their cost-effectiveness and safety for human consumption. Furthermore, to maximize efficacy, synergistic combinations of these agents should be explored. Microorganisms are underutilized reservoirs of potential biomolecules with diverse properties including antibacterial. The emergence of novel human-resistant infections and the associated rise of multidrug-resistant strains have elevated antimicrobial resistance to a critical public health concern. Wide varieties of novel antimicrobial agents are urgently needed to improve treatment for infectious illnesses and for industrial applications. Investigating microbial species presents a promising avenue for discovering novel antimicrobials with potentially superior mechanisms of action compared to existing ones.

Acknowledgment: We acknowledge the support provided by Eternal University, Baru Sahib, Sirmour, Himachal Pradesh, (India), and Maharishi Markandeshwar Deemed to be University, Mullana, Ambala, Haryana (India).

REFERENCES

- Abdulmumeen, H. A., Risikat, A. N., and Sururah, A. R. (2012). Food: Its preservatives, additives and applications. *International Journal of Chemical and Biochemical Sciences*, 1(2012), 36–47. <http://dx.doi.org/10.13140/2.1.1623.5208>
- Ackermann, H.-W., and Prangishvili, D. (2012). Prokaryote viruses studied by electron microscopy. *Archives of Virology*, 157(10), 1843–1849. <https://doi.org/10.1007/s00705-012-1383-y>
- Ambati, R. R., Phang, S.-M., Ravi, S., and Aswathanarayana, R. G. (2014). Astaxanthin: Sources, extraction, stability, biological activities and its commercial applications—A review. *Marine Drugs*, 12(1), 128–152. <https://doi.org/10.3390/md12010128>
- Ammor, S., Tauveron, G., Dufour, E., and Chevallier, I. (2006). Antibacterial activity of lactic acid bacteria against spoilage and pathogenic bacteria isolated from the same meat small-scale facility: 1—Screening and characterization of the antibacterial compounds. *Food Control*, 17(6), 454–461. <https://doi.org/10.1016/j.foodcont.2005.02.006>
- Atarashi, K., Tanoue, T., Shima, T., Imaoka, A., Kuwahara, T., Momose, Y., Cheng, G., Yamasaki, S., Saito, T., and Ohba, Y. (2011). Induction of colonic regulatory T cells by indigenous Clostridium species. *Science*, 331(6015), 337–341. <https://doi.org/10.1126/science.1198469>
- Bajagai, Y. S., Klieve, A. V., Dart, P. J., and Bryden, W. L. (2016). Probiotics in animal nutrition: Production, impact and regulation. *FAO. <https://openknowledge.fao.org/handle/20.500.14283/15933e>*
- Borysowski, J., Weber-Dąbrowska, B., and Górski, A. (2006). Bacteriophage endolysins as a novel class of antibacterial agents. *Experimental Biology and Medicine*, 231(4), 366–377. <https://doi.org/10.1177/153537020623100402>
- Brillet, A., Pilet, M.-F., Prevost, H., Cardinal, M., and Leroi, F. (2005). Effect of inoculation of *Carnobacterium divergens* V41, a biopreservative strain against *Listeria monocytogenes* risk, on the microbiological, chemical and sensory quality of cold-smoked salmon. *International Journal of Food Microbiology*, 104(3), 309–324. <https://doi.org/10.1016/j.ijfoodmicro.2005.03.012>
- Buntyn, J. O., Schmidt, T. B., Nisbet, D. J., and Callaway, T. R. (2016). The role of direct-fed microbials in conventional livestock production. *Annual Review of Animal Biosciences*, 4, 335–355. <https://doi.org/10.1146/annurev-animal-022114-111123>
- Cartman, S. T. (2011). Time to consider Clostridium probiotics? *Future Microbiology*, 6(9), 969–971. <https://doi.org/10.2217/fmb.11.86>
- Chen, G., and Chen, J. (2013). A novel cell modification method used in biotransformation of glycerol to 3-HPA by *Lactobacillus reuteri*. *Applied Microbiology and Biotechnology*, 97(10), 4325–4332. <https://doi.org/10.1007/s00253-013-4723-2>
- Clardy, J., and Walsh, C. (2004). Lessons from natural molecules. *Nature*, 432(7019), 829–837. <https://doi.org/10.1038/nature03194>
- Cleusix, V., Lacroix, C., Vollenweider, S., Duboux, M., and Le Blay, G. (2007). Inhibitory activity spectrum of reuterin produced by *Lactobacillus reuteri* against intestinal bacteria. *BMC Microbiology*, 7(1), 1–9. <https://doi.org/10.1186/1471-2180-7-101>
- Coffey, B., Mills, S., Coffey, A., McAuliffe, O., and Ross, R. P. (2010). Phage and their lysins as biocontrol agents for food safety applications. *Annual Review of Food Science and Technology*, 1, 449–468. <https://doi.org/10.1146/annurev.food.102308.124046>
- Corinaldesi, C., Barone, G., Marcellini, F., Dell'Anno, A., and Danovaro, R. (2017). Marine microbial-derived molecules and their potential use in cosmeceutical and cosmetic products. *Marine Drugs*, 15(4), 118. <https://doi.org/10.3390/md15040118>

- Das, D., and Goyal, A. (2012). Lactic acid bacteria in food industry. In *Microorganisms in sustainable agriculture and biotechnology* (pp. 757–772). Springer. http://dx.doi.org/10.1007/978-94-007-2214-9_33
- Davidson, P. M., and Doan, C. (2020). Natamycin. In *Antimicrobials in Food* (pp. 339–356). CRC Press. <https://doi.org/10.1201/9780429058196>
- Daw, M. A., and Falkiner, F. R. (1996). Bacteriocins: Nature, function and structure. *Micron*, 27(6), 467–479. [https://doi.org/10.1016/s0968-4328\(96\)00028-5](https://doi.org/10.1016/s0968-4328(96)00028-5)
- Dec, M., Puchalski, A., Urban-Chmiel, R., and Wernicki, A. (2014). Screening of *Lactobacillus* strains of domestic goose origin against bacterial poultry pathogens for use as probiotics. *Poultry Science*, 93(10), 2464–2472. <https://doi.org/10.3382/ps.2014-04025>
- Deegan, L. H., Cotter, P. D., Hill, C., and Ross, P. (2006). Bacteriocins: Biological tools for biopreservation and shelf-life extension. *International Dairy Journal*, 16(9), 1058–1071. <https://doi.org/10.1016/j.idairyj.2005.10.026>
- Dijksterhuis, J., Houbakken, J., and Samson, R. A. (2013). 2 fungal spoilage of crops and food. In *Agricultural applications* (pp. 35–56). Springer. https://doi.org/10.1007/978-3-642-36821-9_2
- Dimitrov Todorov, S., and Dicks, L. M. T. (2005). Effect of growth medium on bacteriocin production by *Lactobacillus plantarum* ST194BZ, a strain isolated from boza. *Food Technology and Biotechnology*, 43(2), 165–173. <https://www.ftb.com.hr/images/pdfarticles/2005/April-June/43-165.pdf>
- Dobrogosz, W. J. (1989). *Lactobacillus reuteri* and the enteric microbiota. The Regulatory and Protective Role of the Normal Microflora, 283–292. http://dx.doi.org/10.1007/978-1-349-10723-0_17
- Eaton, P., Fernandes, J. C., Pereira, E., Pintado, M. E., and Malcata, F. X. (2008). Atomic force microscopy study of the antibacterial effects of chitosans on *Escherichia coli* and *Staphylococcus aureus*. *Ultramicroscopy*, 108(10), 1128–1134. <https://doi.org/10.1016/j.ultramicro.2008.04.015>
- Egan, K., Field, D., Rea, M. C., Ross, R. P., Hill, C., and Cotter, P. D. (2016). Bacteriocins: Novel solutions to age old spore-related problems? *Frontiers in Microbiology*, 7, 461. <https://doi.org/10.3389/fmicb.2016.00461>
- El-Ziney, M. G., and Debevere, J. M. (1998). The effect of reuterin on *Listeria monocytogenes* and *Escherichia coli* O157: H7 in milk and cottage cheese. *Journal of Food Protection*, 61(10), 1275–1280. <https://doi.org/10.4315/0362-028x-61.10.1275>
- El-Ziney, M. G., Van Den Tempel, T., Debevere, J., and Jakobsen, M. (1999). Application of reuterin produced by *Lactobacillus reuteri* 12002 for meat decontamination and preservation. *Journal of Food Protection*, 62(3), 257–261. <https://doi.org/10.4315/0362-028x-62.3.257>
- Emilie Wieben. (2017). Food loss and waste and the linkage to global ecosystems. FAO. <http://www.fao.org/publications/card/en/c/7fed720c-18e6-4be4-83d2-385b05b79ace/>
- Engels, C., Schwab, C., Zhang, J., Stevens, M. J., Bieri, C., Ebert, M.-O., McNeill, K., Sturla, S. J., and Lacroix, C. (2016). Acrolein contributes strongly to antimicrobial and heterocyclic amine transformation activities of reuterin. *Scientific Reports*, 6(1), 1–13. <https://doi.org/10.1038/2fresp36246>
- Fischetti, V. A. (2008). Bacteriophage lysins as effective antibacterials. *Current Opinion in Microbiology*, 11(5), 393–400. <https://doi.org/10.1016/2fj.mib.2008.09.012>
- Friedman, M., and Juneja, V. K. (2010). Review of antimicrobial and antioxidative activities of chitosans in food. *Journal of Food Protection*, 73(9), 1737–1761. <https://doi.org/10.4315/0362-028x-73.9.1737>
- García, P., Martínez, B., Obeso, J. M., and Rodríguez, A. (2008). Bacteriophages and their application in food safety. *Letters in Applied Microbiology*, 47(6), 479–485. <https://doi.org/10.1111/j.1472-765x.2008.02458.x>
- García-Anaya, M. C., Sepulveda, D. R., Rios-Velasco, C., & Acosta-Muñoz, C. H. (2023). Incorporation of A511 bacteriophage in a whey protein isolate-based edible coating for the control of *Listeria monocytogenes* in Cheese. *Food Packaging and Shelf Life*, 37, 101095. <https://doi.org/10.1016/j.fpsl.2023.101095>
- Ge, H., Fu, S., Guo, H., Hu, M., Xu, Z., Zhou, X., & Chen, X. (2022). Application and challenge of bacteriophage in the food protection. *International Journal of Food Microbiology*, 380, 109872. <https://doi.org/10.1016/j.ijfoodmicro.2022.109872>
- Gharsallaoui, A., Oulahal, N., Joly, C., and Degraeve, P. (2016). Nisin as a food preservative: Part I: Physicochemical properties, antimicrobial activity, and main uses. *Critical Reviews in Food Science and Nutrition*, 56(8), 1262–1274. <https://doi.org/10.1080/10408398.2013.763765>
- Ghormade, V., Pathan, E. K., and Deshpande, M. V. (2017). Can fungi compete with marine sources for chitosan production? *International Journal of Biological Macromolecules*, 104, 1415–1421. <https://doi.org/10.1016/j.ijbiomac.2017.01.112>
- Goessens, T., Mouchtaris-Michaïlidis, T., Tesfamariam, K., Truong, N. N., Vertriest, F., Bader, Y., ... & De Boevre, M. (2024). Dietary mycotoxin exposure and human health risks: A protocol for a systematic review. *Environment International*, 108456. <https://doi.org/10.1016/j.envint.2024.108456>
- Greifová, G., Májeková, H., Greif, G., Body, P., Greifová, M., and Dubničková, M. (2017). Analysis of antimicrobial and immunomodulatory substances produced by heterofermentative *Lactobacillus reuteri*. *Folia Microbiologica*, 62(6), 515–524. <https://doi.org/10.1007/s12223-017-0524-9>
- Hagens, S., and Loessner, M. J. (2010). Bacteriophage for biocontrol of foodborne pathogens: Calculations and considerations. *Current Pharmaceutical Biotechnology*, 11(1), 58–68. <https://doi.org/10.2174/138920110790725429>
- Holzapfel, W. H., Haberer, P., Geisen, R., Björkroth, J., and Schillinger, U. (2001). Taxonomy and important features of probiotic microorganisms in food and nutrition. *The American Journal of Clinical Nutrition*, 73(2), 365 s–373 s. <https://doi.org/10.1093/ajcn/73.2.365s>
- Hooton, S. P., Atterbury, R. J., and Connerton, I. F. (2011). Application of a bacteriophage cocktail to reduce *Salmonella Typhimurium* U288 contamination on pig skin. *International Journal of Food Microbiology*, 151(2), 157–163. <https://doi.org/10.1016/j.ijfoodmicro.2011.08.015>
- Kazi, M., and Annapure, U. S. (2016). Bacteriophage biocontrol of foodborne pathogens. *Journal of Food Science and Technology*, 53(3), 1355–1362. <https://doi.org/10.1007/s13197-015-1996-8>
- Kuipers, O. P., Buist, G., and Kok, J. (2000). Current strategies for improving food bacteria. *Research in Microbiology*, 151(10), 815–822. [https://doi.org/10.1016/s0923-2508\(00\)01147-5](https://doi.org/10.1016/s0923-2508(00)01147-5)
- Kumar, A., Pramanik, J., Goyal, N., Prajapati, B. G., & Chauhan, D. (2024). Probiotics in the Management of Diabetes. In *Advances in Probiotics for Health and Nutrition*. IntechOpen. <https://doi.org/10.5772/intechopen.110338>
- Kutter, E., and Sulakvelidze, A. (2004). Bacteriophages: Biology and applications. CRC press. <https://doi.org/10.1201/9780203491751>
- Le Lay, C., Dridi, L., Bergeron, M. G., and Ouellette, M. (2016). Nisin is an effective inhibitor of *Clostridium difficile* vegetative cells and spore germination. *Journal of Medical Microbiology*, 65(2), 169–175. <https://doi.org/10.1099/jmm.0.000202>
- Leverentz, B., Conway, W. S., Alavidze, Z., Janisiewicz, W. J., Fuchs, Y., Camp, M. J., Chighladze, E., and Sulakvelidze, A. (2001). Examination of bacteriophage as a biocontrol method for *Salmonella* on fresh-cut fruit: A model study. *Journal of Food Protection*, 64(8), 1116–1121. <https://doi.org/10.4315/0362-028x-64.8.1116>
- Titone, V., Ceraulo, M., Lopresti, F., Garofalo, G., Gaglio, R., Mistretta, M. C., & Botta, L. (2025). Use of Natamycin for the Development of Polymer Systems with Antifungal Activity for Packaging Applications. *Polymers*, 17(5), 686. <https://doi.org/10.3390/polym17050686>
- Martínez, B., Obeso, J. M., Rodríguez, A., and García, P. (2008). Nisin-bacteriophage crossresistance in *Staphylococcus aureus*. *International Journal of Food Microbiology*, 122(3), 253–258. <https://doi.org/10.1016/j.ijfoodmicro.2008.01.011>
- McAuliffe, O., Ryan, M. P., Ross, R. P., Hill, C., Breeuwer, P., and Abee, T. (1998). Lactacin 3147, a broad-spectrum bacteriocin which selectively dissipates the membrane potential. *Applied and Environmental Microbiology*, 64(2), 439–445. <https://doi.org/10.1128/aem.64.2.439-445.1998>
- Mignacca, S. A., Dore, S., Spuria, L., Zanghi, P., Amato, B., Duprè, I., Armas, F., Biasibetti, E., Camperio, C., and Lollai, S. A. (2017). Intramammary infusion of a live culture of *Lactococcus lactis* in ewes to treat staphylococcal mastitis. *Journal of Medical Microbiology*, 66(12), 1798–1810. <https://doi.org/10.1099/jmm.0.000641>
- Mishra, S. K., Malik, R. K., Manju, G., Pandey, N., Singroha, G., Behare, P., and Kaushik, J. K. (2012). Characterization of a reuterin-producing *Lactobacillus reuteri* BPL-36 strain isolated from human infant fecal sample. *Probiotics and Antimicrobial Proteins*, 4(3), 154–161. <https://doi.org/10.1007/s12602-012-9103-1>
- Mobolaji, O. A., and Wuraola, F. O. (2011). Assessment of the antimicrobial activity of lactic acid bacteria isolated from two fermented maize products-ogi and kunni-zaki. *Malaysian Journal of Microbiology*, 7(3), 124–128. <http://dx.doi.org/10.21161/mjm.25710>
- Mohammadi, T. N., Shen, C., Li, Y., Zayda, M. G., Sato, J., Masuda, Y., ... & Miyamoto, T. (2022). Characterization of *Clostridium perfringens* bacteriophages and their application in chicken meat and milk. *International Journal of Food Microbiology*, 361, 109446. <https://doi.org/10.1016/j.ijfoodmicro.2021.109446>
- Monk, A. B., Rees, C. D., Barrow, P., Hagens, S., and Harper, D. R. (2010). Bacteriophage applications: Where are we now? *Letters in Applied Microbiology*, 51(4), 363–369. <https://doi.org/10.1111/j.1472-765x.2010.02916.x>
- Nadarajah, K., Kader, J., Mazmira, M., and Paul, D. C. (2001). Production of chitosan by fungi. *Pakistan Journal of Biological Sciences*, 4(3), 263–265. <https://dx.doi.org/10.3923/pjbs.2001.263.265>
- O'Flynn, G., Ross, R. P., Fitzgerald, G. F., and Coffey, A. (2004). Evaluation of a cocktail of three bacteriophages for biocontrol of *Escherichia coli* O157: H7. *Applied and Environmental Microbiology*, 70(6), 3417–3424. <https://doi.org/10.1128/aem.70.6.3417-3424.2004>
- Obeso, J. M., Martínez, B., Rodríguez, A., and García, P. (2008). Lytic activity of the recombinant staphylococcal bacteriophage ΦH5 endolysin active against *Staphylococcus aureus* in milk. *International Journal of Food Microbiology*, 128(2), 212–218. <https://doi.org/10.1016/j.ijfoodmicro.2008.08.010>
- Peng, X., Adachi, K., Chen, C., Kasai, H., Kanoh, K., Shizuri, Y., and Misawa, N. (2006). Discovery of a marine bacterium producing 4-hydroxybenzoate and its alkyl esters, parabens. *Applied and Environmental Microbiology*, 72(8), 5556–5561. <https://doi.org/10.1128/aem.00494-06>

- Perez, R. H., Zendo, T., & Sonomoto, K. (2022). Multiple bacteriocin production in lactic acid bacteria. *Journal of bioscience and bioengineering*, 134(4), 277–287. <https://doi.org/10.1016/j.jbiosc.2022.07.007>
- Pol, I. E., Mastwijk, H. C., Bartels, P. V., and Smid, E. J. (2000). Pulsed-electric field treatment enhances the bactericidal action of nisin against *Bacillus cereus*. *Applied and Environmental Microbiology*, 66(1), 428–430. <https://doi.org/10.1128/aem.66.1.428-430.2000>
- Rani, A., Saini, K. C., Bast, F., Varjani, S., Mehariya, S., Bhatia, S. K., ... & Funk, C. (2021). A review on microbial products and their perspective application as antimicrobial agents. *Biomolecules*, 11(12), 1860. <https://doi.org/10.3390/biom11121860>
- Rathee, P., Sehrawat, R., Rathee, P., Khatkar, A., Akkol, E. K., Khatkar, S., ... & Sobarzo-Sánchez, E. (2023). Polyphenols: natural preservatives with promising applications in food, cosmetics and pharma industries; problems and toxicity associated with synthetic preservatives; impact of misleading advertisements; recent trends in preservation and legislation. *Materials*, 16(13), 4793. <https://doi.org/10.3390/ma16134793>
- Reis, J. A., Paula, A. T., Casarotti, S. N., and Penna, A. L. B. (2012). Lactic Acid Bacteria Antimicrobial Compounds: Characteristics and Applications. *Food Engineering Reviews*, 4(2), 124–140. <https://doi.org/10.1007/s12393-012-9051-2>
- Ricke, S. C. (2015). Anaerobic microbiology laboratory training and writing comprehension for food safety education. In *Food Safety* (pp. 395–419). Elsevier. <https://doi.org/10.1016/B978-0-12-800245-2.00019-8>
- Rodríguez, J. M., Martínez, M. I., Horn, N., and Dodd, H. M. (2003). Heterologous production of bacteriocins by lactic acid bacteria. *International Journal of Food Microbiology*, 80(2), 101–116. [https://doi.org/10.1016/s0168-1605\(02\)00153-8](https://doi.org/10.1016/s0168-1605(02)00153-8)
- Rojas-Graü, M. A., Oms-Oliu, G., Soliva-Fortuny, R., and Martín-Belloso, O. (2009). The use of packaging techniques to maintain freshness in fresh-cut fruits and vegetables: A review. *International Journal of Food Science & Technology*, 44(5), 875–889. <https://doi.org/10.1111/j.1365-2621.2009.01911.x>
- Ross, R. P., Morgan, S., and Hill, C. (2002). Preservation and fermentation: Past, present and future. *International Journal of Food Microbiology*, 79(1–2), 3–16. [https://doi.org/10.1016/s0168-1605\(02\)00174-5](https://doi.org/10.1016/s0168-1605(02)00174-5)
- Ruocco, N., Costantini, S., Guariniello, S., and Costantini, M. (2016). Polysaccharides from the marine environment with pharmacological, cosmeceutical and nutraceutical potential. *Molecules*, 21(5), 551. <https://doi.org/10.3390/molecules21050551>
- Saarela, M., Lähteenmäki, L., Crittenden, R., Salminen, S., and Mattila-Sandholm, T. (2002). Gut bacteria and health foods—The European perspective. *International Journal of Food Microbiology*, 78(1–2), 99–117. [https://doi.org/10.1016/s0168-1605\(02\)00235-0](https://doi.org/10.1016/s0168-1605(02)00235-0)
- Saeed, F., Afzaal, M., Tufail, T., and Ahmad, A. (2019). Use of natural antimicrobial agents: A safe preservation approach. *Act Antimicrob Food Packag*, Published online January. <https://doi.org/10.5772/intechopen.80869>
- Seal, B. S., Lillehoj, H. S., Donovan, D. M., and Gay, C. G. (2013). Alternatives to antibiotics: A symposium on the challenges and solutions for animal production. *Animal Health Research Reviews*, 14(1), 78–87. <https://doi.org/10.1017/s1466252313000030>
- Shah, S., Das, R., Chavan, B., Bajpai, U., Hanif, S., & Ahmed, S. (2023). Beyond antibiotics: phage-encoded lysins against Gram-negative pathogens. *Frontiers in Microbiology*, 14, 1170418. <https://doi.org/10.3389/fmicb.2023.1170418>
- Shen, W., Zhang, Y., Wang, D., Jiao, S., Zhang, L., & Sun, J. (2024). Improving the production of natamycin in *Streptomyces natalensis* HW-2 by L-valine feeding. *Food Science and Biotechnology*, 1–11. <https://doi.org/10.1007/s10068-024-01570-8>
- Silva, M. M., and Lidon, F. (2016). Food preservatives—An overview on applications and side effects. *Emirates Journal of Food and Agriculture*, 366–373. <https://doi.org/10.9755/ejfa.2016-04-351>
- Stark, J. (2003). Natamycin: An effective fungicide for food and beverages. *Natural Antimicrobials for the Minimal Processing of Foods*, 82–97. <http://dx.doi.org/10.1533/9781855737037.82>
- Sunil, K., and Narayana, B. (2008). Spectrophotometric determination of hydrogen peroxide in water and cream samples. *Bulletin of Environmental Contamination and Toxicology*, 81(4), 422–426. <https://doi.org/10.1007/s00128-008-9477-7>
- Tabla, R., Martínez, B., Rebollo, J. E., González, J., Ramírez, M. R., Roa, I., Rodríguez, A., and García, P. (2012). Bacteriophage performance against *Staphylococcus aureus* in milk is improved by high hydrostatic pressure treatments. *International Journal of Food Microbiology*, 156(3), 209–213. <https://doi.org/10.1016/j.ijfoodmicro.2012.03.023>
- Takeda, T., and Chang, F. (2005). Role of fission yeast myosin I in organization of sterol-rich membrane domains. *Current Biology*, 15(14), 1331–1336. <https://doi.org/10.1016/j.cub.2005.07.009>
- TeWelscher, Y. M., Hendrik, H., Balagué, M. M., Souza, C. M., Riezman, H., De Kruijff, B., and Breukink, E. (2008). Natamycin blocks fungal growth by binding specifically to ergosterol without permeabilizing the membrane. *Journal of Biological Chemistry*, 283(10), 6393–6401. <https://doi.org/10.1074/jbc.m707821200>
- Thames, H. T., & Theradiyil Sukumaran, A. (2020). A review of *Salmonella* and *Campylobacter* in broiler meat: emerging challenges and food safety measures. *Foods*, 9(6), 776. <https://doi.org/10.3390/foods9060776>
- Tharanathan, R. N., and Kittur, F. S. (2003). Chitin—The undisputed biomolecule of great potential. *Critical Reviews in Food Science and Nutrition*, 43, 61–87. <https://doi.org/10.1080/10408690390826455>
- Todorov, S. D., and Dicks, L. M. (2004). Influence of growth conditions on the production of a bacteriocin by *Lactococcus lactis* subsp. *Lactis* ST34BR, a strain isolated from barley beer. *Journal of Basic Microbiology: An International Journal on Biochemistry, Physiology, Genetics, Morphology, and Ecology of Microorganisms*, 44(4), 305–316. <https://doi.org/10.1002/jobm.200410413>
- United Nation (2023). International Day of Awareness on Food Loss and Waste Reduction 29 September. Data was assessed on 30 April, 2024. <https://www.un.org/en/observances/end-food-waste-day#:~:text=the%20consumption%20level,-.An%20estimated%2017%20percent%20of%20total%20global%20food%20production%20is,in%20the%20global%20food%20system>
- Vílchez, C., Forján, E., Cuaresma, M., Bédmar, F., Garbayo, I., and Vega, J. M. (2011). Marine carotenoids: Biological functions and commercial applications. *Marine Drugs*, 9(3), 319–333. <https://doi.org/10.3390/md9030319>
- Vollenweider, S., and Lacroix, C. (2004). 3-Hydroxypropionaldehyde: Applications and perspectives of biotechnological production. *Applied Microbiology and Biotechnology*, 64(1), 16–27. <https://doi.org/10.1007/s00253-003-1497-y>
- Volokhov, D. V., Amselle, M., Beck, B. J., Popham, D. L., Whittaker, P., Wang, H., Kerrigan, E., and Chizhikov, V. E. (2012). *Lactobacillus brantae* sp. Nov., isolated from feces of Canada geese (*Branta canadensis*). *International Journal of Systematic and Evolutionary Microbiology*, 62(9), 2068–2076. <https://doi.org/10.1099/ijs.0.033852-0>
- Wachtler, V., and Balasubramanian, M. K. (2006). Yeast lipid rafts—an emerging view. *Trends in Cell Biology*, 16(1), 1–4. <https://doi.org/10.1016/j.tcb.2005.11.008>
- Weng, S., López, A., Sáez-Orviz, S., Marcet, I., García, P., Rendueles, M., & Díaz, M. (2021). Effectiveness of bacteriophages incorporated in gelatine films against *Staphylococcus aureus*. *Food Control*, 121, 107666. <https://doi.org/10.1016/j.foodcont.2020.107666>
- Xu, Y. (2021). Phage and phage lysins: New era of bio-preservatives and food safety agents. *Journal of food science*, 86(8), 3349–3373. <https://doi.org/10.1111/1750-3841.15843>
- Yang, E., Fan, L., Jiang, Y., Doucette, C., and Fillmore, S. (2012). Antimicrobial activity of bacteriocin-producing lactic acid bacteria isolated from cheeses and yogurts. *Amb Express*, 2(1), 1–12. <https://doi.org/10.1186/2191-0855-2-48>
- Yoong, P., Schuch, R., Nelson, D., and Fischetti, V. A. (2004). Identification of a broadly active phage lytic enzyme with lethal activity against antibiotic-resistant *Enterococcus faecalis* and *Enterococcus faecium*. *Journal of Bacteriology*, 186(14), 4808–4812. <https://doi.org/10.1128/JFB.186.14.4808-4812.2004>
- Younes, I., and Rinaudo, M. (2015). Chitin and chitosan preparation from marine sources. Structure, properties and applications. *Marine Drugs*, 13(3), 1133–1174. <https://doi.org/10.3390/md13031133>
- Zalewska-Piątek, B., & Piątek, R. (2021). Bacteriophages as potential tools for use in antimicrobial therapy and vaccine development. *Pharmaceuticals*, 14(4), 331. <https://doi.org/10.3390/ph14040331>
- Sreeramya, K., Ramachandra, B., Praveen, A. R., & Prabha, R. (2021). Role of Nisin and Natamycin in Dairy Industry International Research Journal of Modernization in Engineering Technology and Science, 3(11), 323–327. https://www.irjmets.com/uploadedfiles/paper/volume_3/issue_11_november_2021/17050/final/fin_irjmets1636811555.pdf
- Delves-Broughton, J., & Weber, G. (2011). Nisin, natamycin and other commercial fermentates used in food biopreservation. In *Protective cultures, antimicrobial metabolites and bacteriophages for food and beverage biopreservation* (pp. 63–99). Woodhead Publishing. <https://doi.org/10.1533/9780857090522.1.63>
- Debonne, E. (2020). Exploring natural antifungal preservation strategies to extend bread shelf-life: from baking technology to biopreservation (Doctoral dissertation, Ghent University). <http://hdl.handle.net/1854/LU-8656300>
- Sara, A. E., Ekbal, M. A., Adham, M. A., & Hamdi, A. M. (2014). The role of natamycin fortification to extend shelf life of plain yoghurt. *Benha Vet Med J*, 27(2), 140–9. <https://bvmbj.bu.edu.eg/issues/27-2/13.pdf>
- Siricururata, P., Iyer, M. M., Manns, D. C., Churey, J. J., Worobo, R. W., & Padilla-Zakour, O. I. (2013). Shelf-life evaluation of natural antimicrobials for Concord and Niagara grape juices. *Journal of food protection*, 76(1), 72–78. <https://doi.org/10.4315/0362-028X.JFP-12-144>