

## Application of antagonistic antibacterial activity cling film in extending the shelf life of perishable agricultural products

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### Abstract

Spoilage of perishable agricultural products during storage and transport leads to significant economic losses. Antimicrobial active preservative film is an emerging technology for preserving these products. This paper reviews the advantages and disadvantages of using antagonistic bacteria in agricultural product preservation, the synergy between antagonistic bacteria and preservative films, the combination of antimicrobial active films with other preservation methods, and their application in fruits, vegetables, chilled meat, aquatic products, and raw milk. The study concludes that while antagonistic and antimicrobial active films offer marked advantages in preserving agricultural products, challenges remain, such as degradation in mechanical properties and reduced stability after incorporating antagonistic bacteria, as well as the limited effectiveness of single-use applications. A recommended approach is to combine antimicrobial active films with other preservation techniques to enhance overall effectiveness. Currently, many antimicrobial active preservative films have demonstrated significant potential in preserving perishable agricultural products in the field of agricultural preservation.

**Keywords:** antagonistic bacteria; mechanism; preservative film; preservation of agricultural products; spoilage bacteria

### Introduction

Perishable agricultural products are primarily animal and plant-based produce that are susceptible to quality

issues, such as spoilage and decay, under natural environmental temperatures. Fruits, vegetables, meat, raw milk, and aquatic products are easily contaminated by spoilage bacteria during processing, storage, and marketing,

leading to significant biochemical changes and accelerated deterioration, causing waste and severe economic losses (Usman *et al.*, 2024; Aziz *et al.*, 2023; Wang *et al.*, 2019). Spoilage bacteria are microorganisms that induce food spoilage and pose food safety risks, including bacteria, molds, and yeasts. Once these microorganisms contaminate agricultural products, they emit distinct odors, make products soft and sticky, and increase volatile basic nitrogen by decomposing proteins, fats, and carbohydrates. According to the Food and Agriculture Organization of the United Nations (Koutsoumanis *et al.*, 2021), global waste due to the spoilage of agricultural products accounts for about one-third of total output. Contamination and decay losses caused by spoilage bacteria are major challenges for the global agricultural processing industry and are of significant concern for governments in terms of agricultural product quality and supply security (Vanegas *et al.*, 2017). With China's "rural revitalization" and "big food concept" policies, along with the growing demand for safe, eco-friendly, low-carbon, high-quality, and commercialized fresh agricultural products, greener, safer, and higher-quality preservation and storage technologies have become the development trend for China's agricultural cold chain storage and transportation industry. Ensuring that global agricultural products reach tables fresh and solving the preservation of perishable goods with advanced technology has drawn researchers' attention. Currently, food and agricultural preservation methods include chemical, physical, and biological techniques to ensure food safety and sustainability (Aziz *et al.*, 2024; Du *et al.*, 2024; Shouket *et al.*, 2024; Shouket *et al.*, 2023; Khan *et al.*, 2022).

Chemical preservation technology employs chemical agents through methods such as application, soaking, and spraying to treat the surface of agricultural products. This impacts the physiological and metabolic activities of organisms, thereby achieving storage and preservation (You *et al.*, 2023). Predominantly, this technology utilizes chemical preservatives like various metal salts, chitosan, ethanol, and certain additives such as calcium salts. While chemical preservation is convenient, efficient, and easily promoted, prolonged use can lead to drug resistance in pathogenic bacteria and environmental pollution due to residual substances. Furthermore, excessive consumption of chemically preserved agricultural products may pose severe health risks, including cancer and teratogenic effects (Javanmardi *et al.*, 2019). Physical preservation technology utilizes physical means to prevent agricultural products from deteriorating. These methods include low-temperature storage, controlled atmosphere storage, heat treatment, ozone storage, and irradiation storage. However, physical preservation has limitations, such as high energy consumption, significant investment, and nutrient loss. Moreover, its effectiveness is often influenced by various environmental factors. With the

advancement of green industries, addressing the preservation challenges of perishable products through eco-friendly technologies has garnered increasing attention. There is an urgent need to find safe, non-toxic, and effective preservation methods (Ng G *et al.*, 2020).

Biological preservation technology utilizes antibiotics, lysozyme, protease, and organic acids produced by antagonistic bacteria to maintain freshness. These substances inhibit harmful pathogens on the surface of agricultural products or prevent the loss of internal nutrients through competitive growth inhibition, heavy parasitism of pathogens, and induction of defense enzymes, thereby achieving preservation. Lee *et al.* discovered that the ethanol extract of chestnut inner shell exhibited antibacterial effects against *Campylobacter jejuni* in chicken at a concentration of 2 mg/mL (Lee *et al.*, 2016). Khaleque *et al.* demonstrated that clove essential oil is more effective than cinnamon essential oil in inhibiting the growth of *Listeria monocytogenes* in beef surimi, enhancing the product's safety (Khaleque *et al.*, 2016). The decay of agricultural products is primarily caused by bacteria and fungi, and traditional methods of prevention and control have largely relied on chemical fungicides and physical preservation. However, these physical and chemical methods have significant drawbacks. In contrast, biological preservation offers advantages such as environmental friendliness, safety, high efficiency, and a reduced risk of inducing drug resistance in pathogens (Schillinger *et al.*, 1996).

In recent years, the use of antagonistic bacteria for the biological preservation of agricultural products has garnered increasing attention from researchers worldwide. Numerous antibacterial substances have been extracted from these bacteria, including small molecular antibiotics, proteinaceous antibacterial substances, polypeptide antibiotics, and secondary metabolism-derived compounds. Studies have discovered that *Bacillus subtilis* can effectively control fruit diseases such as strawberry gray mold, anthracnose, grape gray mold, and apple anthracnose. Methylophilic *Bacillus* has been shown to inhibit banana wilt, pear rot, and other diseases (Madhaiyan *et al.*, 2010). Furthermore, various strains of *Bacillus*, *Alternomonas*, *Pseudomonas*, photosynthetic bacteria, *Marinobacter* bacteria, and *Lactobacillus* can effectively suppress *Vibrio parahaemolyticus* in aquatic products (Bhaskaran *et al.*, 2023). Mannai *et al.* demonstrated that a 2:1 mixture of *Trichoderma harzianum* and *Bacillus subtilis*, applied three times consecutively, achieved an 80.4% control rate of strawberry gray mold. In another study (Mannai *et al.*, 2023), Shi *et al.* inoculated whole milk with bacteriocin K7 produced by *Leuconostoc mesenteroides* K7, which exhibited a significant antagonistic effect on *Listeria monocytogenes*. This bacteriocin operates differently from nisin, indicating potential applications in milk preservation (Shi *et al.*, 2016).

The application of microorganisms for biological control has achieved significant breakthroughs and is regarded as a promising alternative to chemical fungicides and physical preservation methods. When combined with packaging films, it can further inhibit microbial growth. However, even commercial biological control preparations are still less effective compared to chemical fungicides. Therefore, exploring new and efficient antagonistic bacteria and studying their effects and mechanisms in inhibiting the rot of agricultural products is of both theoretical and practical importance. This research can accelerate the commercialization of microbial control for agricultural products, aiding the rapid and healthy development of the agricultural industry and contributing to rural revitalization. This review outlines the current state and applications of antagonistic bacteria and their active preservation film technology in various perishable agricultural products. It aims to offer a theoretical basis for future research on this technology and its industrial application in the production, transportation, and storage of agricultural products.

## Overview of Antagonistic Bacteria

### Definition of antagonistic bacteria

Antagonistic bacteria produce specific metabolites or alter environmental conditions during their life processes, thereby inhibiting the growth and reproduction of other microorganisms, or even killing them. Due to their unique advantages, such as environmental friendliness, good preservation effects, strong antibacterial properties, and high tolerance (Wang *et al.*, 2022), they align well with the development needs of the agricultural product industries worldwide (Ferreira *et al.*, 2021). Consequently, antagonistic bacteria have become a popular biopreservation technology in the field of agricultural product preservation.

### Antibacterial mechanism of antagonistic bacteria

Understanding the preservation mechanism of antagonistic bacteria is crucial for their effective application in preserving agricultural products and advancing new preservation technologies (Madhaiyan *et al.*, 2010). Generally, these mechanisms can be categorized into four types: competition for resources, hyperparasitism, secretion of antimicrobial substances, and induced host resistance (Dianpe *et al.*, 2010).

### Competition for trophic space

Nutrient and space competition is a crucial biocontrol mechanism employed by antagonistic bacteria. These

bacteria swiftly dominate fruit surfaces by competing with pathogens for essential nutrients such as carbohydrates and nitrogen sources. Yu *et al.* discovered that *Candida guilliermondensis* rapidly proliferates at peach fruit wounds through nutritional competition, effectively preventing soft rot (Yu *et al.*, 2009). Similarly, Wang *et al.* found that *B. cepacia* B-1 inhibits the growth of *Botrytis cinerea* and *Penicillium expansum* in strawberry wounds by competing with these pathogens for nutrients and space (Wang *et al.*, 2018).

### Heavy parasitic

Hyperparasitism, a phenomenon where fungi parasitize other fungi, is a well-documented natural occurrence and a crucial mechanism through which biocontrol bacteria eliminate plant pathogens. This process includes identification, contact, entanglement, penetration, and ultimately parasitism (Ahmed *et al.*, 2000). It has been observed that certain yeasts can attach to pathogenic bacteria and directly parasitize them to exert antibacterial effects. Arras *et al.* discovered that *Candida namibiae* can colonize fungal mycelium and promote its lysis, thereby inhibiting the development of citrus penicillium (Giovanni *et al.*, 1996). Claudia *et al.* found that *Pseudozyma aphidis* can parasitize the hyphae of powdery mildew and *Botrytis cinerea*, competing for nutrients and thereby controlling strawberry powdery mildew and gray mold (Calder *et al.*, 2019). Presently, our understanding of hyperparasitism mechanisms remains limited, with many aspects still to be further explored.

### Secretion of antimicrobial substances

Research indicates that when antagonistic bacteria interact with pathogenic bacteria, significant biomass accumulates around yeast cells at the wound sites of fruits. This biomass includes antibiotics, hydrolytic enzymes, organic acids, and toxic proteins. These extracellular active substances likely play a role in the interactions between antagonistic and pathogenic bacteria. Rabbee *et al.* noted that *Bacillus subtilis* secretes antibacterial substances that inhibit sweet cherry rot (Muhammad, 2019). Similarly, Sharma *et al.* highlighted that *Pseudomonas cepacia* Burkh can secrete antibacterial compounds that suppress the growth of *Botrytis cinerea* and *Penicillium expansum* on apple surfaces, as well as *Penicillium digitatum* in lemons (Sharma *et al.*, 2009). Current research underscores that the secretion of antibacterial substances is a critical mechanism through which antagonistic bacteria inhibit pathogens. However, it is important to consider that some antibacterial substances, like antibiotics, may induce resistance in pathogenic bacteria, diminishing the effectiveness of disease

control over time. Additionally, the antibiotics produced by antagonistic bacteria might pose risks to consumers (Rodríguez et al., 2007).

### Inducing Host Resistance

In recent years, the induction of resistance in postharvest fruits by antagonistic bacteria has emerged as a research hotspot in biological control. Wang et al. discovered that *Hansenispora uvarum* (*H. uvarum*) in grape juice could activate the SA signaling pathway in strawberries by upregulating the expression of resistance genes and enhancing the activity of defense-related enzymes, thereby preventing postharvest gray mold (Wang et al., 2019). Tang et al. observed that *Clauretii*, at an appropriate concentration, could elevate the expression of resistance genes and defense-related enzymes in cherry tomatoes, significantly bolstering their resistance to *Botrytis cinerea* and *Alternaria alternata* (Tang et al., 2021). Charles et al. reported that *Pichia membranefaciens* could heighten the disease resistance of citrus fruits by inducing increased activity of defense enzymes or phytoproductin synthesis, thereby averting the onset of citrus green mold and blue mold (Charles, 1992).

### Synergistic effect

The preservation mechanisms for different antagonistic bacteria are often multifaceted, working synergistically to prevent the decay of agricultural products. Research has demonstrated that a mixed culture of *Debaryomyces hansenii* and *Stenotrophomonas rhizophila* significantly inhibits the proliferation and lesion size of *Fusarium* on melon fruits. This effect is attributed to the competition for nutrients among antagonistic bacteria, as well as the production of hydrolytic enzymes and secondary metabolites (Rivas-Garcia et al., 2019).

### Evaluation of antagonistic bacteria in fresh keeping of agricultural products

As the study of antagonistic bacteria mechanisms progresses, our understanding of their preservation capabilities continues to deepen. An increasing number of researchers are examining the preservation effects of various antagonistic bacteria on different agricultural products. This method, which involves using beneficial microorganisms or the antibacterial substances they produce to combat pathogenic or spoilage microorganisms, is known as biological preservation. Currently, yeast, lactic acid bacteria, and actinomycetes are among the most effective antagonistic bacteria used for preserving agricultural products (Lahmamsi et al., 2024).

### Saccharomycetes

Antagonistic yeast is characterized by its wide availability, strong adaptability, robust reproductive ability, non-toxic metabolites, and lack of sensitization (Tahir, 2022). Currently, research on the preservation of agricultural products using antagonistic yeasts primarily targets fruit and vegetable preservation. These yeasts predominantly originate from fruit surfaces, leaves, roots, soil, and seawater, with the majority isolated from fruit surfaces (Li et al., 2017). For instance, Zhang et al. identified *Meyerozyma guilliermondii* from healthy broccoli, discovering that this strain enhances the synthesis of phenolic, terpenoid, and alkaloid substances, thereby improving broccoli's disease resistance (Zhang et al., 2022). Lin et al. isolated *Hannaella sinensis* from orchard soil, demonstrating its significant efficacy in controlling postharvest penicillium disease in apples and reducing natural decay (Lin et al., 2022). Wang et al. isolated *Yarrowia lipolytica* from grape pericarp, which effectively controls *Penicillium rubens* post-harvest (Wang et al., 2018).

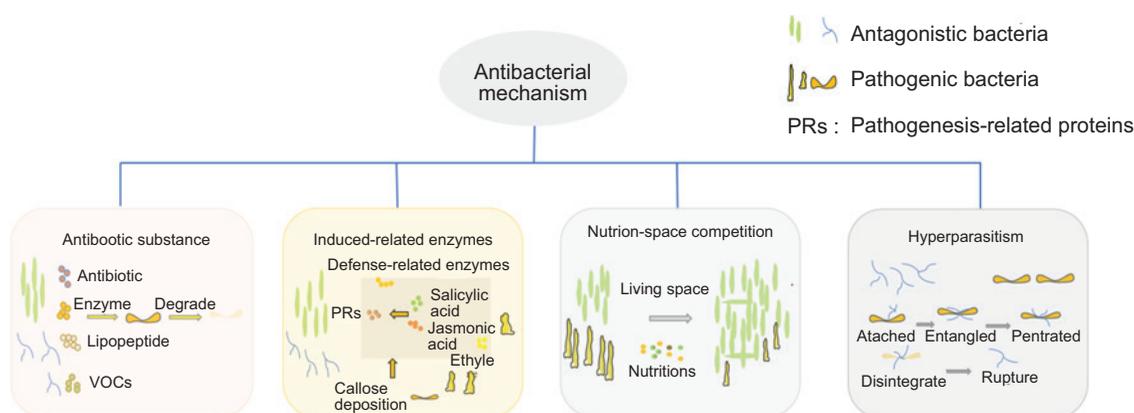


Figure 1. Antibacterial mechanism of antagonistic bacteria.

## Lactic acid bacteria

Lactic acid bacteria are recognized as safe microorganisms in agriculture. They have promising applications due to their abilities to antagonize pathogenic bacteria, enhance immune function, strengthen the intestinal barrier, and balance intestinal flora. These features make them potential candidates as the next generation of safe, stable, and economical biological antibiotics, with the possibility of reducing or even replacing traditional antibiotics (Wang *et al.*, 2018). Currently, research on the use of lactic acid bacteria in meat preservation primarily focuses on specific strains like *Lactococcus*, *Streptococcus*, *Enterococcus*, and *Pediococcus*. These bacteria produce bacteriostatic or bactericidal bacteriocins to achieve preservation. For instance, Nisin produced by *Lactococcus lactis* can improve meat taste, yet it is costly and unstable in acidic environments (Anumudu *et al.*, 2021); Enterocin from *Enterococcus faecium* exhibits strong bactericidal properties but requires stringent environmental conditions to be effective (Wei *et al.*, 2024); Pediocin from *Pediococcus* offers good bacteriostasis without affecting the taste and flavor of meat (Rodríguez *et al.*, 2007).

## Actinomycetes

Actinomyces is a prokaryotic microorganism with characteristics between fungi and bacteria. Research indicates that actinomycetes exhibit antagonistic properties against specific microorganisms. For instance, they show antagonism towards pathogens responsible for common fruit and vegetable diseases, such as tomato gray mold, cucumber downy mildew (Jijakli *et al.*, 1998), *Botryosphaeria dothidea*, *Fusarium oxysporum* f. sp. *niveum*, *Phytophthora capsici*, and *Sclerotinia sclerotiorum* (Wu *et al.*, 2018). Hao *et al.* identified a strain of *Streptomyces albiflaviniger* from soil, whose fermentation filtrate effectively inhibits poplar fusarium wilt, watermelon anthracnose, soybean bacterial spots, and rice bacterial spots (Hao *et al.*, 2019). Similarly, Jain *et al.* isolated a strain of *Streptomyces sampsonii* from tomatoes. This strain was found to inhibit spore germination and hyphal growth of *Botryosphaeria dothidea*, enhance tomato resistance enzyme activity, and provide an excellent preservative effect on stored tomatoes (Jain *et al.*, 2007). It is notable that despite the numerous research findings highlighting the potential of antagonistic bacteria as biological preservatives, there are currently few commercial examples available. This is primarily due to the inherent characteristics of antagonistic bacteria, such as low solubility, weak desorption ability, rapid release, and easy degradation, which restrict their application in agricultural products. Additionally, environmental factors such as pH, storage temperature and duration,

oxygen levels, and light exposure can also impact the effectiveness of natural preservatives. Therefore, to enhance their biological efficacy and applicability, they are typically used in conjunction with other preservation methods, leveraging synergistic effects to achieve preservation and anti-corrosion goals. Packaging is one effective strategy to broaden the applicability of natural preservatives in agricultural products, as it can enhance stability while maintaining antibacterial properties, thus increasing versatility in agricultural product processing. Furthermore, with the growing societal focus on the safety of agricultural products, there is a rising demand for improved packaging materials (Yu *et al.*, 2021). Consequently, the development of antibacterial biological cling films has emerged as a significant research interest (Min *et al.*, 2010).

## Application of Antibacterial Activity Preservative Film in Agricultural Products

### Classification of packaging films suitable for perishable products

Agricultural product packaging is crucial for preventing microbial contamination and is an essential component of processing and storage. Given the diverse characteristics of packaging materials, selecting the appropriate material is particularly important. Currently, common packaging film materials include polyethylene (PE), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyamide (PA), polyvinyl ether (PVE), and polyvinyl alcohol (PVA). Common types of packaging films include microporous, antibacterial, anti-fog, and nanocomposite films. This article discusses the properties of these films, categorizing them into polymer chemically synthesized films, degradable films, and edible films.

### Degradable film

Natural polymers such as starch, cellulose, and chitosan are extensively utilized for postharvest fruit preservation due to their excellent reproducibility, biodegradability, biocompatibility, and environmental friendliness (Mohammad *et al.*, 2013). Polylactic acid (PLA) is a degradable semi-crystalline polyester produced by fermenting sugars, corn, and other substances into lactic acid, which is then polymerized. However, the varying degrees of PLA crystallization and its low impact toughness limit its application in the packaging industry (Lizundia *et al.*, 2016). Geng *et al.* developed a degradable Cur-ZIF-8/CS/Zein composite membrane by chemically crosslinking the zinc ion of imidazole framework zeolite-8, containing curcumin, with hydrophilic chitosan (CS) and corn flavone. This approach addressed the

interfacial incompatibility issues between hydrophobic and hydrophilic polymers. While chitosan membranes exhibit poor barrier properties against water vapor, oxygen, and carbon dioxide and tend to dissolve easily, zein films suffer from limited flexibility and brittleness, restricting their use in fruit preservation. The Cur-ZIF-8/CS/Zein composite film demonstrated superior barrier properties, mechanical strength, and antibacterial efficacy compared to traditional polymer composites, ultimately extending the shelf life of lychee by 8 days (Geng *et al.*, 2023).

### Chemical synthesis of polymer films

Polymer films exhibit superior strength, heat resistance, and chemical stability, with the ability to adjust the CO<sub>2</sub>/O<sub>2</sub> transmission ratio based on the characteristics of agricultural products. Despite their numerous benefits, polymer flexible packaging materials contribute significantly to environmental pollution. Mannan *et al.* developed PLLA-PEG-PLLA (PLGLxGy) and PLLA-PCL-PLLA (PLCLxCy) copolymers using polyethylene glycol (PEG) and poly (L-lactic acid) (PLLA), which were applied in the packaging of cherry tomatoes and strawberries. The study revealed that both polymer films could maintain suitable high CO<sub>2</sub> and low O<sub>2</sub> concentrations. This environment effectively inhibits fruit respiration and water loss, suppresses microbial growth and enzyme reactions, delays ripening and aging, and significantly extends the shelf life of cherry tomatoes and strawberries (Mannan *et al.*, 2013).

### Edible film

Edible films are utilized as packaging materials and components of agricultural products. They are designed to be efficient, safe, and environmentally friendly. These films can be composed of proteins, carbohydrates, lipids, and other compounds. Among these, chitosan is a popular active packaging material (Gomes *et al.*, 2019). Various agricultural products have unique packaging requirements, necessitating the selection of appropriate films based on their specific characteristics. Due to their environmental benefits and high efficiency, edible films have become a focal point in agricultural preservation. Sharma *et al.* used chitosan films containing *Candida utilis* to inhibit rot in tomatoes caused by *Alternaria alternata* and *Geotrichum candidum*. The results indicated that the lesion diameters with 0.25% and 0.5% chitosan were 16±3mm and 15±1mm, respectively, while another study showed a lesion diameter of 6mm and a significantly reduced decay rate with the same chitosan concentrations (Sharma *et al.*, 2006). De Lacey *et al.* prepared edible films from gelatin solutions enriched with probiotics (*Bifidobacterium bifidum* and *Lactobacillus*

*acidophilus*), sorbitol, and glycerol as plasticizers, evaluating the survival rate and functionality of the probiotics. The results demonstrated that the probiotic count in the coating remained stable for ten days. To avoid impacting the sensory properties of fish, the number of probiotics stabilized after high-pressure treatment to remove gram-negative bacteria (Guo *et al.*, 2025). The findings showed that lactic acid bacteria and bifidobacteria were unaffected by high pressure when combined with the film (De Lacey *et al.*, 2012). Soukoulis *et al.* incorporated *Lactobacillus rhamnosus* GG into films made of starch, soy protein concentrate, gelatin, and sodium caseinate, using glycerol as a plasticizer. During the drying process, the *Lactobacillus rhamnosus* count decreased significantly across the four film solutions, ranging from 0.81 to 1.87 log CFU/g. The inactivation rate was highest in starch films without protein. The activity of *Lactobacillus rhamnosus* increased by 3-4 times and 5-7 times when proteins were added to starch films made from corn and rice (Soukoulis *et al.*, 2016).

While edible films are widely used in preservation, they still have some drawbacks. For instance, their water solubility reduces the environmental resistance of the films, which can easily impact the appearance and quality of agricultural products when exposed to moisture. However, edible films combined with other technologies or additives can not only maximize the benefits of these films but also mitigate certain defects.

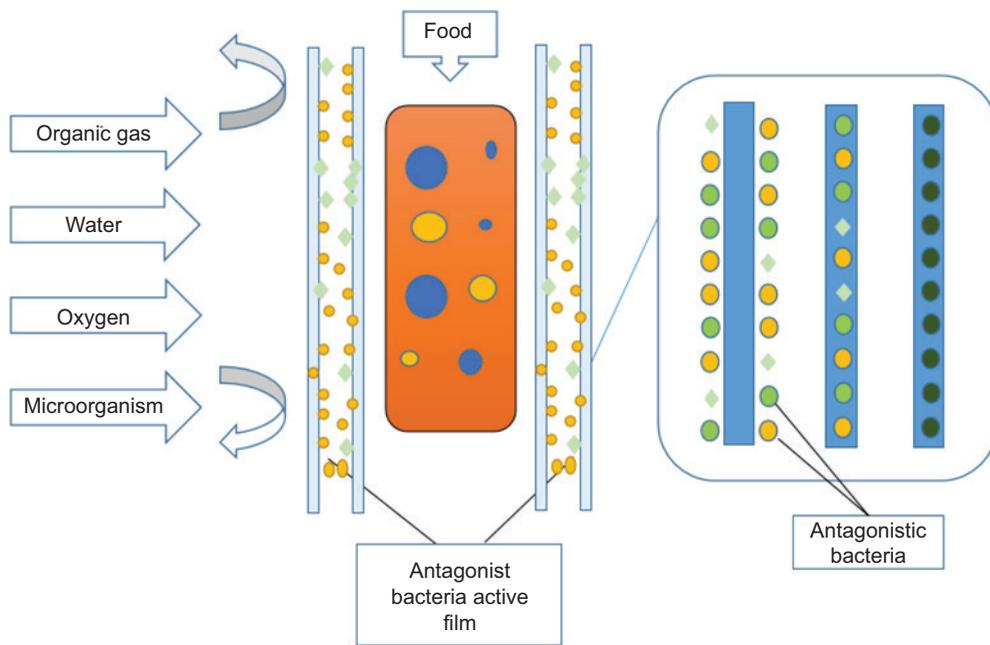
### Combination mode and effect of antagonistic bacteria and fresh-keeping film

The primary function of antibacterial cling film is to enhance the quality and safety of agricultural products while extending their shelf life. This is achieved by incorporating active substances into the polymer matrix, which are then slowly and continuously released from the packaging to provide long-term antibacterial effects (Patrícia *et al.*, 2010), as illustrated in Figure 2.

The primary techniques for combining antagonistic bacteria with packaging films to achieve antibacterial and preservative effects include casting, blowing, dipping, and spraying (Zhang *et al.*, 2017).

### Casting method

The casting method involves thoroughly mixing the antagonist solution with the preservative film matrix solution, pouring the mixture into a mold, and drying it to create a uniform preservative film with antagonistic properties. This fresh-keeping film contains antagonistic bacteria both within and on the surface, enabling a slow and even



**Figure 2. Mechanism of action of antibacterial plastic film.**

release onto perishable products, thereby ensuring long-term preservation. Moreover, when perishable products are placed in environments where antagonistic bacteria struggle to survive, the plastic wrap acts as a protective barrier, aiding in the preservation of these bacteria (Cheng *et al.*, 2016). A. M. López de Lacey *et al.* incorporated *Lactobacillus acidophilus* and *Bifidobacterium bifidum* directly into the film-forming solution, adjusting the bacterial concentration to  $10^9$  CFU. The solution was then poured into a square plastic dish and dried in an oven at  $45^\circ\text{C}$  for 15 hours, resulting in a uniform dry film containing viable bacteria. The number of viable bacteria in the film remained stable for six days. Tapia *et al.* developed edible alginate and gellan coatings containing *Bifidobacterium lactis* BB-12, applying them to apples and papayas. The researchers dissolved alginate or gellan gum and heated the solutions to form the film. Bifidobacteria were then added, and the mixture was poured into dishes to dry, forming a film. Although the concentration of viable bacteria in the film solution was two logarithmic cycles lower compared to the film on the fruit, the results showed that the bacteria on the fruit film remained viable and stable in number over ten days at  $2^\circ\text{C}$  (Tapia *et al.*, 2007).

### Blown film method

The blown film method involves using a circular machine head to inflate a thin film material into a tube, which is then cooled and shaped by a wind ring. This thin film, now double-layered and half the circumference of the

film tube, is gradually stacked by a zigzag plate and finally rolled up by a curling device to form a semi-finished film. This method is both economical and straightforward for thin film formation and processing (Benjamin *et al.*, 2024). Barbiroli *et al.* developed a paper infused with lysozyme and lactoferrin, metabolites of antagonistic bacteria. Their tests on the Gram-positive bacterium *Listeria monocytogenes* revealed that the combined antibacterial agents significantly extended the lag period from 1.86 hours to 6.5 hours, whereas lysozyme alone extended it only to 5.81 hours. For Gram-negative bacteria such as *Escherichia coli*, lysozyme alone extended the lag period from 1.08 hours to 1.79 hours, while the paper containing lactoferrin extended it from 1.80 hours to 3.25 hours (Barbiroli *et al.*, 2012). Wang *et al.* found that integrating Nisin, chitosan, and perilla essential oil into a composite film via an open-loop reaction exhibited effective antibacterial activity against *Staphylococcus aureus*, *Escherichia coli*, *Salmonella enterica*, and *Pseudomonas aeruginosa*. Additionally, Nisin enhanced the film's mechanical properties, water vapor barrier properties, and optical attributes (Wang *et al.*, 2021).

### Impregnation method

The dipping method involves submerging a prepared film in a solution containing antagonistic bacteria to aid in future fruit preservation. The soaked film, with bacteria on both surfaces, can effectively contact the antagonistic bacteria with the fruit by wrapping it, thus facilitating bacterial colonization on the fruit's surface. Dawson *et al.*

discovered that soybean film with lauric acid (8%) and nisin (2.5%) significantly reduced the number of *Listeria monocytogenes* in turkey intestines within the first 8 hours, although its bacteriostatic effect was notably lower compared to the film in a liquid medium (Dawson *et al.*, 2002). Xie *et al.* soaked PVCD film in bacteriocin plantaricin BM-1 solution, applied it to *Listeria*-inoculated pork, and observed a distinct bacteriostatic effect. The bacteriostatic zone measured approximately  $16.28 \pm 0.37$  mm, indicating a positive effect on extending pork's cold storage period (Xie *et al.*, 2018).

### Spray method

The spraying method involves evenly applying antagonistic bacteria on the surface of a preservative film, integrating it with the common preservation of agricultural products. Zhang *et al.* combined PE, low-density PE (LDPE), and high-density PE (HDPE) films with the bacteriocin plantaricin BM-1 using the spraying method. They discovered that the inhibitory effect of active films incorporating bacteriocin on *Listeria* at 25°C remained stable for at least 120 days, indicating significant potential for these active preservative films in controlling *Listeria* infection (Zhang *et al.*, 2017.).

The integration of antagonistic bacteria with active films benefits the preservation of agricultural products. However, the preservation methods involving these bacteria and films have drawbacks. For instance, starch and pullulan exhibit excellent physicochemical and mechanical properties as films. Paulraj Kanmani *et al.* developed new edible films based on pullulan and starch by incorporating various probiotic strains. The inclusion of probiotics was found to decrease the viscosity, pH, transparency, and water vapor permeability of the film-forming solution, while the addition of starch reduced the probiotics' activity. Moreover, issues such as poor film stability and inadequate adhesion between the film and antagonistic bacteria cannot be overlooked. To enhance long-term preservation effects, antimicrobial active preservative films can be combined with other preservation methods to counteract the limitations of using these films alone. Kanmani *et al.* have explored the combination of antimicrobial active cling films with controlled atmosphere technology, refrigeration, and high-pressure techniques, demonstrating that such combinations more effectively preserve perishable products (Kanmani *et al.*, 2013).

### Application of Antimicrobial Active Biofilm and Other Technologies in Agricultural Products

Fruits, vegetables, aquatic products, fresh meat, and dairy products are highly perishable. Without proper

preservation, these agricultural products can rot and deteriorate, leading to significant economic losses and posing health risks if consumed unknowingly.

### Application in fruit preservation

According to statistics, China experiences an annual post-harvest fruit loss of approximately 80 million tons, which accounts for about 25%-30% of the total yield (Neegam *et al.*, 2021). In developed countries, the loss rate of fruits and vegetables is controlled to below 5%, while the loss rate in the logistics link is only 1%-2%, highlighting a significant gap. Due to their high moisture and sugar content, fruits are highly susceptible to infection by pathogenic bacteria and damage after harvest. For instance, citrus fruits suffer from postharvest rot primarily caused by *Penicillium digitatum*, *Penicillium italicum*, brown rot, and black rot. Pears are mainly affected by *Penicillium expansum* and *Botrytis cinerea*, while peaches are predominantly infected by *Penicillium expansum*, *Botrytis cinerea*, and *Rhizopus stucoides*. Strawberries, on the other hand, are primarily infected by *Penicillium expansum*, *Botrytis cinerea*, and *Rhizopus stucoides* (Gianfranco *et al.*, 2001). Infection by these pathogens leads to a reduction in hardness, color changes, and decreases in ascorbic acid, titratable acid, reducing sugars, and soluble solids, thereby diminishing the sensory characteristics and commercial value of the fruits.

Active preservative films have been developed as natural, pollution-free alternatives to common waxes. These films extend the shelf life of fruits, enhance their appearance, and reduce water loss. Numerous antagonistic bacteria, particularly antagonistic yeasts, are now employed in fruit disease treatment due to their high inhibitory capabilities, survival rates, rapid colonization, production of volatile organic compounds, and low nutritional requirements. Fan *et al.* tested the addition of *Cryptococcus laurenti* to an alginate coating to extend the shelf life of strawberries. After five days of storage, the mildew rate in the active preservative film group was reduced by 25% compared to the control group. The edible alginate biofilm had no significant impact on the strawberries' external color or anthocyanin content but did significantly decrease decay and weight loss rates, maintain fruit hardness, and improve overall quality and storage performance. The inhibition mechanisms may include: 1) the film sealing the fruit surface, and 2) the antagonistic yeast inhibiting pathogenic bacteria infection. Additionally, plasticizers and hydrophilic compounds can enhance the film's flexibility, plasticity, and hydrophilicity. Glycerol, for example, reduces the film's brittleness, and these additives optimize its performance, prolonging the activity and distribution of microorganisms within the film

(Fan *et al.*, 2009). Ren *et al.* studied the preservation effects of carboxymethyl cellulose and alginate-based coatings, which included Brewer's Yeast, on grapes. After 13 days at room temperature, coatings with  $1.5 \times 10^7 \sim 1.5 \times 10^9$  cfu/mL Brewer's Yeast reduced decay compared to the control. By the 13th day, peroxidase activity in grapes treated with the coating plus yeast increased by 48.4% and 27.5% compared to the control and coating-only treatments, respectively. The yeast-enhanced coating also reduced weight loss, maintained soluble solids content, and elevated the activities of superoxide dismutase, peroxidase, and catalase, which together neutralize free radicals and minimize fruit cell damage. Moreover, this coating protected ascorbic acid from degradation, delaying senescence and preventing fruit damage (Ren *et al.*, 2013). Aloui *et al.* compared abnormal *Wickerhamomyces anomalus* in sodium alginate and locust bean gum base films. The locust bean gum film demonstrated superior flexibility and barrier properties. After 14 days, the yeast population decreased by 0.75 log CFU/cm<sup>2</sup> in the locust bean gum film and by 0.95 log CFU/cm<sup>2</sup> in the alginate film, likely due to nutrient depletion and reduced moisture content. Overall, after 21 days of storage at 25°C, microbial viability did not significantly drop; both types of films retained 85% of the initial yeast population, suggesting that both films could provide nutrients to *Wickerhamomyces anomalus* (Aloui *et al.*, 2015). Parafati *et al.* applied locust bean gum-based coatings, supplemented with strains of *Wickerhamomyces anomalus*, *Metschnikovia pulcherrima*, and *Aureobasidium pullulans*, as biocontrol agents on citrus surfaces. All yeast strains bound to the film reduced the incidence of citrus diseases and significantly improved yeast viability. The antagonistic bacteria enhanced citrus disease resistance by stimulating POD and SOD enzyme production, with SOD activity levels exceeding control values. High concentrations of antagonistic bacteria can boost pathogen inhibition capabilities, and immersion experiments demonstrated that membrane bacteria had increased survival rates, aiding their antibacterial efficacy (Parafati *et al.*, 2016).

The use of antagonistic activity cling film in the preservation of fruits has become widespread, demonstrating significant effectiveness. The primary mechanisms through which this film preserves fruits are hypothesized as follows: the film isolates fruits from direct contact with the external environment, regulates the permeability of carbon dioxide, oxygen, and water vapor, providing a low-oxygen and low-humidity environment. This slows down pathogenic infections, reduces the respiration rate and other biochemical reactions of the fruits, thereby maintaining their quality. The antagonistic bacteria within the film enhance the fruits' disease resistance by inhibiting pathogenic bacteria and competing for nutritional space. This includes increasing the activity of

disease-resistant enzymes and delaying fruit aging. The protein-based membrane may also nourish the antagonistic bacteria, facilitating their growth and rapid colonization. Introducing high concentrations of antagonistic bacteria into the film ensures they dominate the fruit surface, thereby enhancing their pathogen-inhibiting capabilities. The combination with the membrane boosts the survival rate of directly inoculated antagonistic bacteria, aiding in rapid colonization. Additives in the film improve its mechanical properties and contribute to fruit preservation. Optimizing the film's formula further prolongs the activity and distribution of the antagonistic bacteria, enhancing the inhibition rate of pathogens.

The future research direction primarily focuses on exploring the synergistic combination of substances that can enhance the biocontrol efficacy of antagonistic bacteria, along with substances that sustain the probiotic population. Additionally, investigating the integration of antagonistic bioactive cling film with other preservation methods is crucial (Guimaraes *et al.*, 2018). Considering the unique characteristics of different agricultural products, it is also essential to develop film formulations tailored to each specific product type.

### In vegetable preservation

Fresh vegetables are highly fragile and moist, which makes them susceptible to mechanical damage during the picking process. This damage intensifies respiration and metabolic reactions, leading to a series of physiological and biochemical changes such as discoloration, taste alteration, aging, and water loss. The infection of exogenous microorganisms like *Pseudomonas* spp. (Pinto *et al.*, 2015), aerobic thermophilic bacteria, yeast, and gray mold (Mansur *et al.*, 2015) further diminishes their freshness before sale, significantly impacting their commercial value. According to statistics, approximately 35% to 40% of vegetables rot and deteriorate post-harvest annually, resulting in a total loss of 80 million tons and economic losses amounting to 80 billion yuan (Peng *et al.*, 2022). Thus, there is an urgent need to develop efficient and cost-effective vegetable preservation technologies. Antagonistic bacteria preservative film technology is a safe, low-cost, and user-friendly method. It has been increasingly applied in packaging materials and remains a current research focus. Guo *et al.* discovered that a composite membrane made of nisin, gellan gum, and guar gum can inhibit bacterial growth in water chestnut, thereby extending its shelf life. This composite membrane forms a thin film on the surface of the water chestnut, reducing its exposure to external microorganisms (Guo *et al.*, 2020). Song found that combining nisin,  $\epsilon$ -polylysine, and chitosan effectively maintains the quality of fresh-cut carrots, suppresses microbial growth and reproduction, and

Table 1. Application of antimicrobial active biofilm in fruits.

Fruit	Inhibiting pathogen	Antagonistic bacteria	Polymer matrix	Additive	Effect evaluation	Reference
Strawberry	Natural growth	<i>Cryptococcus laurentii</i>	Alginate	Glycerin, palmitic acid, monoglyceride, B-cyclodextrin	The microbial decay rate of strawberry was significantly reduced, the weight loss of strawberry was reduced, the hardness of strawberry was maintained, and the quality and storage performance of strawberry were improved during the whole storage process.	Mansur et al., 2015
Grapes	Untested for pathogens	Brewer Yeast	Carboxymethyl cellulose and alginate	There is no	Reduced weight loss rate, maintained soluble solid content and high activity of superoxide dismutase, peroxidase and catalase.	Jin et al., 2022
orange	<i>Penicillium digitatum</i>	<i>Wickerhamomyces anomalus</i>	Sodium alginate and locust bean gum	Glycerin	There was no significant decrease in microbial activity after 21 days of storage at 25°C.	Guo et al., 2020
Citrus	<i>Penicillium digitatum</i> and <i>Penicillium italicum</i>	<i>Wickerhamomyces anomalus</i> and <i>Metschnikovia pulcherrima</i>	Locust bean gum	There is no	The yeast strains bound to the film all reduced the incidence of citrus, and the film significantly improved the viability of the yeast.	Song et al., 2017
Apple and papaya	Untested for pathogens	<i>Bifidobacterium lactis</i> Bb-12	Alginate and gellan gum	Glycerin, N-acetylcysteine, ascorbic acid, sunflower oil. CaCl <sub>2</sub> as crosslinker	After being stored at 2°C for 10 days, the live bacteria applied to the film on the fruit remained alive and the number was stable.	Nain et al., 2021
Grape	<i>Botrytis cinerea</i>	<i>Candida sake</i> CPA-1	Hydroxypropyl methylcellulose, corn starch, sodium caseinate and pea protein	Oleic acid, Span-80 and Tween 85 are surfactants. Glycerin acts as a plasticizer	The protein membrane showed superior ability of preserving strain activity.	Marin et al., 2016
Grape fruit	Penicilliosis	<i>Cryptococcus laurentii</i>	Chitosan	There is no	Effectively induce and improve the activity of fruit disease resistance and defense enzymes, inhibit penicillium disease, delay the wrinkle of fruit peel, enhance the brightness of fruit peel, reduce the decline rate of fruit soluble solid, ascorbic acid, titrable acid, reducing sugar and other contents, slow down the consumption of internal nutrients in fruit, and maintain the nutritional quality of postharvest grapefruit fruit.	Deng et al., 2021

prolongs shelf life. This is achieved by forming a film on the carrot surface, creating an internal environment of high CO<sub>2</sub> and low O<sub>2</sub>, which enhances enzyme activity and increases the resistance of the fresh-cut carrots (Song et al., 2017). Sami et al. observed that treatment with

2.0 g·L<sup>-1</sup> chitosan, 0.4 g·kg<sup>-1</sup> nisin, and 1.5% acetic acid extends the shelf life of postharvest *Pleurotus eryngii* to 7 days. This may be due to chitosan and nisin reducing polyphenol oxidase activity by slowing the respiratory rate of *Pleurotus eryngii* (Sami et al., 2021).

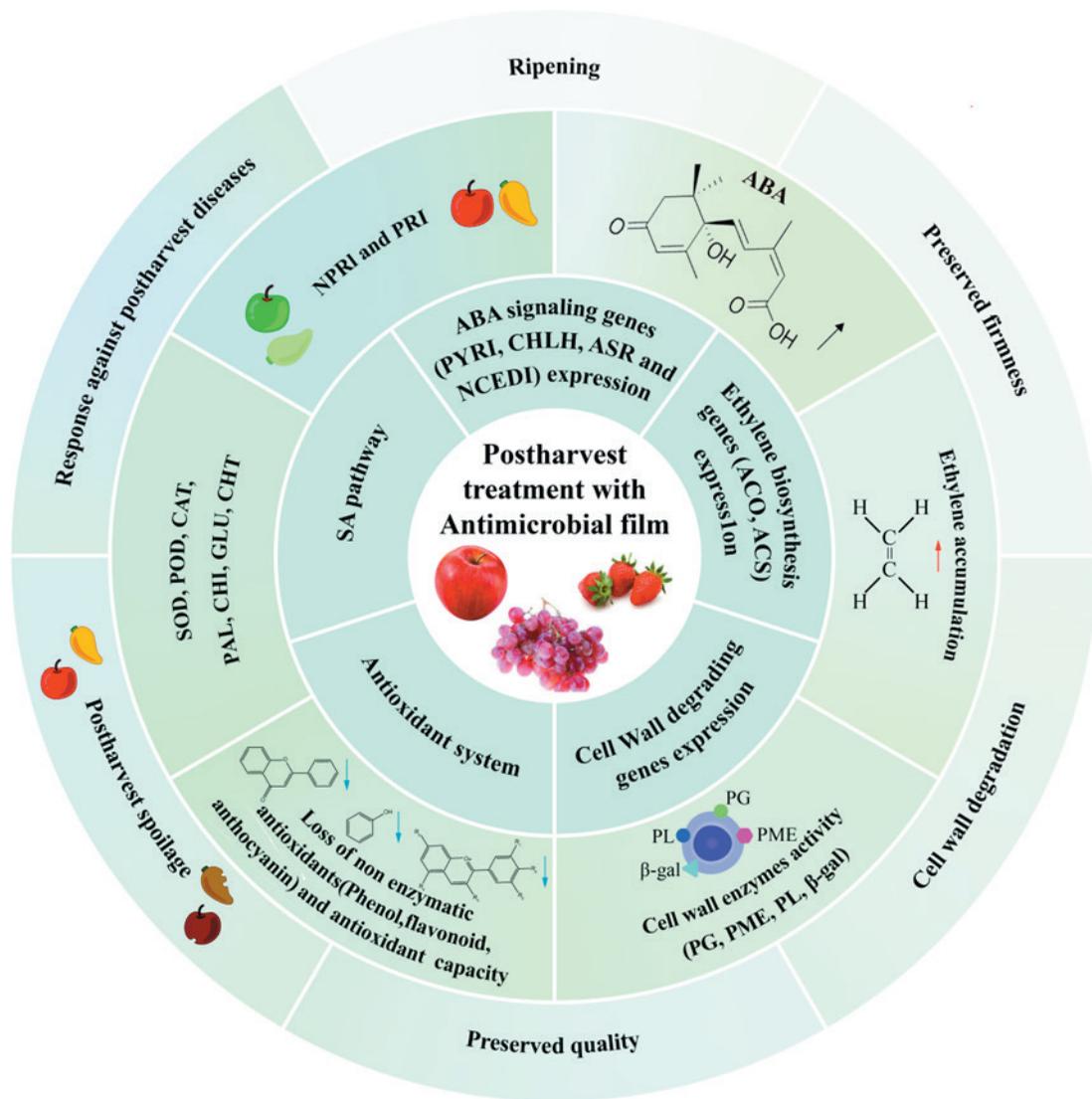


Figure 3. Bacteriostasis mechanism of biological preservative film in fruits.

By examining the application of antagonistic bacterial preservative films in vegetable preservation, we can identify three primary mechanisms through which these films function: Formation of a semi-permeable barrier: These films typically create a semi-permeable layer on the vegetable surface when applied by spraying or soaking, serving as a protective barrier against mechanical damage. Regulation of postharvest physiology: The semi-permeable layer maintains a gas composition of low O<sub>2</sub> and high CO<sub>2</sub> around the vegetables, thereby regulating various physiological and metabolic activities of plant tissues and enhancing postharvest quality. Natural bacteriostatic agents: The films often contain natural bacteriostatic substances, which work synergistically to inhibit the growth and reproduction of microorganisms.

The combination of antagonistic bacteria and film is characterized by safety and health benefits. More

importantly, it can be used as an additive to enhance the functionality of the film. The incorporation of various agricultural preservatives has improved the film's forming characteristics, rendering its antibacterial properties more stable and effective in extending the shelf life of fresh vegetables. Nonetheless, the variety of known film-forming materials remains limited, and certain agricultural preservatives pose safety risks. Therefore, future efforts should focus on discovering new film-forming materials and natural additives to ensure zero health risks and achieve better product efficacy.

#### Application in cold fresh meat preservation

Meat is a food with high nutritional value, but its high protein content makes it susceptible to contamination by *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Proteus*

**Table 2.** Application of antagonistic bacterial biofilm in vegetable preservation.

Breed	Pathogenic bacteria	Antagonistic bacteria or their metabolites	Polymer mechanism	Additive	Effect evaluation	Reference
Water chestnut	<i>Bacillus subtilis</i> <i>E. coli</i> bread yeast	Nisin	Guar gum, Gellan gum	Glycerol	Inhibit the growth of <i>subtilis</i> , <i>Escherichia coli</i> and baker's yeast in water chestnut. Delaying the quality decline of water chestnut during storage increased the good fruit rate and POD activity of water chestnut.	Rajabian <i>et al.</i> , 2019
Fresh-cut carrot	yeast mold Total colony Total <i>E. coli</i> <i>Bacillus pseudomonas</i> <i>Bacillus cereus</i>	<i>Lactistreptococcin</i> , $\epsilon$ -polylysine	Chitosan	Propylene glycol Tween 80	Effectively maintain the nutritional value of fresh-cut carrots; Inhibit the growth and reproduction of microorganisms; Improve the resistance of fresh cut carrot, maintain the sensory value and commercial value of fresh cut carrot and extend the shelf life of fresh cut carrot.	Haralampos <i>et al.</i> , 2010
Pleurotus-eryngii	Not clear	<i>Lactistreptococcin</i>	Chitosan	Acetic acid, ethanol	The shelf life of pleurotus eryngii after harvest was extended to 7 days after treatment with 2.0 g.L-1 chitosan, 0.4g.kg-1 lactostreptococcus and 1.5% acetic acid.	Silva <i>et al.</i> , 2023
Cucumber	Not clear	<i>Lactococcin</i>	Konjac powder, shellac	No one	Inhibit the respiration of cucumber, reduce the water loss rate and decay rate of cucumber, and maintain the Vc content in cucumber.	Wei <i>et al.</i> , 2015
Tomato	Not clear	<i>Lactococcin</i>	Konjac powder, shellac	No one	Inhibit the respiration of tomato, reduce the water loss rate and decay rate of tomato, and maintain the Vc content in tomato.	He <i>et al.</i> , 2016
Tomato	<i>Alternaria</i> <i>Geotrichum candidum</i>	Producing candida epigastric	Chitosan	Tween-80	The germination of <i>alternatispora</i> and <i>Geodetia albospora</i> was significantly inhibited, and the preservation time of tomato was prolonged.	Sharma <i>et al.</i> , 2006

vulgaris, leading to spoilage. The corruption of meat products has caused significant economic losses to agricultural processing enterprises. According to WWF's report, 18 percent of the meat is wasted per person. In China, the decay rate of meat products is as high as 12%, resulting in losses worth hundreds of billions of yuan due to microbial contamination. Therefore, finding effective preservation methods for meat is urgent. Compared to other preservation methods, antagonistic bacterial biofilm technology not only retains moisture and prevents the migration of oxygen and solutes but also effectively reduces juice loss and dehydration. It prevents contact between meat products and spoilage microorganisms,

thereby delaying spoilage. This technology has emerged as a highly promising method for meat preservation (Shi *et al.*, 2025; Adame *et al.*, 2024a; Shi *et al.*, 2024; Adame *et al.*, 2024b; Lin *et al.*, 2024; Cui *et al.*, 2024a; Sji *et al.*, 2024b; Cui *et al.*, 2024b; Ayhan *et al.*, 2019). Currently, numerous studies have explored the application of antagonistic bacterial biofilm technology in meat preservation. For instance, Rajabian *et al.* discovered that a potato starch composite film containing *Lactiplantibacillus plantarum* 7-1 can maintain the quality of chicken and extend its storage period. This may be due to *Lactiplantibacillus plantarum* 7-1 metabolizing and producing lactic acid and bacteriocins, which lower the

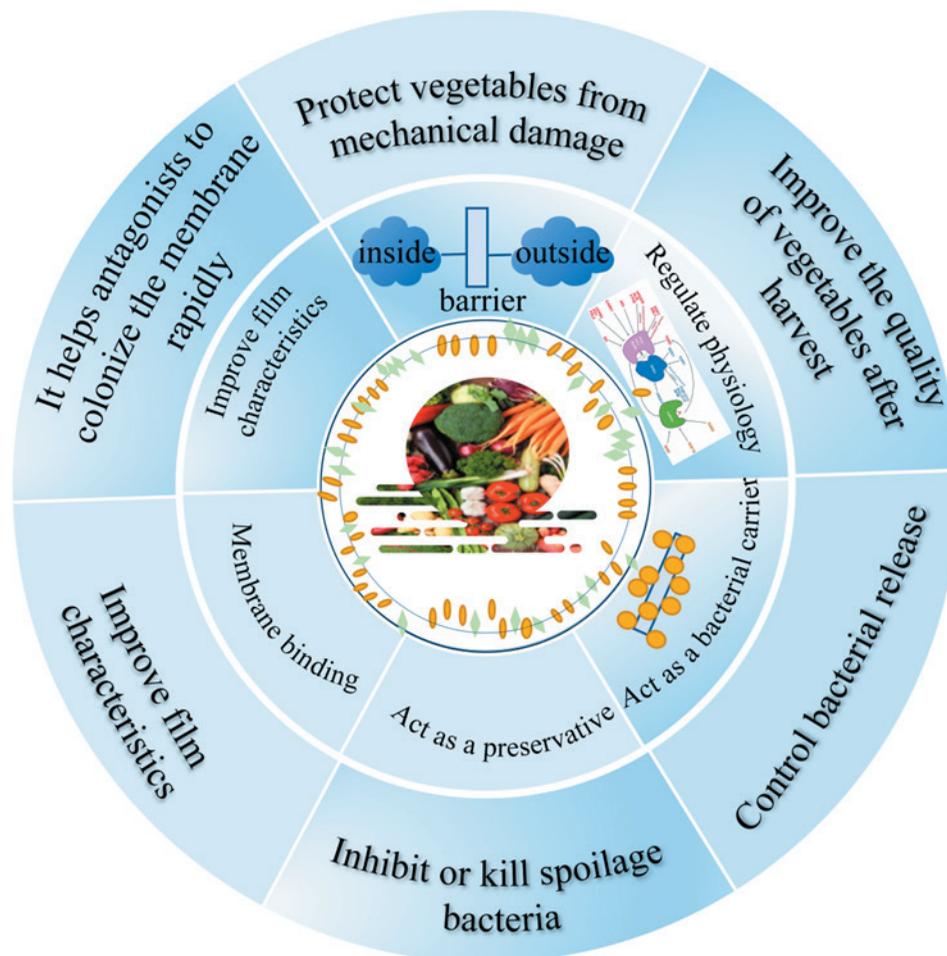


Figure 4. Bacteriostasis mechanism of biological preservative film of antagonistic bacteria in vegetables.

environmental pH, as well as producing hydrogen peroxide, which exerts antioxidant effects and inhibits bacterial growth (Rajabian *et al.*, 2019). Gialamas *et al.* prepared edible films by inoculating *Saccharomyces cerevisiae* into a sodium caseinate solution, demonstrating a significant inhibitory effect on *Listeria monocytogenes* in fresh beef. This is likely because *Saccharomyces cerevisiae* secretes lactic acid and competes for space and nutrients with *Listeria monocytogenes* (Haralampos *et al.*, 2010). Silva *et al.* (2023) found that sodium alginate carboxymethyl cellulose edible films containing *Lactococcus lactis* 23609 can extend the shelf life of beef. This might be attributed to Nisin, a metabolic product of *Lactococcus lactis*, which diffuses to the beef surface to kill microorganisms. Additionally, the film isolates oxygen and inhibits the growth of aerobic (Silva *et al.*, 2023).

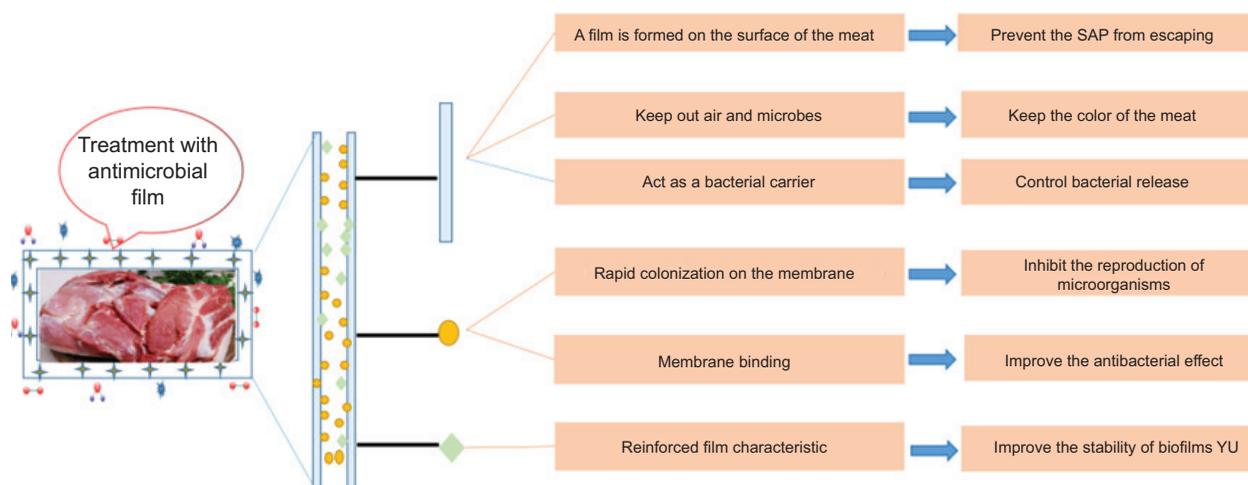
Through the analysis of the aforementioned application examples, we can summarize the preservation mechanisms of antagonistic bacteria biological preservative films as follows: The coating materials partially isolate

oxygen and moisture; the films prevent contamination from external microorganisms on chilled meat; antagonistic bacteria within the films inhibit spoilage bacteria by disrupting the structure, permeability, and integrity of cell membranes, thereby extending the storage period of chilled meat. Additionally, these coating materials exhibit excellent barrier properties. Applying the preservation coating on the surface of chilled meat helps prevent moisture migration caused by external environmental factors and reduces juice loss in the meat.

Meat and meat products are rich in nutrients and play a crucial role in people's daily diet. However, current preservation technologies are often limited, and the overall state of preservation is not encouraging (Sánchez-Ortega *et al.*, 2014). Antagonistic bacteria preservative films offer unique advantages such as natural composition, high efficiency, and environmental friendliness, presenting promising commercial prospects. Currently, the use of single antagonistic bacteria or their metabolites combined with film results in unstable preservation effects. Therefore,

**Table 3. Application of biological preservative film of antagonistic bacteria in meat and meat products.**

Breed	Pathogenic bacteria	Antagonistic bacteria or their metabolites	Polymer mechanism	Additive	Effect evaluation	Reference
Chicken breast	Total colony	<i>Lactiplantibacillus plantarum</i> 7-1	Chitosan and potato starch	Glycerin	Effectively inhibit the growth of bacteria, prevent juice loss, fat oxidation to extend the storage period.	Barbiroli et al., 2017
Fresh beef	<i>Listeria monocytogenes</i>	<i>Lactobacillus schackerii</i>	Sodium caseinate	Sorbitol	It can significantly inhibit the growth of listeria in beef and improve the safety of agricultural products.	Irais et al., 2014
Fresh beef	Total colony	<i>Lactococcus lactis</i> 23609	Sodium alginate – Sodium carboxymethyl cellulose	Glycerin, dry matter	Inhibit the growth of bacteria during beef storage and prolong the shelf life of beef.	Çiçek et al., 2023
Chilled mutton	Total colony	<i>Lactiplantibacillus plantarum</i>	Sodium alginate, gelatin	There is no	Inhibit the growth of bacteria in chilled mutton, delay the spoilage of mutton, reduce the loss of mutton water, and extend the storage time of chilled mutton.	He et al., 2016
Fresh beef	Fungus	<i>Lactobacillus paracei</i> ZX1231 cell-free fermentation supernatant	Acetic acid bacteria nanocellulose	There is no	Effectively inhibit fungal growth and extend the shelf life of agricultural products.	Zheng et al., 2022
Raw meat	Total colony	<i>Lactistreptococcin</i> (nisin)	Pullulan, sodium alginate	Glycerin	Delay the growth of the total number of colonies in fresh meat, effectively extend the shelf life of fresh meat to 16d.	Wei et al., 2023
Sliced beef	<i>Listeria monocytogenes</i>	Bacteriocin sakacin-A	gelatin	Glycerin	After 48 hours of refrigeration, the number of Liszt on beef slices can be reduced by 1.5lg CFU/g.	Barbiroli et al., 2017



**Figure 5. Bacteriostasis mechanism of biological preservative film of antagonistic bacteria in chilled meat.**

future research should focus on developing technologies that combine multiple antagonistic bacteria or integrate them with other natural preservatives.

### Application in preservation of aquatic products

China is a major producer and consumer of aquatic products. In 2021, the country produced 66.9029 million tons of aquatic products, marking a year-on-year increase of 2.16%. In the same year, the global apparent consumption of aquatic animal food was 162.5 million tons. According to a report by the Ministry of Agriculture and Rural Affairs, aquatic products offer a more effective source of protein compared to meat, with additional dietary advantages (Çiçek *et al.*, 2023). Preservation methods for aquatic products primarily include salting and icing. However, due to their high moisture content and rich protein levels, these products are susceptible to oxidation, spoilage, and microbial contamination by pathogens like *Salmonella*, *Listeria*, and *Staphylococcus aureus*. These factors compromise the quality and reduce the commercial value of aquatic products. Statistics reveal that about 30% of aquatic products are wasted due to microbial spoilage, while chemical degradation accounts for an additional 25% of total losses in primary agricultural and fishery products annually, leading to significant economic losses for the country and society (Xie *et al.*, 2024). Research indicates that the loss rate due to spoilage after catching fish can reach 15% in China, compared to less than 5% in developed countries (Jinjin *et al.*, 2023). Thus, developing effective packaging films with active antagonistic bacteria to inhibit oxidation and microbial contamination is crucial.

Lu *et al.* coated northern Chinese black fish fillets with calcium alginate films containing cinnamon oil and Nisin. Compared to the control group, these edible films provided antioxidant and antibacterial protection, significantly preserving the quality of the fish (Lu *et al.*, 2010). De Lacey *et al.* incorporated *Lactobacillus acidophilus* and *Bifidobacterium* into gelatin edible films. The results demonstrated that *Bifidobacterium* significantly inhibited H<sub>2</sub>S-producing microorganisms in cod. Additionally, the combination of edible film, bacteria, and high pressure exhibited a synergistic effect, effectively reducing volatile alkali content and lowering pH by over 1 unit, resulting in notable preservation effects (De Lacey *et al.*, 2012). Shi *et al.* added lysozyme produced by antagonistic bacteria to chitosan to create an antagonistic bacteria film applied to pomfret fish. This treatment effectively slowed the growth of volatile basic nitrogen (TVB-N), trimethylamine (TMA), and thiobarbituric acid (TBA) values, delaying the spoilage of pomfret and extending the shelf life to 12 days compared to 5-6 days under refrigeration alone (Shi *et al.*, 2013).

Hadis *et al.* explored the preparation of Piscidin 1 PG/poly(lactic acid) (Pis-1 PG/PLA) nanofiber membranes via electrospinning to treat sea bass meat. The total colony count in treated fish was reduced by 2.02-3.23 lg(cfu/mL) compared to the control group, effectively inhibiting increases in pH and volatile amino nitrogen content, and extending the cold storage period of sea bass by more than 3 days (Hadis *et al.*, 2020).

Through a review of the literature, the mechanisms behind the antibacterial activity of fresh-keeping films for aquatic products can be summarized as follows:

Antagonistic bacteria can replace and compete for nutrients, as well as produce antibacterial metabolites, which can kill or inhibit the growth of closely related competitor bacteria and pathogenic bacteria in aquatic products. When aquatic products are treated with antagonistic antibacterial film, microbial growth is effectively inhibited, and the production and accumulation of alkaline substances are slowed, stabilizing pH levels and enhancing the preservation of freshness. Additionally, due to the slow-release effect of the film, antagonistic bacteria are continuously released, providing long-term inhibition of microorganisms in fish. The combination of bacterial films also broadens the bacteriostatic range of single organisms, improving bacteriostatic efficacy and extending the shelf life of aquatic products.

To examine its interaction with various packaging methods, such as vacuum packaging, and its retention in different polymers, the goal is to elucidate possible mechanisms of action for additives and optimize the use of antagonists and derived metabolites in aquatic products.

### Application in raw milk preservation

Raw milk is rich in fat, protein, lactose, vitamins, and minerals, making it an ideal dietary food due to its unique nutritional value. However, its high nutritional content not only benefits human health but also serves as an ideal culture medium for the growth of spoilage bacteria and pathogenic microorganisms. Raw milk is highly susceptible to environmental influences, leading to microbial contamination and spoilage. The quality of raw milk is crucial for dairy products, and it typically has a short shelf life. Statistics show that approximately one-quarter of raw milk is lost at the production level or wasted at retail and consumption annually (Martin *et al.*, 2021), second only to meat (Buzby *et al.*, 2014). Therefore, developing new preservation technologies is essential. For instance, adding antagonistic bacteria can extend the shelf life of raw milk without compromising its sensory and quality attributes, thus meeting consumer demands. Jin *et al.* observed the efficacy of

Table 4. Application of antagonistic bacterial biofilm in the preservation of aquatic products.

Aquatic product	Pathogenic bacteria	Antagonistic bacteria	Polymer mechanism	Additive	Effect evaluation	Reference
Snakehead	<i>Listeria</i> , etc	<i>Lactistreptococcin</i> (nisin)	Calcium alginate, cinnamon	Calcium chloride	To better preserve the quality of blackfish, edible film containing cinnamon oil and Nisin provides antioxidant and antibacterial coating for blackfish filets.	Baek et al., 2018
Codfish	<i>Bacillus</i> , <i>Salmonella</i> , <i>Lactobacillus rhamnosus</i>	<i>Lactobacillus acidophilus</i> and <i>Bifidobacterium</i>	Gelatin	Glucose, cysteine, sorbitol and glycerol	Inhibit the growth of microorganisms and reduce the content of volatile alkali.	Gao et al., 2022
Oyster	Aerobic bacteria, <i>E. coli</i>	<i>Lactistreptococcin</i> (nisin) NK24	Polythene (LDPE)	Ethanol, propyl alcohol	The shelf life is extended from 5 days to 12 days.	Kim et al., 2002
Pomfret	<i>Listeria</i> , etc	Lysozyme	Chitosan, tea polyphenols	Acetic acid	Effectively reduce volatile basic nitrogen (TVB-N) content, trimethylamine (TMA) content, The increase rate of thiobarbituric acid (TBA) value delayed the rot of pomfret blocks, and the shelf life was extended to 12 days compared with 5 ~ 6 days under single refrigeration condition.	Zhang et al., 2021
Sea perch	<i>Shewanella putrefaciens</i>	Antimicrobial peptide Pliscidin 1 PG	Poly(lactic acid electrospinning nanofibers	N, n-dimethylformamide, dichloromethane	Continuously inhibited <i>Shewanella putrefaciens</i> within 6 h, effectively inhibited the increase of pH value and volatile base nitrogen content of fish, and extended the cold storage period of sea bass for more than 3 days.	Anumudu et al., 2021
Grouper	Coliform, aeromonas, pseudomonas	<i>Lactobacillin</i>	Chitosan - poly(lactic acid	Ethylenediamine tetraacetic acid	The levels of spoilage bacteria ( <i>Coliform</i> , aeromonas, pseudomonas) and volatile basic nitrogen were significantly reduced.	Chang et al., 2021
Salmon	Gram-positive and Gram-negative bacteria	<i>Lactistreptococcin</i> (nisin)	Chitosan, carvacrol	Sodium hydroxide and sodium chloride	Both gram-positive and Gram-negative bacteria showed obvious inhibition, and the volatile base nitrogen content, pH value and water loss rate all increased slowly, which extended the shelf life of salmon fillet.	Yuan et al., 2022

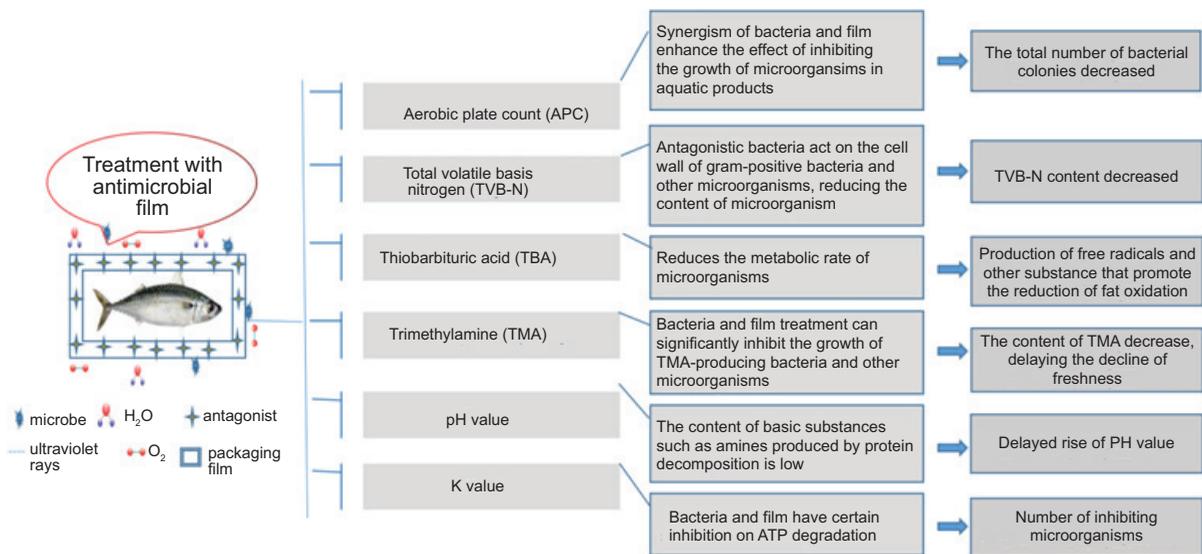


Figure 6. Bacteriostasis mechanism of antagonistic bacteria biological preservative film in aquatic products.

a mixture coating in inactivating *Listeria monocytogenes* when skim milk inoculated with *Listeria monocytogenes* Scott A was stored in glass jars coated with a mixture of polylactic acid (PLA) polymer and nisin. They found that PLA and nisin coating treatments effectively inactivated *Listeria monocytogenes* cells in these foods at both 4°C and 10°C (Jin, 2010). Cui *et al.* used a coating film of nisin and sodium lactate to study milk preservation. After five days of low-temperature storage, the inhibitory effect of PE film without coating, coating film only containing carrier (chitosan), coating film containing sodium lactate, coating film containing nisin, and coating film containing nisin and sodium lactate on microorganisms in milk increased sequentially (Cui *et al.*, 2017). Kim *et al.* studied the migration differences of nisin in various coating films. When nisin was infiltrated into a vinyl acetate-ethylene copolymer coating film, the migration speed was higher and faster, showing significant inhibition of microbial growth in milk (Kim *et al.*, 2002). Lee *et al.* prepared antimicrobial paperboard by co-coating nisin and chitosan, providing a broad antimicrobial spectrum that effectively inhibited Gram-positive bacteria and *Listeria monocytogenes*, thus improving the microbial stability of milk at 10°C (Lee *et al.*, 2003). Wan *et al.* advocated for the use of an alginate and nisin complex membrane to preserve skim milk. This combination, which integrates alginate with nisin at a rate of 87%-93%, maintains 100% activity against *Lactobacillus curvatus* in skim milk (Wan *et al.*, 1997).

The primary mechanisms of the antibacterial active fresh-keeping film for raw milk preservation include: (1) The compound film prevents nutrients from reaching bacteria, disrupting their normal metabolic activities, thereby inhibiting microbial growth and the

decomposition of proteins and fats in raw milk; (2) The film increases the water activity of raw milk, slightly alters the protein structure, reduces fat oxidation, and preserves the flavor and texture of raw milk; (3) It inhibits lactic acid bacteria and other contaminants, resulting in lower lactic acid production and slower pH changes; (4) The compound film serves as a barrier to isolate air, delaying the dehydration and oxidation of raw milk; (5) The combined packaging effectively inhibits protein degradation, reduces oil precipitation, and extends the shelf life of raw milk.

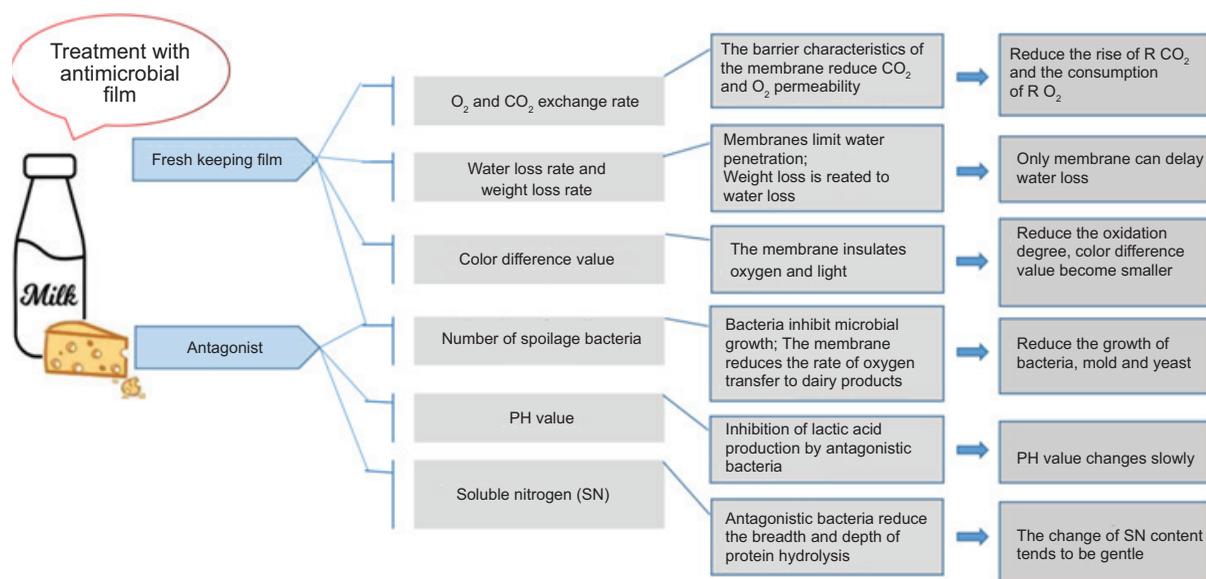
The composition of raw milk is both complex and nutritious, with variations in milk sources, processing methods, and production equipment across different products. Consequently, it is challenging to uniformly apply a single antibacterial approach. Therefore, multiple preservation technologies must be explored to achieve synergistic effects that inhibit the growth of harmful microorganisms in raw milk. Further investigation into the metabolic pathways of antagonistic bacteria at the molecular level can lay a solid foundation for practical applications (Wu *et al.*, 2024; Liu *et al.*, 2023a; Liu *et al.*, 2023b)

## Conclusion and Future Perspective

Although significant progress has been made in the research, development, and application of antagonistic bacteria biological preservative films, their commercial production remains limited, particularly in agricultural applications, where they are still largely experimental. The understanding of the bacteriostatic mechanisms of these films is still at a fundamental theoretical stage, with insufficient research at the molecular level. Additionally, films

**Table 5. Application of antagonistic bacteria biological preservative film in dairy preservation.**

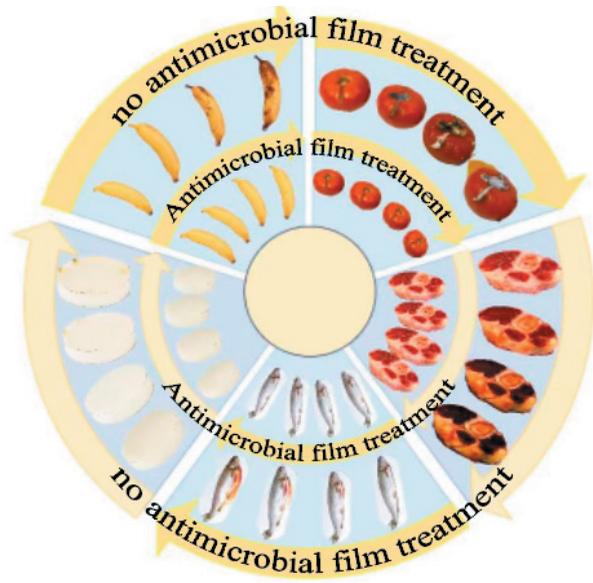
Raw milk	Pathogenic bacteria	Antagonistic bacteria	Polymer matrix	Additive	Effect evaluation	Reference
Milk	Aerobic bacteria, yeast Cryogenic bacteria	Nisin	Polyethylene film	Sodium lactate, glycerin, Coomassie brilliant Blue G-250, etc	The combination of Nisin and sodium lactate has the strongest antibacterial effect, inhibiting the growth of bacteria in milk stored at low temperature.	Gharsallaoui et al., 2016
Milk	Listeria monocytogenes Scott A, Aerobic bacteria, saccharomyces	Nisin	Polylactic acid (PLA) polymer	Dichloromethane	The coating film treatment was effective in inactivating <i>Lactobacillus</i> cells in these foods at both 4°C and 10°C.	Zahidova et al., 2023
Milk	Aerobic bacteria, yeast Cryogenic bacteria	Nisin	Vinyl acetate- vinyl copolymer	There is no	The growth of microorganism in milk was inhibited obviously.	Nagai et al., 2017
Milk	Aerobic bacteria, yeast Cryogenic bacteria	Nisin	Ethylene- vinyl acetate copolymer paperboard	Ethylene, ethanol, etc	Effectively inhibit gram-positive bacteria and listeria monocytogenes and improve the microbial stability of milk at 10°C.	King et al., 1993
Skimmed milk	Staphylococcus aureus, E. coli, etc	Nisin	Alginate	Calcium chloride	Alginate binds to nisin with a binding rate of 87% to 93% and has 100% activity against <i>Lactobacillus campylobacter</i> indicator cultures in skim milk.	Wan et al., 1997



**Figure 7. Bacteriostasis mechanism of antagonistic bacteria biological preservative film in dairy products.**

created by simply combining antagonistic bacteria with film-forming materials have certain shortcomings. These include unstable coating effects, susceptibility to environmental factors, extended drying times, and a higher risk of microbial contamination, all of which hinder the industrial production of such preservation methods. Therefore, future development should focus on creating

compound antagonistic bacteria preservative films with enriched components and incorporating natural additives that enhance film-forming characteristics. This approach would facilitate the commercialization of these films for agricultural products, significantly contributing to the rapid and healthy development of the agricultural industry and rural revitalization.



**Figure 8.** Treatment changes of antibiofilm in perishable agricultural products.

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## Authors Contributions

All authors contributed equally to this article.

## Conflicts of Interest

The authors declare no conflict of Interest.

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## References

Adame MY, Shi C, Li C, Aziz T, Alharbi M, Cui H, Lin L. (2024). Fabrication and characterization of pullulan/tapioca starch-based antibacterial films incorporated with *Litsea cubeba*

essential oil for meat preservation. *Int J Biol Macromol.* 296:139799. <https://doi.org/10.1016/j.ijbiomac.2025.139799>.

Adame MY, Wang Y, Shi C, Aziz T, Al-Asmari F, Sameeh MY, Cui H, Lin L. (2024). Fortification of pullulan/cassava starch-based edible films incorporated with LC-EO nanoparticles and the application for beef meat preservation. *Int J Biol Macromol.* 279(Pt 4):135629.

Ahmad, R.M., Deog-Hwan, O. (2015). Combined effects of thermo-sonication and slightly acidic electrolyzed water on the microbial quality and shelf life extension of fresh-cut kale during refrigeration storage. *Food Micro.* 51(2015): 154–162. <https://doi.org/10.1016/j.fm.2015.05.008>.

Ahmed, E.G., Joseph, L.S., Charles, L.W. (2000). Enhancement of the performance of *Candida saitoana* by the addition of glycol-chitosan for the control of postharvest decay of apple and citrus fruit. *Postharvest Bio and Tech.* 19(1): 103–110. <https://doi.org/10.1016/j.biocontrol.2010.05.003>.

Alberto, B., Francesco, B., Giorgio, C., Stefania, I., Matilde, M., Luciano, P., & Manuela, R. (2012). Antimicrobial activity of lysozyme and lactoferrin incorporated in cellulose-based food packaging. *Food Cont.* 26(2): 387–392. <https://doi.org/10.1016/j.foodcont.2012.01.046>

Ana, G., Luís, A., Lorenzo, M. P., & Miguel, A. C. (2018). Edible films and coatings as carriers of living microorganisms: A new strategy towards biopreservation and healthier foods. *Comp. Rev. Food Sci. and Food Saf.* 17: 594–614. <https://doi.org/10.1111/1541-4337.12345>

Anumudu, C., Hart, A., Miri, T., & Onyeaka, H. (2021). Recent advances in the application of the antimicrobial peptide nisin in the inactivation of spore-forming bacteria in foods. *Molecules.* 26(18): 5552. <https://doi.org/10.3390/molecules26185552>

Ayhan, D., & Halil, I. K. (2019). The effect of chitosan coating and vacuum packaging on the microbiological and chemical properties of beef. *Meat Sci.* 162: 107961. <https://doi.org/10.1016/j.meatsci.2019.107961>

Aziz, T., Li, Z., Naseeb, J., Sarwar, A., Zhao, L., Lin, L., & Al Asmari, F. (2024). Role of bacterial exopolysaccharides in edible films for food safety and sustainability. *Current trends and future perspectives.* *Italian J Food Sci.* 36(4): 169–179. <https://doi.org/10.15586/ijfs.v36i4.2690>

Aziz, T., Shah, Z., Sarwar, A., Ullah N, Khan AA, Sameeh MY, Cui H, Lin L. (2023). Production of bioethanol from pretreated rice straw, an integrated and mediated upstream fermentation process. *Biomass Conv. Bioref.* 2023:1–12.

Bae, S. K., Kim, S., & Shin, K. B. (2018). Characterization of *Ecklonia cava* alginate films containing cinnamon essential oils. *Inter. J Molecular Sci.* 19(11): 3545. <https://doi.org/10.3390/ijms19113545>.

Barbiroli, A., Musatti, A., Capretti, G., Iametti, S., & Rollini, M. (2017). Sakacin-A antimicrobial packaging for decreasing *Listeria* contamination in thin-cut meat: Preliminary assessment. *J Sci. Food and Agri.* 97(3): 1042–1047. <https://doi.org/10.1002/jsfa.8120>

Benjamín, R. H., & Antje, L. (2024). Flexible PLA copolymers with low melt flow index for blown film applications. *Chemie Ingenieur Technik.* 96(5): 586–597. <https://doi.org/10.1002/CITE.202300150>

- Bhaskaran, R., Ramachandra, K. S. S., Peter, R., Gopakumar, S. T., Gopalan, M. K., & Mozhikulangara, R. R. (2023). Antimicrobial resistance and antagonistic features of bivalve-associated *Vibrio parahaemolyticus* from the south-west coast of India. *Enviro. Sci. Pollu. Res. Inter.* 30(49): 107681–107692. <https://doi.org/10.1007/s11356-023-29924-5>
- Buzby, J.C., Farah-Wells, H., Hyman, J. (2014). The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States. *USDA-ERS Economic Information Bulletin.*
- Calderón, C. E., Rotem, N., Raviv, H., David, V. C., & Maggie, L. (2019). *Pseudozyma aphidis* activates reactive oxygen species production, programmed cell death and morphological alterations in the necrotrophic fungus. *Botrytis cinerea*. *Molecular Plant Patho.* 20(4): 562–574. <https://doi.org/10.1111/mpp.12775>
- ChanHo, L., DuckSoon, A., HyunJin, P., & DongSun, L. (2003). Wide spectrum antimicrobial packaging materials incorporating nisin and chitosan in the coating. *Pack. Techno. Sci.* 16(3): 99–106. <https://doi.org/10.1002/pts.617>
- Chao, G., Xueying, L., Jinlian, M., Haina, B., Hedong, B., Guohuan, H. (2023). High strength, controlled release of curcumin-loaded ZIF-8/chitosan/zein film with excellence gas barrier and antibacterial activity for litchi preservation. *Carbo. Poly.* 306(2023): 120612–120612. <https://doi.org/10.1016/j.CARBPOL.2023.120612>
- Charles, L.W., Michael, E.W., Charles, L.B., Randy, M., Edo, C., Samir, D. (1992). *Wisniewski Biological Control of Postharvest Diseases of Fruits and Vegetables: Recent Advances.* *HortSci.* 27(2): 94–98. [https://doi.org/10.1016/0261-2194\(91\)90039-T](https://doi.org/10.1016/0261-2194(91)90039-T)
- Cheng, S.-H., Chen, Y.-J., Tsai, H.-J., Hsu, H.-I., Chen, H.-J., Su, K.-C., Peng, C.-L., & Tsai, G.-J. (2021). Applications of nisin and EDTA in food packaging for improving fabricated chitosan-poly lactate plastic film performance and fish fillet preservation. *Membranes.* 11(11): 852. <https://doi.org/10.3390/membranes11110852>
- Christos, S., Poonam, S., William, M., Christopher, P., Ian, D.F. (2016). Compositional and physicochemical factors governing the viability of *Lactobacillus rhamnosus* GG embedded in starch-protein based edible films. *Food Hydrocolloids.* 52: 876–887. <https://doi.org/10.1016/j.foodhyd.2015.08.025>
- Çiçek, S., Özoğul, F. (2023). Nanotechnology-based preservation approaches for aquatic food products: A review with the current knowledge. *Crit. Rev. Food Sci and Nutr.* 63(19): 3255–3278. <https://doi.org/10.1080/10408398.2022.2096563>
- Cui H, Chen Y, Aziz T, Al-Asmari F, Alwethayanu MS, Shi C, Lin L. (2024b). Antibacterial mechanisms of diacetyl on *Listeria monocytogenes* and its application in Inner Mongolian cheese preservation via gelatin-based edible films. *Food Cont.* 168: 110920, <https://doi.org/10.1016/j.foodcont.2024.110920>
- Cui H, Gao J, Khin MN, Aziz T, Al-Asmari F, Alamri AS, Alhomrani M, Lin L. (2024). Preparation and application of pH-sensitive protein nanofibre membrane loaded with Alizarin and Curcumin for meat preservation. *Pack. Tech. and Sci.* 2024: 794–807. <https://doi.org/10.1002/pts.2823>
- Dawson, P.L., Carl, G.D., Acton, J.C., Han, I.Y. (2002). Effect of lactic acid and nisin-impregnated soy-based films on the growth of *Listeria monocytogenes* on turkey bologna. *Poultry Sci.* 81(5): 721–726. <https://doi.org/10.1093/ps/81.5.721>
- Diana, C. V., Carmen, L. G., Nicholas, D. C., Daniel, G. E., & Eric, S. M. (2017). Emerging biorecognition and transduction schemes for rapid detection of pathogenic bacteria in food. *Comp. Rev. Food Sci. and Food Safety.* 16(6): 1188–1205. <https://doi.org/10.1111/1541-4337.12294>
- Dianpeng, Z., Davide, S., Angelo, G., & Maria, L. G. (2010). Efficacy of the antagonist *Aureobasidium pullulans* PL5 against post-harvest pathogens of peach, apple and plum and its modes of action. *Bio. Con.* 54(3): 172–180. <https://doi.org/10.1016/j.biocontrol.2010.05.003>
- Dongdong, Y., Xu, H., Guorong, L., Ying, Y., & Jiaojiao, D. (2022). A novel composite edible film fabricated by incorporating W/O/W emulsion into a chitosan film to improve the protection of fresh fish meat. *Food Chem.* 385: 132647. <https://doi.org/10.1016/J.FOODCHEM.2022.132647>
- Du, Y., Tian, Q., Li, G., Yi, J., Hu, X., Jiang, Y. (2024). Advanced application of slightly acidic electrolyzed water for fresh-cut fruits and vegetables preservation. *Food Res. Inter.* 195: 114996. <https://doi.org/10.1016/j.foodres.2024.114996>
- Erlantz, L., Elena, F., Franco, D., José, L. V., Luis, M. L., Ilaria, A., Luigi, T., & José, M. K. (2016). PLLA grafted cellulose nanocrystals: Role of the CNC content and grafting on the PLA bionanocomposite film properties. *Carbohydrate Polymers.* 142: 105–113. <https://doi.org/10.1016/j.carbpol.2016.01.041>
- Fei, L., Yuting, D., Xingqian, Y., & Donghong, L. (2010). Cinnamon and nisin in alginate–calcium coating maintain quality of fresh northern snakehead fish fillets. *LWT - Food Sci. and Tech.* 43(9): 1331–1335. <https://doi.org/10.1016/j.lwt.2010.05.003>
- Feng, S., Yanwei, W., Yongfu, L., & Xiaoyuan, W. (2016). Mode of action of leucocin K7 produced by *Leuconostoc mesenteroides* K7 against *Listeria monocytogenes* and its potential in milk preservation. *Bio. Letters.* 38(9): 1551–1557. <https://doi.org/10.1007/s10529-016-2127-y>
- Flavia, V. E., & Matías, A. M. (2021). *Trichoderma* as biological control agent: scope and prospects to improve efficacy. *World J Micro. and Bio.* 37(5): 90. <https://doi.org/10.1007/s11274-021-03058-7>
- Gharsallaoui, A., Oulahal, N., Joly, C., & Degraeve, P. (2016). Nisin as a food preservative: Part 1: Physicochemical properties, antimicrobial activity, and main uses. *Critical Rev. Food Sci. Nut.* 56(8): 1262–1274. <https://doi.org/10.1080/10408398.2013.763765>
- Gianfranco, R., Franco, N., Antonio, I., & Mario, S. (2001). Effect of short hypobaric treatments on postharvest rots of sweet cherries, strawberries and table grapes. *Postharvest Bio. and Tech.* 22(1): 1–6. [https://doi.org/10.1016/S0925-5214\(00\)00188-5](https://doi.org/10.1016/S0925-5214(00)00188-5)
- Giovanni, A. (1996). Mode of action of an isolate of *Candida famata* in biological control of *Penicillium digitatum*
- González, T. R., Álvarez, B. M., González, A. N., Escalante, G. R., Cordero, R. G., & Hernández, L. G. (2019). Enhanced biocontrol of fruit rot on muskmelon by combination treatment with marine *Debaryomyces hansenii* and *Stenotrophomonas rhizophila* and their potential modes of action. *Postharvest Bio. and Tech.* 61–67. <https://doi.org/10.1016/j.postharvbio.2019.01.013>

- Guo, X., Chen, K., Chen, L., Le, T. N., Zhao, M., Cai, H. (2025). Effects of Cold Post-Fermentation Process on Microbial Diversity and Biogenic Amines in Protease-Assisted Fermented sufu. *Foods*. 14(5): 735. <https://doi.org/10.3390/foods14050735>
- Hadis, R., Elham, A., Hoda, S. T., Seid, R. F., & Seid, M. J. (2020). Electrospinning approach for nanoencapsulation of bioactive compounds; recent advances and innovations. *Trends in Food Sci. and Tech.* 100: 190–209. <https://doi.org/10.1016/j.tifs.2020.04.012>
- Haitam, L., Samir, A., Rachid, L., & Abdessalem, T. (2024). Lactic acid bacteria as an eco-friendly approach in plant production: Current state and prospects. *Folia Microbiologica (Praha)*. 69(3): 465–489. <https://doi.org/10.1007/s12223-024-01146-3>
- Haiyan, W., Sha-lei, Z., Chi To, N., & Cheng, T. C. E. (2019). Coordinating quality, time, and carbon emissions in perishable food production: A new technology integrating GERT and the Bayesian approach. *Inter. J. Prod. Eco.* 225: 107570. <https://doi.org/10.1016/j.ijpe.2019.107570>
- Haiying, C., Juan, W., Changzhu, L., & Lin, L. (2017). Improving anti-listeria activity of cheese packaging via nanofiber containing nisin-loaded nanoparticles. *LWT – Food Sci. and Tech.* 81: 233–242. <https://doi.org/10.1016/j.lwt.2017.04.003>
- Hajer, A., Fabio, L., Khaoula, K., Moktar, H., & Cristina, R. (2015). Physical properties and antifungal activity of bioactive films containing *Wickerhamomyces anomalus* killer yeast and their application for preservation of oranges and control of postharvest green mold caused by *Penicillium digitatum*. *Inter. J. Food Micro.* 200: 22–30. <https://doi.org/10.1016/j.ijfoodmicro.2015.01.015>
- Haralampos, G., Kyriaki, G. Z., Costas, G. B., & Konstantinos, P. K. (2010). Development of a novel bioactive packaging based on the incorporation of *Lactobacillus sakei* into sodium-caseinate films for controlling *Listeria monocytogenes* in foods. *Food Res. Inter.* 43(10): 2402–2408. <https://doi.org/10.1016/j.foodres.2010.09.020>
- Hongsu, W., Ling, G., Lu, L., Baoqing, H., & Xiaodi, N. (2021). Composite chitosan films prepared using nisin and *Perilla frutescens* essential oil and their use to extend strawberry shelf life. *Food Biosci.* 41: 101037. <https://doi.org/10.1016/j.FBIO.2021.101037>
- Huang, L., Zhang, X., Wu, Y., Liu, S., Shao, C., & Xie, Y. (2019). Inhibition of tomato early blight disease by culture extracts of a *Streptomyces puniceus* isolate from mangrove soil. *Phytopathology*. 109(7): 1149–1156. <https://doi.org/10.1094/PHYTO-12-18-0444-R>
- Huijuan, G., Xin, L., Xi Tian, C., Deng, H., Chuang, W., Lei, Z., & Peifeng, L. (2022). The functional roles of *Lactobacillus acidophilus* in different physiological and pathological processes. *J Micro. and Biotech.* 32(10): 1–8. <https://doi.org/10.4014/jmb.2205.05041>
- HwanHee, Y., YoungWook, C., & HyunDong, P. (2021). Application of natural preservatives for meat and meat products against food-borne pathogens and spoilage bacteria: A review. *Foods*. 10(10): 2418. <https://doi.org/10.3390/foods10102418>
- Jain, P.K., & Jain, P.C. (2007). Isolation, characterization and antifungal activity of *Streptomyces sampsonii* GS 1322. *Indian J Exp. Bio.* 45(2): 203–206.
- Javanmardi, F., Rahmani, J., Ghiasi, F., Hashemi, G. H., & Mousavi, K. A. (2019). The association between the preservative agents in foods and the risk of breast cancer. *Nutrition and Cancer*. 71(8): 1229–1240. <https://doi.org/10.1080/01635581.2019.1608266>
- Jia, D., Li, W., Ma, D., Liu, Y., Yang, H., Li, J., Sun, G., Nithesh, N., Gao, Z., & Wu, F. (2021). Synergistic effect of carboxymethylcellulose and *Cryptococcus laurentii* on suppressing green mould of postharvest grapefruit and its mechanism. *Inter. J Bio. Macromolecules*. 181: 253–262. <https://doi.org/10.1016/J.IJBIOMAC.2021.03.155>
- Jijakli, M. H., & Lepoivre, P. (1998). Characterization of an exo-beta-1,3-glucanase produced by *Pichia anomala* strain K, antagonist of *Botrytis cinerea* on apples. *Phytopathology*. 88(4): 335–343. <https://doi.org/10.1094/PHYTO.1998.88.4.335>
- Jinjin, H., Min, Z., Mujumdar, A. S., & Yamei, M. (2023). Technological innovations enhance postharvest fresh food resilience from a supply chain perspective. *Critical Rev. Food Sci. and Nutr.* 21–23. <https://doi.org/10.1080/10408398.2023.2232464>
- Khaleque, M. A., Keya, C. A., Hasan, K. N., Hoque, M. M., Inatsu, Y., & Bari, M. L. (2016). Use of cloves and cinnamon essential oil to inactivate *Listeria monocytogenes* in ground beef at freezing and refrigeration temperatures. *LWT - Food Sci. and Tech.* 74: 219–223. <https://doi.org/10.1016/j.lwt.2016.07.042>
- Khan, J., Khurshid, S., Sarwar, A., Aziz, T., Naveed, M., Ali, U., Makhdoom, S. I., Nadeem, A. A., Khan, A. A., Sameeh, M. Y., Alharbi, A. A., Filimban, F. Z., Rusu, A. V., Göksen, G., & Trif, M. (2022). Enhancing Bread Quality and Shelf Life via Glucose Oxidase Immobilized on Zinc Oxide Nanoparticles—A Sustainable Approach towards Food Safety. *Sustainability*. 14(21): 14255. <https://doi.org/10.3390/su142114255>
- King, A., Bethune, L., & Phillips, I. (1993). In vitro activity of MDL 62,879 (GE2270 A) against aerobic gram-positive and anaerobic bacteria. *Antimicrobial Agents and Chemotherapy*. 37(4): 746–749. <https://doi.org/10.1128/AAC.37.4.746>
- Koutsoumanis, K., Tsaloumi, S., Aspidou, Z., Tassou, C., & Gougouli, M. (2021). Application of quantitative microbiological risk assessment (QMRA) to food spoilage: Principles and methodology. *Trends in Food Sci. & Tech.* 114: 2. <https://doi.org/10.1016/j.tifs.2021.05.011>
- Lee, N.-K., Bae, S. J., Do, S. N., Yu, H. H., Kim, J.-S., & Park, H.-D. (2016). The impact of antimicrobial effect of chestnut inner shell extracts against *Campylobacter jejuni* in chicken meat. *LWT - Food Sci. & Tech.* 65: 746–750. <https://doi.org/10.1016/j.lwt.2015.09.004S>
- Li, H., Zou, L., Yuan, Q., Xiao, J., Kang, Z., Zhang, Y., Hu, X., Peng, B., He, B., Dai, W., & Liu, S. (2016). Antimicrobial activities of nisin, tea polyphenols, and chitosan and their combinations in chilled mutton. *J of Food Sci.* 81(6): M1466–M1471. <https://doi.org/10.1111/1750-3841.13312>
- Li, Q., Lan, C., Li, P., Zhang, H., Zhang, X., Zhang, X., Yan, Q., Alexander, M. T., & Sun, Y. (2017). The biocontrol effect of *Sporidiobolus pararoseus* Y16 against postharvest diseases in table grapes caused by *Aspergillus niger* and the possible mechanisms involved. *Bio. Cont.* 113: 18–25. <https://doi.org/10.1016/j.biocontrol.2017.06.009>

- Lin Lin, Xu Liu, Ce Shi, Xiaochen Chen, Tariq Aziz, Fahad Al-Asmari, Amal A. (2024). Mohamed, Haiying Cui. (2024). Preparation and Characterization of Chitosan- Polysaccharide Edible Films for Meat Preservation. *Pack. Tech. and Sci.* 38(3): 211–226. <https://doi.org/10.1002/pts.2865>
- Liu S, Jiang X, Fu F, Aziz T, Li G, Zhao J, Shah S, Xiao G, Gong J, He G. (2023a). Assessing the effect of powder characteristics of infant milk to the compressibility of milk powder compression molding. *Food Sci Nutr.* 11: 4625–4633. <https://doi.org/10.1002/fsn3.3425>
- Liu S, Lei T, Li G, Liu S, Chu X, Hao D, Xiao G, Khan AA, Haq TU, Sameeh MY, Aziz T, Tashkandi M, He G. (2023b). Rapid detection of micronutrient components in infant formula milk powder using near-infrared spectroscopy. *Front Nutr.* 10: 1273374. <https://doi.org/10.3389/fnut.2023.1273374>
- López de Lacey, A. M., López-Caballero, M. E., Gómez-Estaca, J., Gómez-Guillén, M. C., & Montero, P. (2012). Functionality of *Lactobacillus acidophilus* and *Bifidobacterium bifidum* incorporated into edible coatings and films. *Innovative Food Sci. & Emer. Tech.* 16: 277–282. <https://doi.org/10.1016/j.ifset.2012.07.001>
- Madhaiyan, M., Poonguzhali, S., Kim, S. W., & Song, T. M. (2010). *Bacillus methylothrophicus* sp. nov., a methanol-utilizing, plant-growth-promoting bacterium isolated from rice rhizosphere soil. *Inter. J. of Sys. and Evolutionary Microbio.* 60(Pt 10): 2490–2495. <https://doi.org/10.1099/ijs.0.015487-0>
- Mannai, S., & Boughalleb, M. N. (2023). Evaluation of *Trichoderma harzianum*, *Bacillus subtilis*, and *Aspergillus* species efficacy in controlling *Pythium ultimum* associated with apple seedlings decline in nurseries and their growth promotion effect. *Egyptian J. of Bio. Pest Cont.* 33(1). <https://doi.org/10.1186/S41938-023-00705-Z>
- Mannan, H. A., Mukhtar, H., Murugesan, T., Nasir, R., Mohshim, D. F., & Mushtaq, A. (2013). Recent applications of polymer blends in gas separation membranes. *Chemical Engineering & Tech.* 36(11): 1838–1846. <https://doi.org/10.1002/ceat.201300342>
- Marín, A., Cháfer, M., Atarés, L., Chiralt, A., Torres, R., Usall, J., & Teixidó, N. (2016). Effect of different coating-forming agents on the efficacy of the biocontrol agent *Candida sake* CPA-1 for control of *Botrytis cinerea* on grapes. *Biological Cont.* 96: 108–119. <https://doi.org/10.1016/j.biocontrol.2016.02.012>
- Min, B. J., Han, I. Y., & Dawson, P. L. (2010). Antimicrobial gelatin films reduce *Listeria monocytogenes* on turkey bologna. *Poultry Sci.* 89(6): 1307–1314. <https://doi.org/10.3382/ps.2009-00451>
- Mohamad, A. S., Mahmood, G., Davood, B., & Hasan, S. (2012). Effect of postharvest putrescine application and chitosan coating on maintaining quality of table grape cv. “Shahroudi” during long-term storage. *J Food Proc. and Preser.* 37(5): 999–1007. <https://doi.org/10.1111/j.1745-4549.2012.00735.x>
- Muhammad, F. R., Ali, S., Choi, J., Hwang, S., Jeong, C., & Bae, K. H. (2019). *Bacillus velezensis*: A valuable member of bioactive molecules within plant microbiomes. *Molecules.* 24(6): 1046. <https://doi.org/10.3390/molecules24061046>
- Na, G., Guilan, Z., Ding, C., Dongkun, W., Fangyan, Z., & Zhilan, Z. (2020). Preparation and characterization of gellan gum-guar gum blend films incorporated with nisin. *J Food Sci.* 85(6): 1799–1804. <https://doi.org/10.1111/1750-3841.15143>
- Nagasawa, K., Doi, H., Okamoto, M., Sato, T., Takahashi, Y., & Arai, Y. (2017). Antimicrobial activity of ethylene-vinyl acetate containing bioactive filler against oral bacteria. *Dental Materials Journal.* 36(6): 784–790. <https://doi.org/10.4012/dmj.2016-321>
- Nain, N., Katoch, G. K., Kaur, S., & Rasane, P. (2021). Recent developments in edible coatings for fresh fruits and vegetables. *J Hort. Res.* 29(2): 127–140. <https://doi.org/10.2478/JOHR-2021-0022>
- Patrícia, M., Daniel, J. D., & Adriano, B. (2010). Food applications of liposome-encapsulated antimicrobial peptides. *Trends in Food Sci. and Tech.* 21(6): 284–292. <https://doi.org/10.1016/j.tifs.2010.03.003>
- Paulraj, K., & Seung, T. L. (2013). Development and characterization of novel probiotic-residing pullulan/starch edible films. *Food Chem.* 141(2): 1041–1049. <https://doi.org/10.1016/j.foodchem.2013.03.103>
- Peng, J. (2022). Latest advances in preservation technology for fresh fruit and vegetables. *Foods.* 11(20): 3236. <https://doi.org/10.3390/foods11203236>
- Pereira, L. G., Silva, K. S. S., Carvalho, M. C., Almeida, T. A., Silva, F. S., Gomes, P. G., Fernandes, M. F., & Kumar, N. (2019). Edible chitosan films and their nanosized counterparts exhibit antimicrobial activity and enhanced mechanical and barrier properties. *Molecules.* 24(1): 127. <https://doi.org/10.3390/molecules24010127>
- Pinto, L., Vinderola, G., Rocchetti, G., & Cichoski, A. (2016). The effect of locust bean gum (LBG)-based edible coatings carrying biocontrol yeasts against *Penicillium digitatum* and *Penicillium italicum*, causal agents of postharvest decay of mandarin fruit. *Food Micro.* 58: 87–94. <https://doi.org/10.1016/j.fm.2016.03.014>
- Pitto, L., Iannetta, A., & Bernbom, F. (2015). Control of spoilage *Pseudomonas* spp. on fresh cut vegetables by neutral electrolyzed water. *Food Micro.* 50: 102–108. <https://doi.org/10.1016/j.fm.2015.04.003>
- Qiong, T., Xiaodong, Z., Wen, C., Xiang, Y., & Pengcheng, T. (2021). Metabolomics reveals key resistant responses in tomato fruit induced by *Cryptococcus laurentii*. *Food Chem. Molecular Sci.* 100066. <https://doi.org/10.1016/j.fochms.2021.100066>
- Rajabian, M., Bonyadian, M., Abbasvali, M., & Khanjari, A. (2019). Effects of potato starch edible coating containing *Ziziphora clinopodioides* and *Thymus daenensis* essential oils on chemical organoleptic properties of chicken breast. *J Veterinary Res.* 74(4): 450–463. <https://doi.org/10.22059/JVR.2018.237327.2662>
- Rodríguez, J. M., Martínez, M. I., & Kok, J. (2002). Pediocin PA-1, a wide-spectrum bacteriocin from lactic acid bacteria. *Critical Rev. Food Sci. and Nutr.* 42(2): 91–121. <https://doi.org/10.1080/10408690290825475>
- Rouling, L., Qiya, Y., Jinwei, X., Solairaj, D., Ngea, G. L. N., & Hongyin, Z. (2022). Study on the biocontrol effect and physiological mechanism of *Hannaella sinensis* on the blue mold decay of apples. *Int. J of Food Micro.* 382: 109931. <https://doi.org/10.1016/J.IJFOODMICRO.2022.109931>
- Sami, R., Elhakem, A., Alharbi, M., Benajiba, N., Fikry, M., & Helal, M. (2021). The combined effect of coating treatments to nisin, nano-silica, and chitosan on oxidation processes of stored button mushrooms at 4°C. *Scientific Reports.* 11(1): 6031. <https://doi.org/10.1038/S41598-021-85610-X>

- Sánchez-Ortega, I., García-Almendárez, B. E., Santos-López, E. M., Amaro-Reyes, A., Barboza-Corona, J. E., & Regalado, C. (2014). Antimicrobial edible films and coatings for meat and meat products preservation. *Sci. World J.* 2014: 248935. <https://doi.org/10.1155/2014/248935>
- Schillinger, U., Geisen, R., & Holzapfel, W. H. (1996). Potential of antagonistic microorganisms and bacteriocins for the biological preservation of foods. *Trends in Food Sci. & Tech.* 7(5): 158–164. [https://doi.org/10.1016/0924-2244\(96\)81256-8](https://doi.org/10.1016/0924-2244(96)81256-8)
- Shaoling, C., Yapei, Z., Ruitao, C., Jinliang, Y., & Xingyu, J. (2016). Water-soluble nanocrystalline cellulose films with highly transparent and oxygen barrier properties. *Nanoscale.* 8(2): 973–978. <https://doi.org/10.1039/c5nr07647a>
- Sharma, N., Verma, U., & Awasthi, P. (2006). A combination of the yeast *Candida utilis* and chitosan controls fruit rot in tomato caused by *Alternaria alternata* (Fr.) Keissler and *Geotrichum candidum* Link ex Pers. *J of Horti. Sci. and Bio.* 81(6): 1043–1051. <https://doi.org/10.1080/14620316.2006.11512170>
- Sharma, R. R., Dinesh, R., & Rajbir, S. (2009). Biological control of postharvest diseases of fruits and vegetables by microbial antagonists: A review. *Bio. Cont.* 50(3): 205–221. <https://doi.org/10.1016/j.biocontrol.2009.05.001>
- Sharma, R., Verma, M., & Awasthi, P. (2006). A combination of the yeast *Candida utilis* and chitosan controls fruit rot in tomato caused by *Alternaria alternata* (Fr.) Keissler and *Geotrichum candidum* Link ex Pers. *J Horti. Sci. and Bio.* 81(6): 1043–1051. <https://doi.org/10.1080/14620316.2006.11512170>
- Shen, J., Xia, J., Gao, Z. L., Liu, L., Xu, Q., & He, R. (2013). Effects of tea polyphenols, lysozyme, and chitosan on improving preservation quality of pomfret fillet. *Adv. Materials Res.* 781–784: 1582–1588. <https://doi.org/10.4028/www.scientific.net/AMR.781-784.1582>
- Shi C, Jia L, Tao H, Hu W, Li C, Aziz T, Al-Asmari F, Sameeh MY, Cui H, Lin L. (2024). Fortification of cassava starch edible films with *Litsea cubeba* essential oil for chicken meat preservation. *Int J Biol Macromol.* 276(Pt 2): 133920. <https://doi.org/10.1016/j.ijbiomac.2024.133920>
- Shi C, Jia L, Tao H, Li C, Aziz T, Alhomrani M, Cui H, Lin L. (2024b). Effects of guar gum/chitosan edible films functionalized with citronellal/HP $\beta$ CD inclusion complex on Harbin red sausage preservation. *Int J Biol Macromol.* 282(Pt 6): 137312. <https://doi.org/10.1016/j.ijbiomac.2024.137312>
- Shi C, Xu R, Hu W, Aziz T, Alhomrani M, Cui H, Lin L. (2025). Fabrication of alginate dialdehyde-gelatin crosslinked hydrogels incorporated with cinnamaldehyde nanoparticles for meat preservation. *Int J Biol Macromol.* 298: 140063. <https://doi.org/10.1016/j.ijbiomac.2025.140063>
- Shouket S, Khurshid S, Khan J, Batool R, Sarwar A, Aziz T, Alhomrani M, Alamri AS, Sameeh MY, Zubair Filimban F. (2023). Enhancement of shelf-life of food items via immobilized enzyme nanoparticles on varied supports. A sustainable approach towards food safety and sustainability. *Food Res Int.* 169: 112940. <https://doi.org/10.1016/j.foodres.2023.112940>
- Shouket, S., khurshid, S., Khan, J. Nadeem AA, Sarwar A, Aziz T, Alotaibi MN, Alamri AS, Alhomrani M, Sameeh MY. (2024). Biosynthetically produced glucose oxidase immobilized silver nanoparticle bioconjugate treatment improves the shelf life of mango fruit: an innovative method towards food safety and sustainability. *Biomass Conv. Bioref.* 14: 31357–31368. <https://doi.org/10.1007/s13399-023-04753-1>
- Silva, S. P. M., Teixeira, J. A., & Silva, C. C. G. (2023). Recent advances in the use of edible films and coatings with probiotic and bacteriocin-producing lactic acid bacteria. *Food Biosci.* 56: 103196. <https://doi.org/10.1016/j.fbio.2023.103196>
- Tahir, H. E., Arslan, M., Mahunu, G. K., Hashim, S. B. H., Jiyong, S., Wen, Z., Xiaowei, H., Adam, M. A., Abdalla Isameldeen, I. H., & Xiaobo, Z. (2022). Efficacy of biologically active agents and antagonistic yeast to control the incidence of postharvest diseases: A meta-analysis and meta-regression. *Biological Cont.* 172: 104952. <https://doi.org/10.1016/j.biocontrol.2022.104952>
- Tapia, M. S., Rojas Graü, M. A., Rodríguez, F. J., Ramírez, J., Carmona, A., & Martín-Belloso, O. (2007). Alginate- and gellan-based edible films for probiotic coatings on fresh-cut fruits. *J of Food Sci.* 72(4): E190–E196. <https://doi.org/10.1111/j.1750-3841.2007.00318.x>
- Tony, J. (2010). Inactivation of *Listeria monocytogenes* in skim milk and liquid egg white by antimicrobial bottle coating with polylactic acid and nisin. *J of Food Sci.* 75(2): M83–M88. <https://doi.org/10.1111/j.1750-3841.2009.01480.x>
- Usman, M., Zia, A., Nauman Ahmad, M., Alam, S., Ullah, N., Us Salam, M. B., Aziz, T., Alhomrani, M., Alsanie, W. F., & Alamri, A. S. (2024). Extraction and characterization of cellulose from agricultural waste of hemp (*Cannabis sativa*) and parthenium (*Parthenium hysterophorus*). *Italian J of Food Sci.* 36(4): 17–25. <https://doi.org/10.15586/ijfs.v36i4.2659>
- Wan, J., Gordon, J. B., Muirhead, K., Hickey, M. W., & Coventry, M. J. (1997). Incorporation of nisin in micro-particles of calcium alginate. *Letters in Applied Microbio.* 24(3): 153–158. <https://doi.org/10.1046/j.1472-765x.1997.00294.x>
- Wang, J., Lin, J. X., Xiao, W., Jia, X., Han, N., Wang, H., Ji, S., & Pan, J. (2018). Blend of organic acids and medium chain fatty acids prevents the inflammatory response and intestinal barrier dysfunction in mice challenged with enterohemorrhagic *Escherichia coli* O157: H7. *Inter. Immun.* 58: 64–71. <https://doi.org/10.1016/j.intimp.2018.03.014>
- Wang, L., Du, G., Guo, H., Zhang, Q., Qi, X., Yu, W., Jiang, C., & Xu, H. (2019). Volatile organic compounds of *Hanseniaspora uvarum* increase strawberry fruit flavor and defense during cold storage. *Food Sci. & Nutr.* 7(8): 2625–2635. <https://doi.org/10.1002/fsn3.1116>
- Wang, M., Zhao, L., Zhang, X., Solairaj, D., Mandour, H. A., Yan, Q., Jiang, Z., & Zhang, H. (2018). Study on biocontrol of postharvest decay of table grapes caused by *Penicillium rubens* and the possible resistance mechanisms by *Yarrowia lipolytica*. *Bio. Cont.* 130: 110–117. <https://doi.org/10.1016/j.biocontrol.2018.11.004>
- Wang, X., Pei, J., Zhang, C., Yang, C., Chen, H., & Xu, B. (2015). Structure and properties of moisture-resistant konjac glucomannan films coated with shellac/stearic acid coating. *Carbohydrate Poly.* 118: 119–125. <https://doi.org/10.1016/j.carbpol.2014.11.009>
- Wang, X., Sun, J., & Wu, R. (2018). Effect of *Burkholderia contaminans* on postharvest diseases and induced resistance of

- strawberry fruits. *The Plant Pathol. J.* 34(5): 403–411. <https://doi.org/10.5423/ppj.oa.02.2018.0031>
- Wang, Y., Pallen, D. P. A., & Pothin, K. L. P. (2024). *Enterococcus faecium*: Evolution, adaptation, pathogenesis, and emerging therapeutics. *Nature Rev. Micro.* 22(11): 705–721. <https://doi.org/10.1038/s41579-024-01058-6>
- Wu, J., Zhang, M., Luo, T., Liu, T., Ren, Q., Zhou, Z., Yang, Z., Aziz, T., Shami, A., Al-Asmari, F., Fahad Alabbosh, K., & El-Ghareeb Keshek, D. (2025). Assessing the effects of homofermentative *Lactiplantibacillus plantarum* K25 and heterofermentative *Limosilactobacillus fermentum* 13-1 on the flavor and functional characteristics of fermented milk analyzed by metabolomics approach. *Italian J Food Sci.* 37(1): 150–181. <https://doi.org/10.15586/ijfs.v37i1.2779>
- Xie, Y., Zhang, M., Gao, X., Shao, Y., Liu, H., Jin, J., Yang, W., & Zhang, H. (2018). Development and antimicrobial application of plantaricin BM-1 incorporating a PVDC film on fresh pork meat during cold storage. *J Appl. Micro.* 125(4): 1108–1116. <https://doi.org/10.1111/jam.13912>
- Yan, F., Ying, X., Dongfeng, W., Li, Z., Jipeng, S., Liping, S., & Bin, Z. (2009). Effect of alginate coating combined with yeast antagonist on strawberry (*Fragaria × ananassa*) preservation quality. *Postharvest Bio. and Techn.* 53(1): 84–90. <https://doi.org/10.1016/j.postharvbio.2009.03.002>
- Yanli, Y., Yunna, Z., Xuewu, D., Xin, M., & Yanshen, L. (2023). Research progress on the application of different preservation methods for controlling fungi and toxins in fruit and vegetables. *Critical Rev. in Food Sci. and Nutr.* 63(33): 11–12. <https://doi.org/10.1080/10408398.2022.2101982>
- Ying, T., Chao, J., Li, H., & Zhang, X. (2009). Indole-3-acetic acid improves postharvest biological control of blue mold rot of apple by *Cryptococcus laurentii*. *Phytopathology.* 99(3): 258–264. <https://doi.org/10.1094/PHYTO-99-3-0258>
- Yinzhe, R., & Shaoying, Z. (2013). Effect of carboxymethyl cellulose and alginate coating combined with brewer yeast on postharvest grape preservation. *Inter. Sch. Res. Notices.* 2013: 871396. <https://doi.org/10.1155/2013/871396>
- YoungMin, K., DuckSoon, A., HyunJin, P., JongMoon, P., & DongSun, L. (2002). Properties of nisin-incorporated polymer coatings as antimicrobial packaging materials. *Pack. Tech. and Sci.* 15(5): 247–254. <https://doi.org/10.1002/pts.594>
- YoungMin, K., HyunDong, P., & DongSun, L. (2002). Shelf-life characteristics of fresh oysters and ground beef as affected by bacteriocin-coated plastic packaging film. *J Sci. of Food and Agri.* 82(9): 998–1002. <https://doi.org/10.1002/jsfa.1125>
- Yuan, X., Jie, Z., Pingping, Z., Joe, M. R., Dasong, L., & Peng, Z. (2024). Improving the microbiological safety and quality of aquatic products using nonthermal processing. *Comprehensive Rev. Food Sci. and Food Safety.* 23(3): e13368–e13368. <https://doi.org/10.1111/1541-4337.13368>
- Zahidova, F., Yildiz, S., Özdemir, A., Gülfen, M., & Yemiş, G. P. (2023). Modification of poly(L-lactic acid)-based films and evaluation of physical and antibacterial properties by using multivariate data analysis. *Inter. J Bio. Macromolecules.* 30(241): 124583. <https://doi.org/10.1016/j.ijbiomac.2023.124583>
- Ze, W., Lingli, H., Xinyu, F., Feng, C., Ruijie, W., Qingjun, K., Keyu, S., Jianhua, G., Jun, G. (2023). Development of functional, sustainable pullulan-sodium alginate-based films by incorporating essential oil microemulsion for chilled pork preservation. *Inter. J Bio. Macromolecules.* 253(P6): 127257–127257. <https://doi.org/10.1016/J.IJBIOMAC.2023.127257>
- Zhang J.N., Zarin, M.A., Chee Keong, L., Joo Shun, T. (2020). Application of bacteriocins in food preservation and infectious disease treatment for humans and livestock: a review. *RSC Adv.* 10(64): 38937–38964. <https://doi.org/10.1039/d0ra06161a>
- Zhang, M., Gu, X., Zhang, H., Li, H., Jiang, J., Yu, W., & Xu, Y. (2017). Development and antilisterial activity of PE-based biological preservative films incorporating plantaricin BM-1. *FEMS Microbio. Letters.* 364(7): fnw283. <https://doi.org/10.1093/femsle/fnw283>
- Zhang, Q., Zhang, J., Zhang, J., Xu, D., Li, Y., Li, Y., Zhang, X., Zhang, R., Wang, Z., & Wu, P. (2021). Antimicrobial effect of tea polyphenols against foodborne pathogens: A review. *J Food Prot.* 84(10): 1801–1808. <https://doi.org/10.4315/JFP-21-043>
- Zhang, X., Zhang, H., Yuan, Y., Wang, J., Guo, X., Li, B., Zhang, L., & Zhang, H. (2022). Metabolomic profiling and energy metabolism modulation unveil the mechanisms involved in enhanced disease resistance of postharvest broccoli by *Meyeromyza guilliermondii*. *Scientia Horticulturae.* 303: 111239. <https://doi.org/10.1016/j.scienta.2022.111239>
- Zhenshuo, W., Yuan, S., Jishun, L., Xiaoli, T., Qi, W. (2022). Biological control of postharvest fungal decays in citrus: a review. *Critical Rev. Food Sci. and Nutr.* 62(4): 11–10. <https://doi.org/10.1080/10408398.2020.1829542>
- ZhiMing, W., Cheng Jian, L., Shuai Wen, Z., Zeng Xin, Q., Man Ming, Z., Kun Tai, L. (2018). Inhibitory activities of metabolite produced by *Streptomyces* sp. N2 and its efficacy on fruit storage. *Southwest China J of Agri. Sci.* 31(7): 1393–1398. <https://doi.org/10.16213/j.cnki.scjas.2018.7.011>
- Zhou, X., Ni, W., Xu, J., Zhang, H., Li, X., & Chen, Z. (2022). Characterization of antifungal cyclic dipeptides of *Lactiacaseibacillus paracasei* ZX1231 and active packaging film prepared with its cell-free supernatant and bacterial nanocellulose. *Food Res. Inter.* 162: 12024. <https://doi.org/10.1016/j.foodres.2022.112024>
- Zunyang, S., Feng, L., Hui, G., Yunfeng, X., Quanjuan, F., Dapeng, L. (2017). Combination of nisin and  $\epsilon$ -polylysine with chitosan coating inhibits the white blush of fresh-cut carrots. *Food Cont.* 74(2017): 34–44. <https://doi.org/10.1016/j.foodcont.2016.11.026>