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Exploring the untapped potential of naturally occurring antimicrobial compounds: novel advancements in food preservation for enhanced safety and sustainability

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Current research trends emphasize the strategic utilization of natural and renewable resources, specifically within food and medicine, focusing on naturally occurring antimicrobial compounds. While growing interest is in extracting secondary metabolites from plants, bacteria, and enzymes, a substantial portion of these naturally derived molecules remains inadequately explored. These antimicrobial agents exhibit heightened safety compared to their synthetic counterparts, posing no health risks to consumers. This presents an opportunity to replace perilous synthetic chemicals within the food sector. Despite the increasing popularity of natural additive sources, there is a potential for adverse effects on product sensory qualities. Therefore, notwithstanding recent advancements, further investigation is imperative to optimize effective quantities for the successful inhibition of pathogenic microorganisms. This article delves into pioneering developments in food preservation, offering contemporary insights into natural preservation solutions, especially for perishable commodities.

KEYWORDS

food antimicrobials, food preservation, nanoparticles antimicrobials, microbial metabolites, medicinal properties

1 Introduction

For years, the food industry has been utilising a variety of chemicals to prevent the spread of bacteria that cause food to decay. They are used in association with high temperatures to prolong the storage life of goods by killing off harmful and spoilage-causing microorganisms (Appendini and Hotchkiss, 2002; Gyawali and Ibrahim, 2014). However, their use can diminish particular food's organoleptic and sensory aspects. Bio preservatives are natural organic substances and are derived from plants, animals, or microorganisms (Gyawali and Ibrahim, 2014) (Figure 1). They are used to extend the time for food products to be consumed safely. These compounds contribute to the enhancement of food functionality and quality by reducing pathogens to minimal levels or eliminating them entirely (Babaei-Ghazvini et al., 2021; Mshana et al., 2021; Budiati et al., 2022). The predominant mechanism involves their antimicrobial and antioxidant properties, exerted

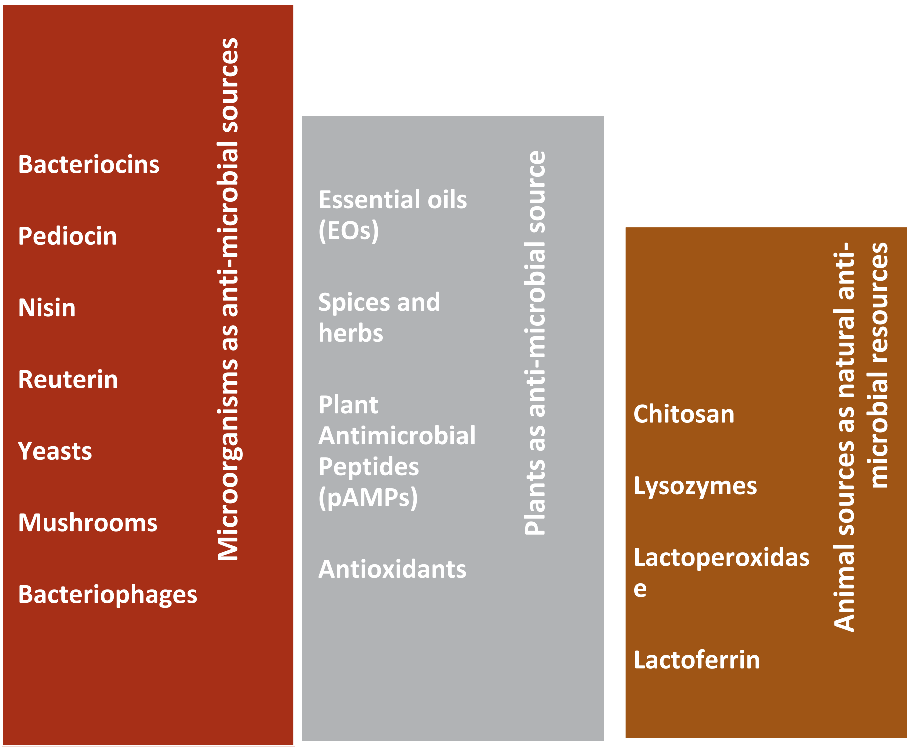

FIGURE 1
Different sources of anti-microbials and their examples used in the food industry.

through the disruption of cell walls and metabolic processes in microbial entities (Babaei-Ghazvini et al., 2021). However, in response to the environmental and health concerns associated with synthetic food additives, there is a growing consumer preference for natural preservatives. This shift is driven by heightened awareness among consumers regarding the substantial health risks linked to the consumption of meals containing synthetic ingredients and additives (Ahmed et al., 2022). These natural preservatives produced from animals, plants, and microbes that benefit humans have recently been promoted as a feasible alternative to synthetic food additives (Table 1). Organic acids and polymers from natural sources, such as chitosan, are currently used as anti-microbial compounds in foods (Angane et al., 2022; Baindara and Mandal, 2022). Some of these substances, like lysozyme and lactoferrin, are produced by microorganisms, whereas essential oils derive predominantly from plants, and certain enzymes, like lysozyme and lactoferrin, emanate from animals (Ahmed et al., 2022). Because of this, scientists are continuously working to find efficient replacements for preserving food by entirely or partially replacing synthetic additives utilized for anti-microbial protection.

In addition, one of the most significant issues associated with utilizing natural chemicals is the performance of these compounds. Consumers may be exposed to a significant health risk through toxins derived from microbial sources, i.e., *Aspergillus niger*, *Campylobacter*, *Bacillus cereus*, *Escherichia coli*, *Staphylococcus aureus*, *Salmonella*, and *Clostridium perfringens* (Roges et al., 2020; Titouche et al., 2020; Sornchuer et al., 2022); however, chemical-additives usage presents an even higher level of hazard to consumers. Therefore, naturally occurring chemicals will restrict and inhibit the proliferation of harmful microbes, increase food safety, and reassure customers' confidence in food (Lucera et al., 2012; Hintz et al., 2015).

Anti-microbials from natural origin are generally recognized as safe (GRAS), and their usage in certain nations is authorized (El-Saber Batiha et al., 2021). Although natural food preservative chemicals are recommended over chemical preservatives, prolonged usage and above the permitted limit raise health concerns. In this context, this work concentrates on the naturally occurring anti-microbial compounds that are currently available, the origins of these compounds, and the applications of these compounds in the industry to limit the growth of microorganisms that cause spoiling in products made from cereal and legumes, vegetables and fruits, dairy products, animal meat products, and marine foods (considered as major food commodities), as well as on the regulations that govern the storage of food. Other potential technologies, such as nanoparticles and hurdles, are also discussed for extending food components' shelf-life.

2 Microorganisms as anti-microbial sources

Many bacteria and their metabolites restrict the development of other microorganisms. These microbes can potentially eliminate and prevent the development of different microbes that cause spoilage and human pathogens in food products. When foods are used, their shelf-life increases, and their safety and overall quality are improved (Arqués et al., 2008). The lactic acid bacteria (LAB) are a common microorganism in industrial food processing. The European Food Safety Authority (EFSA) has given a tag to LAB, i.e., the "Qualified

TABLE 1 Summary of the sources and effects of natural anti-microbial agents in food packaging.

Natural anti-microbial agent	Applicable food product	Edible-film matrix	Targeting microorganism	Effect	Reference
Anti-microbials from plant sources					
Rosemary EOs	Spinach	Whey-protein concentrate	Coliform	Reduction in bacterial population and reduced chlorophyll loss in plants	Appendini and Hotchkiss (2002)
Nano-emulsion of cumin EOs	Refrigerated beef loins	Chitosan	*S. typhimurium*; *E. coli*; *L. monocytogenes*	Reduction in bacterial population, enhanced antioxidant activity	Appendini and Hotchkiss (2002) and Gyawali and Ibrahim (2014)
Clove EOs	Cold-stored prawn shrimp	Deacetylated chitosan	Aerobic microbes (bacteria)	Aerobic bacteria proliferation reduction, reduction in colour changes, and melanosis	Gyawali and Ibrahim (2014)
Chitin nano-fibre and Ajowan EOs	Cold-stored raw beef	Gelatin and carboxymethyl cellulose	Molds and yeast; *S. aureus*, *Pseudomonas*; LAB	Prevent the growth of pathogens and enhance the sensory characteristics of food	Gyawali and Ibrahim (2014)
Garlic EOs	Vacuum-packed sausages and Kasar cheese slices	whey protein and Chitosan	Spoilage bacteria *S. aureus*; *L. monocytogenes*; *S. enteritidis*; *E. coli*	Inhibit spoilage-causing bacteria, fat oxidation reduced and anti-microbial activity against bacterial pathogens	Appendini and Hotchkiss (2002)
Nano-emulsion of resveratrol and oregano EOs	Fresh pork	Pectin-edible coating		Prevent microbial growth, prolonged shelf-life, and enhanced sensory characteristics of food	Torres Dominguez et al. (2019)
Musk-lime extract	Squids	Chitosan	*V. parahaemolyticus*; *P. aeruginosa*	Inhibit Gram-negative bacteria	Torres Dominguez et al. (2019)
Ginger EOs	Chicken breast fillet	Sodium caseinate	Psychrophilic aerobic bacteria	Anti-bacterial activity	Torres Dominguez et al. (2019)
Cinnamon EOs	Banana	Sodium alginate and carboxymethyl cellulose	*E. coli*; *S. aureus*	Anti-bacterial activity	Gyawali and Ibrahim (2014)
Pomegranate peel-extract	NA	Starch	*Salmonella* Spp.; *S. aureus*	Bacterial growth reduction	Gyawali and Ibrahim (2014)
Herba lophatheri-extract	NA	Chitosan	*E. coli*; *S. aureus*	Effectively reduced bacterial growth and their numbers	Appendini and Hotchkiss (2002)
Thymol EOs	Tomatoes	Chitosan	*B. cinerea*	Antifungal action against Botrytis	Gyawali and Ibrahim (2014)
Turmeric extract	NA	Chitosan	*S. aureus*; *Salmonella* spp.	Bacterial growth reduction with turmeric extract	Gyawali and Ibrahim (2014)
Propolis extract	Minced beef	Chitosan with cellulose	LAB; *Pseudomonas* spp.; psychrotrophic bacteria	Delayed microbial growth	Appendini and Hotchkiss (2002)
Carvacrol EOs	NA	Thermoplastic starch	*E. coli*	Disturbance of equilibrium and partial breakdown of the cell membrane	Torres Dominguez et al. (2019)
Cinnamon EOs	Fresh pistachio	Sago starch	*S. aureus*; *S. typhimurium*; *E. coli*	Delayed microbial growth	Njoga et al. (2021)
Nano-emulsions of polyphenols	Chicken meat	Gelatin	*S. aureus*; *S. typhimurium*; *E. coli*	Enhanced shelf-life and anti-bacterial effect	Torres Dominguez et al. (2019)
Anti-microbials from animal sources					
Casein phosphor-peptides	NA	Gelatin	*B. cereus*; *S. aureus*	Inhibitory effect against Gram-positive, enhanced antioxidant activity	Njoga et al. (2021)
Cinnamon EOs	NA	Chitosan	*S. aureus*; *E. coli*	Up to 98% anti-bacterial activity	Gyawali and Ibrahim (2014)

(Continued)

TABLE 1 (Continued)

Natural anti-microbial agent	Applicable food product	Edible-film matrix	Targeting microorganism	Effect	Reference
Clove EOs and fish protein hydrolysates	Chilled bonito fillets	Protein and agar	Bacteria; yeast; mold	Up to 98% anti-microbial activity, enhanced shelf-life	Mshana et al. (2021)
Lysozyme	Sliced smoked salmon	Whey protein	*L. innocua*	Enhanced shelf-life and anti-microbial action	Mantilla et al. (2013)
Anti-microbials from microorganism sources					
Natamycin	Casting method	Cassava starch and chitosan	*A. parasiticus*; *A. flavus*	Improved antifungal potential and increased shelf life	Torres Dominguez et al. (2019)
Nisin	NA pork patties	Carrageenan and chitosan	*Pseudomonas* spp.; *S. aureus* (MRSA)	Bactericidal efficacy increased up to 99%, enhanced shelf-life was by two times, and antioxidant activity	Kasimanickam et al. (2021)
Lactococcus lactis cell-free supernatant	Tryptone soya agar	Sodium alginate/ sodium carboxy-methyl-cellulose	*E. coli*; *S. aureus*	Decrease growth during cold storage, and antagonistic affect	Torres Dominguez et al. (2019)
Bacteriophages	Meat	Whey protein	*E. coli*	Up to 100% reduction in *E. coli* numbers	Kasimanickam et al. (2021)
Bacteriophage	Tomatoes	Chitosan	*Enterobacteriaceae* spp.	Reduction in growth and increased generation time	Torres Dominguez et al. (2019)

Presumption of Safety" (QPS), while the Food and Drug Administration (FDA) has given it the "Generally Recognized as Safe" (GRAS) designation (Fu and Dudley, 2021). They synthesize nutrients and anti-microbial metabolites, making them useful as protective cultures for food industries. LAB is applied as a competitive bio-protective agent in fresh vegetables and fruits because it prevents pathogenic microorganisms' growth. LAB grows primarily in food due to food characteristics such as temperature, ionic strength, pH, and food matrix (Furlaneto-Maia et al., 2020). LAB is also known as lactic acid bacteria. LAB can hardly grow in fruit juices and condiments due to low pH, but limited growth was reported in low-pH food when stored at elevated temperatures >60°C.

For example, LAB has shown promise as a protective culture against spoilage and microbial pathogens in food distribution systems. In an earlier study, Delavenne et al. (2015) used a bio-preservative commonly found in yogurt, and the results showed that adding *Lactobacillus harbinensis* strain K.V9.3.1-Np was sufficient to prevent yeast contamination completely. Other authors (Rozman et al., 2022) effectively reduced *Penicillium* fungus growth at room temperature in cottage cheese by employing *L. plantarum*. In addition, the application of *Lactobacillus sakei* C2 and produced sakacin-C2 bacteriocin reduced *L. monocytogenes* CMCC 54002 population to a microscopic level (10 CFU/g) when the sliced-cooked ham was stored in a vacuum pack for 30 days at 4°C (Gao et al., 2015). Bacteriocins derived from LAB have garnered much attention as potential food bio preservatives, including nisin and pediocin, while nisin is the more well-known of the two. Therefore, antimicrobial metabolites should be used to their full potential in the food preservation industry (Timbe et al., 2021).

2.1 Bacteriocins

Bacteriocins are another category of anti-microbial agents that are effective against infections caused in many food products, particularly those that have undergone minimal processing, such as those made from fruits and vegetables (Furlaneto-Maia et al., 2020) (Figure 2). However, their efficiency may be increased when combined with other preservation techniques in the food industry. Bacteriocins have many benefits in food preservation (Furlaneto-Maia et al., 2020; Nebbia et al., 2020), including,

i food shelf-life extension,
ii they protect food from extreme temperatures,
iii they minimize pathogen and spoilage microbe spread in food-supply systems,
iv food spoilage losses are reduced,
v they minimize synthetic anti-bacterial usage.

Bacteriocins, derived from both gram-positive and gram-negative bacteria, constitute antimicrobial peptide compounds exhibiting cationic, anionic, or neutral characteristics. Synthesized in bacterial ribosomes, these peptides showcase a broad spectrum of activity against pathogenic bacteria. Notable examples from lactic acid bacteria in the food industry include nisin, diplococcin, acidochilin, bulgarican, helventicin, lactacin, and plantaricin. Pediocins, produced by *Pediococcus* spp., offer an alternative preservative in the food industry. Plantaricin, another bacteriocin, hails from gram-positive bacteria like *Lactobacillus plantarum*, inhibiting pathogenic gram-negative bacterial growth. Bacteriocins, employed as biopreservatives, present several advantages: (a) non-toxicity and easy biodegradability due to their protein nature, (b) digestive tract enzyme digestibility, preserving intestinal microflora, (c) reduction of chemical food preservative use, and (d) versatile utilization in various forms, including bacteriocin-producing bacterial culture strains, purified, or semi-purified bacteriocin compounds.

Bacteriocins such as nisin, known for inhibiting *Clostridium botulinum* and *Listeria monocytogenes*, have been directly incorporated into cheese, a dairy product (Nebbia et al., 2020). Notably, the addition of 2000 IU/g of nisin to cottage cheese extended its storage life, resulting in a significant reduction in the *L. monocytogenes* population by a factor of 1,000 after 7 days of storage at 20°C, compared to a 10-fold reduction observed in the control group. Sharma et al. (2023) synthesized silver nanoparticles (AgNPs) using bacteriocins from probiotics (*Lactobacillus pentosus* S6, *Lactobacillus crustorum* F11, and *Lactobacillus spicheri* G2). These eco-friendly AgNPs were applied to cellulose paper for packaging tomatoes, with F11 AgNPs-coated paper demonstrating superior antimicrobial efficacy.

The bactericidal properties of various bacteriocins have led to their exploration in expediting cheese maturation. In semi-hard and hard cheeses, bacteriocins were employed to induce lysis of the starter lactic acid bacteria (LAB) culture under controlled conditions. This lysis released intracellular proteinases and peptidases, enhancing ripening and flavor (Rollini et al., 2020). However, using bacteriocins for lysing starter microbial cultures may reduce the acidification rate. To address this challenge, a proposed three-strain system involves a bacteriocin-sensitive starter as the target, a bacteriocin-producing adjunct, and a bacteriocin-resistant species functioning as an acidifier (Morgan et al., 2002). Zhang et al. (2023) characterized the LAB bacteriocin RSQ01 from *Lactococcus lactis*, revealing its broad antimicrobial spectrum, resilience to environmental factors, and preservation effects on milk quality. Global metabolomics identified 238 metabolites impacted by RSQ01, emphasizing its potential for milk preservation.

Furthermore, bacteriocins have been found to have applications in combination with packaging to interact directly with the stored food. This method involves incorporating bacteriocins into materials commonly used for food packaging, enhancing the product's resistance to environmental factors (Gumienna and Gorna, 2021). Given that the initial step in food spoilage involves bacterial growth on food surfaces, incorporating bacteriocins into food packaging enhances food safety, quality, and shelf life by preventing such microbial growth. Consequently, the synergistic action of bacteriocins with other LAB components demonstrates promising potential for improving customer safety in food products. Zhao et al. (2023) explored the synergistic antibacterial potential of nisin and phytic acid (PA) against *E. coli* isolates. The combination showed a synergistic effect on O157 strains and an additive effect on non-O157 strains, with remarkable bactericidal efficacy observed in *E. coli* O157:H7. The study suggests using PA to enhance nisin's effectiveness, potentially exploring other metal ion chelators.

2.2 Pediocin

A Gram-positive homo-fermentative bacteria, *Pediococcus* spp. synthesizes pediocin and belongs to the Lactobacillaceae family (Setiarto and Anshory, 2024). It includes different *Pediococcus* spp., such as *P. ethanolidurans*, *P. acidilactici*, *P. inopinatus*, *P. claussenii*, *P. cellicola*, and *P. parvulus*. Pediocin exerts its effect by producing cytoplasmic pores of particular target cells (Diez et al., 2012). This lowers the pH of the cell cytoplasm, which leads to the inhibition of proteins responsible for producing energy within cells. Several variables can impact the pediocin activity in food (Setiarto and Anshory, 2024), including pH, salt, temperature, the presence of proteolytic enzymes, and how long the food has been stored (Sun et al., 2015). The use of pediocin in preserving fermented sausages, vegetables, and dairy products has been documented. Concentrating pediocin has shown to be useful and promising in creating innovative functional foods and preserving food commodities prone to deterioration in a relatively short time (Bedard et al., 2018).

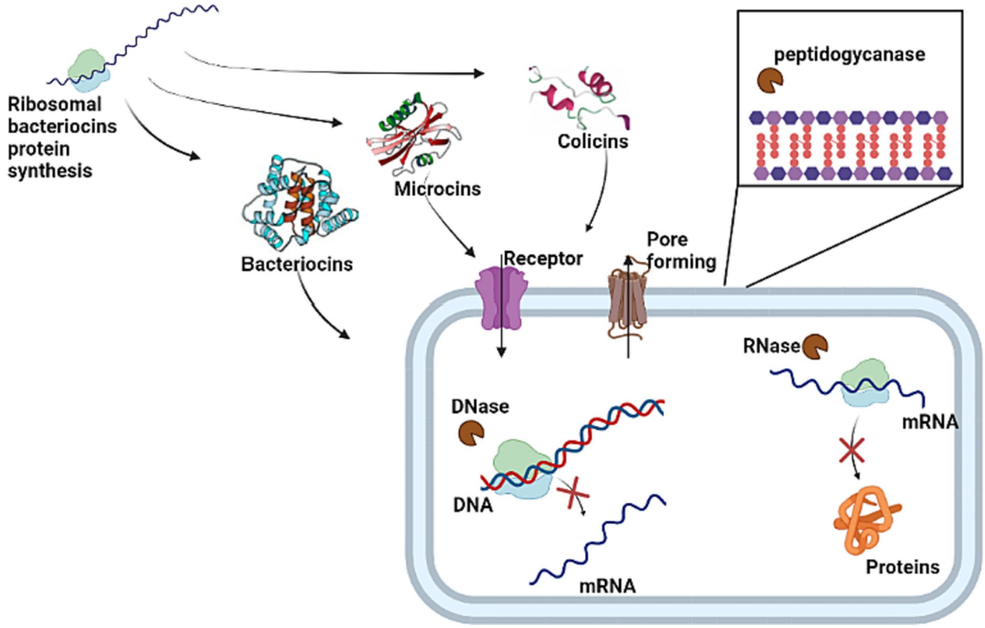

FIGURE 2
Bacteriocin functioning as antimicrobial agent.

2.3 Nisin

A heat-stable bacteriocin named nisin is produced by *L. lactis* strains (Timbe et al., 2021). These isolates are effective against Gram-positive bacteria, such as *Micrococcus*, *C. sporogenes*, *C. botulinum*, *Leuconostoc*, *L. monocytogenes*, *Staphylococcus*, *Lactobacillus*, *B. cereus*, and *Enterococcus* spp. (Nebbia et al., 2020; Timbe et al., 2021; Maresca and Mauriello, 2022). Nisin adheres to specific cellular membranes and forms pores in the cell membrane, and finally, nisin inhibits target cells, resulting in the loss of intracellular contents. Nisin functions more effectively in liquid foods than solid foods because nisin molecules diffuse better in liquid systems (Maresca and Mauriello, 2022). In addition, the effectiveness of nisin has been shown in various food products, such as canned foods, confectionery, brewing, animal and sea-foods, dairy products, and poultry (Nebbia et al., 2020).

2.4 Reuterin

Lactobacillus reuteri produces reuterin in the presence of glycerol and fatty acids. Reuterin inhibits several disease-causing and food-spoiling bacteria (El-Ziney et al., 1999). It has a bacteriostatic effect on *L. monocytogenes* and has been discovered to have activity against *Campylobacter jejuni*, *S. aureus*, *S. choleraesuis*, *E. coli* O157:H7, *Aeromonas hydrophila* subsp. *hydrophila*, and *Y. enterocolitica* (Arqués et al., 2008). Bio-preservative research into reuterin has shown that it can reduce the number of *L. monocytogenes* and the activity of *E. coli* O157:H7 in contaminated cooked pork. Reuterin has also been found to be effective in reducing the number of *L. monocytogenes* that can be isolated from beef-sausage. According to another study, reuterin combined with nisin and LPS was shown to effectively inactivate *S. aureus* and *L. monocytogenes* in cuajada dairy products (Arqués et al., 2008). The results of this study showed that the bacteria were rendered non-viable. It has been observed that reuterins could be used effectively in the food business as a bio-preservative because of growth suppressing potential of the key food spoilage and human pathogens throughout a broad pH range (Juneja et al., 2012). Furthermore, their tolerance to different lipolytic and proteolytic enzymes generally found in foods makes them an excellent candidate for application.

2.5 Yeasts

Yeast has a significant inhibiting effect and can effectively colonize wounds in vegetables and fruits, reducing quality loss and microbial contamination. Examples of such products include fruits and vegetables (Han et al., 2022). Yeast plays its antagonistic role by outcompeting other organisms for food and space, producing large amounts of ethanol, and altering the pH through the production of organic acids; this can lead to the formation of poisonous toxins called "mycocins" (Delavenne et al., 2015). The use of antagonistic yeast has been widely documented as an effective strategy for preventing postharvest infections in a wide range of fruits (Ahmed et al., 2022; Sornchuer et al., 2022). As a result of being treated with *Pichia membranaefaciens*, citrus fruits stored for 4 days at 20°C showed a 66 and 83% reduction in green and blue mold infections, respectively. Other studies have also reported the detrimental impact of *Wickerhamomyes anomalus* strain (BS91) on *P. digitatum* in Citrus fruits (Platania et al., 2012). Moreover, it was reported that the application of *Metschnikowia pulcherrima* strain MPR3, *W. anomalus* strain BS91, and *Aureobasidium pullulans* prevented *B. cinerea* induced infections in table-grapes (Parafati et al., 2015). The fermentation process that turns grapes into wine relies heavily on yeast to prevent microbial contamination. Additionally, various studies mentioned that *W. anomalus* Cf20 and *Saccharomyces cerevisiae* Cf8 were also useful in limiting the development of spoilage yeasts during wine fermentation.

2.6 Mushrooms

There are around 140,000 different types of mushrooms have been identified so far, and numerous studies have shown that they have antimicrobial and bioactive properties. Scientists have investigated the potential of edible mushrooms in the food industry (Berteli et al., 2022; Han et al., 2022). However, more studies are going to be conducted in this area because there are so few reports available mentioning the actual uses of mushroom anti-microbial as control agents for food safety. Large-scale processing techniques have made it possible in recent years to prepare mushroom anti-microbials for industrial application in the food industry (Berteli et al., 2022). These heat-sensitive or heat-resistant mushrooms and mushroom products can be used to make foods or supplements, respectively, through spray drying or freeze drying. It was found that the rotational concentration method was effective for separating polysaccharides from water extracts of mushrooms like *Ganoderma*, *Agaricus*, and *Tremella* spp. for use in the production of polysaccharide powders for use as dietary supplements. This process has been scaled up to an industrial level and is currently being utilized to produce a wide variety of nutraceutical products for mushrooms. The process of freeze-drying is a type of dehydration that is widely employed to preserve materials that would otherwise spoil from exposure to heat (Baraza et al., 2016). This technique was applied in the preparation of heat-sensitive mushroom compounds. Anti-microbial products developed from processed mushrooms can be used directly in food as a substitute for anti-microbials and preservatives. These mushroom anti-microbials manage stomach microflora when utilized as antibiotics and improve food storage life when applied as preservatives. *Leucoagaricus* ethanol extract was shown to have antimicrobial activity (Sevindik et al., 2018) against *Candida tropicalis*, *Candida albicans*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Enterobacter faecalis*, and *Escherichia coli*. There is evidence that the dichloro-methane, methanol, and ethanol extracts of *Lentinus tigrinus* exerted an active function against *Acinetobacter baumannii*, *P. aeruginosa*, *E. coli*, *E. faecalis*, *S. aureus* MRSA, *S. aureus*, *C. krusei*, *C. albicans*, and *C. glabrata* (Sevindik et al., 2018). Extracts of *Ganoderma lucidum* in methanol and dichloro methane have also been shown to be effective against *P. aeruginosa*, *E. faecalis*, *S. aureus* MRSA, *S. aureus*, *E. coli*, *Acinetobacter baumannii*, *C. glabrata*, *C. albicans*, and *C. krusei* (Cör et al., 2018). Methaloic and acetone extracts of *Leccinum carpini, Boletus aestivalis*, and *Boletus edulis* have anti-microbial activity against a various microorganisms, including *Penicillium purpurescens*, *Candida albicans*, *Paecilomyces variotii*, *Aspergillus fumigatus*, *Aspergillus flavus*, *P. aeruginosa*, *K. pneumoniae*, *S. aureus*, *E. coli*, and *E. faecalis* (Kosanić et al., 2012). Similarly, *Ramaria formosa* (Pers.) Qu'el reported with antibacterial properties against *P. aeruginosa*, *C. albicans*, *S. aureus*, *E. coli*, *and B. subtilis* (Ramesh and Pattar, 2010).

Bacillus cereus, *Candida albicans*, *Escherichia coli*, *Klebsiella pneumoniae*, and *Aspergillus flavus* have all been shown to be susceptible to methanol extracts of *Tricholoma lobayense* R. Heim, *Daedalea elegans* Spreng., *Daldinia concentrica* (Bolton), *Corilopsis occidentalis*, and *Auricularia polytricha* (Mont.) Sacc. (Gbolagade et al., 2005). *Osmoporus odoratus* when extracted in petroleum ether, acetone, chloroform, and water have shown anti-microbial activity against *E. coli*, *P. aeruginosa*, *B. subtilis*, *S. pyogenes*, and *S. aureus* (Titouche et al., 2020; Gómez-Llorente et al., 2023). Further, *Pleurotus ostreatus* (Jacq.) P. kumm. Ethanol extracts have been found to be effective against *S. aureus*, *E. coli*, *Proteus mirabilis*, *E. faecium*, *K. pneumoniae*, *S. typhimurium*, and *C. albicans* (Yilmaz et al., 2016). Extensive research by various scientists has established that both water and organic mushroom extracts are effective against a wide range of pathogenic and spoilage bacteria. The widespread availability of mushrooms makes them an ideal anti-bacterial agent, and food preservation companies should promote their use.

2.7 Bacteriophages

Bacteriophages are abundant in all environments and are widely found in various foods. They are also found in high quantities in our bodies. They can be utilized to inhibit and suppress bacterial communities, regulate animal diseases with phage therapy, cleanse processed meats and other unprocessed foods like fresh fruit and vegetables, and sanitize work surfaces with phage sanitation procedures (Au et al., 2021). Through a process known as phage biocontrol, bacteriophages have also been used in the food sector to increase the shelf-life of various goods. During slaughtering and milking livestock, they can help reduce the germs in the animals. In chickens, bacteriophages are efficient against *Salmonella* and *Campylobacter*, whereas in ruminant animals, they are effective against pathogenic *E. coli* (Furlaneto-Maia et al., 2020).

Phages can also be administered in biofilms as biosanitants to minimize and kill skin-colonizing pathogenic bacteria, i.e., *S. aureus* in food-handlers (Au et al., 2021). This can also be accomplished by reducing nasal or skin exposure to the bacteria. During fermentation, bacteriophages can work as a bio-preservative by acting as a symbiotic organism with fermentative microbes. These phages work as potential bio-preservatives in the food manufacturing and processing sectors by eliminating *L. monocytogenes* from semi-hard and coagulated cheese (Furlaneto-Maia et al., 2020). Additionally, it reduces *Salmonella* in cheddar production and stops the growth of *S. aureus* in curds. Bacteriophages have been employed to prevent the growth of *S. typhimurium* and *Enterobacter sakazakii* in reconstituted newborn formula milk and on chicken frankfurters, respectively (Whichard et al., 2003).

3 Plants as anti-microbial source

Anti-microbial substances derived from plant extracts are constantly being developed as a result of the importance and need to minimise the consumption of chemically produced food-additives. The majority of these compounds are essential oils, herbs, and spices (Choudhary et al., 2022; Lopez-Garcia et al., 2022; Shwaiki et al., 2022). Some examples of these spices and herbs are basil, thyme, rosemary, garlic, oregano, clove, cinnamon, and others (Table 1).

3.1 Essential-oils

Essential oils (EOs) can be extracted from a variety of plant parts, including the roots, leaves, flowers, and bark, using a variety of methods (Angane et al., 2022). These methods include,

- solvent-free extraction using the microwave,
- distillation (hydro-distillation, hydro-diffusion, and steam),
- solvent extraction using subcritical water, supercritical CO_2, and solvent, and
- combined method (steam and solvent).

These phytochemicals are secondary metabolites and aromatic in nature. EOs have been shown to have anti-microbial and antioxidant effects, most notably reducing lipid oxidation and lowering the pathogenic bacteria population (Table 2). They inhibit bacterial growth and work as antioxidants, which prevents food from deteriorating and becoming rancid. This accomplishment is made possible by the presence of biologically active molecules that can prevent the growth of microbial pathogens. These compounds include ketones, terpenes, terpenoids, phenolic acids, and aldehydes (Angane et al., 2022).

It is estimated that essential oils can have anywhere from 20 to 60 different components, each of which can be present in varying concentrations. Because they include a diverse array of components, essential oils exert their anti-microbial effect in many distinct and distinct ways (Amor et al., 2021). In most cases, the prominent components (also known as significant compounds) impact the biological function of the preservative through the application of different mechanisms and affect different cellular areas. However, the anti-bacterial effect of essential oils might be enhanced by the synergistic action of the different components available in food. The cytoplasmic membrane, however, is generally agreed upon as being the primary target in a microbial cell. The permeability of the cytoplasmic membrane in microbial cells is affected by the membrane composition and the molecular hydrophobicity of different molecules that travel through it (Bouarab Chibane et al., 2019). Because of the complex nature of its composition, EOs can exert their anti-microbial effects in many ways. The primary target in bacteria is the cytoplasmic membrane, which regulates cell membrane constituents and molecules' hydrophobicity that flow across the cell membrane. Thus, hydrophobicity of EOs causes functional and structural damage to bacterial cells and cellular membrane, reducing the ATP pool, dissipating proton force, influencing their configuration and fluidity, internal pH imbalance, and loss of metabolites and ions important for cellular functionality, i.e., K and PO_4^{3-}, resulting in cell death (El-Saber Batiha et al., 2021).

For instance, the essential oils (EOs) derived from herbs and spices like mountain pepper (*Tasmannia lanceolata*), galangal (*Alpinia galanga*), lemon iron bark (*Eucalyptus staigerana*), and goraka (*Garcinia quaesita*) have substantial anti-microbials potentials work against food-borne pathogens and bacteria that cause spoilage. The essential oils (EOs) from rosemary and liquorice can potentially limit the different pathogens potential such as *Salmonella typhi*, *Pseudomonas aeruginosa*, *Lactobacillus* spp., *Bacillus cereus*, *Pseudomonas fluorescens*, *E. coli*, and *Listeria monocytogenes*, and when added to specific foods (Angane et al., 2022). In addition to having potent antioxidant and anti-bacterial capabilities, these compounds significantly altered the sensory and organoleptic qualities of the foods to which they were added. As a result, these compounds can be paired with innovative food packaging and preservation techniques. It has been observed that the shelf-life of different animal meats, i.e., Beef and Chicken meat, was enhanced by adding oregano essential oil with modified environment packaging (MAP) (Mokh et al., 2020). In addition, it has been found that terpene and terpenoids agents, such as menthol, geraniol, carvacrol, and thymol, have good anti-bacterial characteristics against *Enterobacter aerogenes*, *L. monocytogenes*, *E. coli*, *S. flexneri*, *S. sonnei*, and *Aspergillus* spp. A group of scholars (Kurita et al., 1979) found thirteen mono-terpenes, including (+)terpinene-4-ol, terpinoel, linalool, (+) pinene, myrcene, (+) limonene, cymene, terpinolene, pinene-1,8-cineole, phellandrene, and terpinene, that possessed. Furthermore, Lin and Zhao (2007) listed the potential anti-bacterial properties of twenty-one mono-terpenes against 25 bacterial strains. These mono-terpenes include carvacrol, geraniol, borneol, d-3-carene, eugenol, R(+) limonene, (2)-linalool, geranyl acetate, cis-3-Hexen-1-ol, cis/trans citral, methyl ester, carvacrol, nerol, menthone, α-pinene, (−) thujone, terpinene-4-ol, α-terpinene, (+) sabinene, β-pinene, and thymol. Carvacrol, eugenol, terpineole, and thymol phenolic monoterpenes are effective against various bacterial strains. They achieve this by preventing biofilm formation by *Staphylococcus aureus* and *Staphylococcus typhimurium*. It has been demonstrated that the monoterpene component linalool, which can be extracted from lavender essential oil, possesses significant anti-bacterial activity against resistant *K. pneumoniae* (Bagheri et al., 2020). It was reported by Torres et al. (2021) that 1′-acetoxy-6′-, 9′-di-benzoyl-oxy-dihydro-agarofuran and di-hydro-agarofuran

TABLE 2 Essential oils (EOs) as anti-microbial agents for food preservation.

EOs source	Applicable food product	Targeting microorganism	Effect	Reference
Thyme	Ground beef	Entero-hemorrhagic *E. coli* O157:H7	Inhibitory action on *E. coli* O157:H7 at 10°C	Solomakos et al. (2008)
Oregano	Minced sheep meat	*Salmonella enteritidis*	Essential oil with a concentration of 0.9% is effective in preventing the proliferation of *Salmonella enteritidis*	Govaris et al. (2010)
Marjoram	Minced pork	*E. coli*	*E. coli* numbers were reduced by one log CFU after 24 h	Munekata et al. (2020)
Thyme	Feta soft cheese, minced beef meat	Vancomycin-resistant enterococci (VRE) and enterohemorrhagic *E. coli* O157:H7	Bacterial growth reduction	Selim (2011)
Purple gromwell, red gromwell, red-root gromwell	Tomato juice	Aerobic mesophiles	No effect on microbes	Balasubramanian et al. (2022)
Cumin-seed	Wheat and chickpea samples	Spoilage causing molds	Molds growth control	Gottardi et al. (2016)
Oregano and garlic	Chicken breast	Natural microflora in native food	The shelf life has been increased from 6 days to 13 days	Giannakourou et al. (2021)
Bay-leaf	Tuscan sausage	Coli-forms	The coliform population was reduced by 3 log CFU/g, and the product's shelf life was increased by 2 days	da Silveira et al. (2014)
Subshrub	Pork meat	*L. monocytogenes*	Bacterial growth reduction	Riešutė et al. (2022)
Clove, cumin	Meat	Natural microflora in native food	The shelf life has been increased up to 15 days	Liu et al. (2017)
Thyme	Minced fish	*Listeria monocytogenes*	*L. monocytogenes* population reduction after 6 days below 2 log CFU/g levels	Yousefi et al. (2020)
Eucalyptus	Apple and orange mixed juice	*Saccharomyces cerevisiae*	Yeast population reduction	Gómez-Llorente et al. (2023)
Mentha	Minced beef meat	Aerobic and psychrotrophic bacteria, i.e., *Pseudomonas* spp., *Enterobacteriaceae* spp.	Bacterial population reduction	Papadochristopoulos et al. (2021)

sesquiterpenes had an inhibiting effect on the growth of *Bacillus* spp. Farnesol, an isoprenoid natural acyclic sesquiterpene alcohol, has been shown to have good anti-bacterial properties against the biofilm formation of *Staphylococcus mutans*, *Staphylococcus sobrinus*, *Staphylococcus epidermidis*, and *Staphylococcus aureus* (Kim et al., 2019; Mahizan et al., 2019). Farnesol and xylitol were also reported to be effective against *Staphylococcus aureus*-induced atopic dermatitis (Katsuyama et al., 2005). These effects occurred without altering the microbiome and efficiently suppressed biofilm creation by *S. aureus*. Another study (Jiménez-Arellanes et al., 2013) showed the potential of *Radermachera boniana* synthesized two triterpenoids (bonianic acid A and B and oleanic acid) effective against *M. tuberculosis*. In addition, the combination therapy of ursolic acid and ergosterol peroxide presented a collegial impact against *M. tuberculosis*. Cunha et al. (2010) reported the anti-bacterial activity of ursolic and oleanic acids produced by *Miconia ligustroides* on various human pathogenic bacterial species like *S. choleraesuis*, *S. pneumoniae*, *Bacillus cereus*, *Vibrio cholerae*, and *Klebsiella pneumoniae*. The minimum inhibitory concentration (MIC) for *B. cereus* when treated with ursolic acid was 20 g/mL, but the MIC for *B. cereus* and *S. pneumoniae*, when treated with oleanic acid, was 80 g/mL. In addition, Kurekci et al. (2013) also mentioned the anti-bacterial potential of organic acids (ursolic and oleanic) against *L. monocytogenes*; however, this activity does not influence the toxin secretion process. Garlic essential oils have a potent anti-bacterial effect against *Salmonella typhimurium*, *Escherichia coli*, and *Staphylococcus aureus*, which causes the cell membranes of the bacterium to be destroyed. Several different essential oils (EOs) are effective against bacteria that cause food to deteriorate. These EOs come from rosemary, basil, citrus peel, and lemongrass (Aloui et al., 2014).

EOs have been shown to suppress the growth of microbes in various food products, including dairy and fruit juice. It has been observed that cinnamon essential oils (EOs) in heated apple juice effectively suppress the growth of *L. monocytogenes*. Additionally, clove and cinnamon-based essential oils have a preservative effect when applied to semi-skimmed milk (Tang et al., 2018). Similarly, essential oils (EOs) derived from clove, bay, cinnamon, and thyme are helpful in preventing the growth of *L. monocytogenes* found in various dairy products, i.e., cheese (Figueroa-Lopez et al., 2020). In another study, a combined effect of MAP gasses with EOs from thyme, oregano, and lemongrass was evaluated for their anti-microbial potential against mesophilic bacteria community in sprouts, radishes, and cabbage (Karabagias et al., 2011). This synergy produced an almost complete inhibitory effect on the microbial community, exhibiting the strongest efficacy of these EOs compared to alternative packaging approaches against a large microbial community.

The utilization of EOs has resulted in an extension of the shelf-life of meat and the products derived from it. Thyme and oregano EOs were combined with MAP at 0.1–0.3% concentrations. Additionally, they were utilized with nisin and significantly decreased the populations of food-borne pathogens like *L. monocytogenes* and *E. coli* O157:H7 (Solomakos et al., 2008). The application of rosemary EOs and subsequent refrigeration of the minced beef resulted in a considerable decrease in *Campylobacter jejuni* found in the meat. All of these factors lead to the efficacy of essential oils (EOs) as anti-microbial agents when utilized in low-temperature storage environments (Piskernik et al., 2011).

The volatile components of EOs from various plants were tested for spoilage caused by many fungi, including *Trogoderma granarium*, *A. niger*, and *A. flavus*. In addition to food preservation, EOs are used in pharmaceuticals, cosmetics, and skin-care products (Li et al., 2022). *Putranjiva roxburghii* essential oil has the strongest fungicidal potential without affecting plant morphological characteristics or plant health (Tripathi and Kumar, 2007). Consequently, essential oils are an efficient solution for synthetic chemicals currently utilized as antifungals. These synthetic compounds may leave behind toxic residues and harm consumers. Furthermore, many reports (Guidotti-Takeuchi et al., 2022; Gulin-Sarfraz et al., 2022; Li et al., 2022) advise about microbial cross-adaptation induced by sub-lethal dosages and improper anti-bacterial cycling in the food business. Both of these factors may reduce the effectiveness of compounds.

3.2 Spices and herbs

Numerous studies have underscored the efficacy of spices, herbs, and their extracts in various forms—whole, powdered, and encapsulated—as potent natural antimicrobial agents (El-Saber Batiha et al., 2021; Khatri et al., 2023). The anti-microbial and antioxidant properties of these plant-derived substances are attributed to the presence of secondary metabolites, encompassing alkenyl phenols, phenolic acids, alkaloids, flavonoids, tannins, terpenoids, sesquiterpenes, saponins, and glycol (Salamatullah et al., 2021). These compounds not only combat spoilage microorganisms but also impart antioxidant benefits, mitigating oxidative spoilage.

The aromatic and volatile molecules inherent in spices and herbs serve as a natural defense mechanism for plants against organisms that feed on them, found in various plant parts such as flowers, bark, and roots (Jung and Rubin, 2020; Rajput et al., 2023). Beyond their microbial-fighting attributes, these plant chemicals act as antioxidants, enhancing both color and flavor in plants. Applications of grape seed, oregano, clove, and cinnamon extracts have been reported to not only influence the color characteristics of food but also elevate its flavor profile (Baindara and Mandal, 2022; Coimbra et al., 2022; Elshafie et al., 2022; Khatri et al., 2023).

While some safety concerns exist, the majority of plant-derived antimicrobials are generally recognized as safe (GRAS). These extracts play a crucial role in limiting the growth of pathogenic microbes responsible for causing diseases, requiring their presence in sufficient quantities to effectively inhibit bacteria harmful to food. Various extraction processes are employed to extract these biomolecules (Tako et al., 2020; Mandal et al., 2023). Shan et al. (2009) demonstrated the regulatory effects of herb-derived extracts, including grape seed, cinnamon, oregano, clove, and pomegranate peel, on spoilage and pathogenic microorganisms in raw pork-meat stored at 20°C for 9 days. These extracts reduced oxidative deterioration and microbial load, with clove proving most effective against bacterial deterioration and oxidative rancidity (Gonelimali et al., 2018; Sharma et al., 2020; Friedlein et al., 2021; Rajput et al., 2023).

Notably, clove, a spice with culinary and therapeutic uses, possesses antioxidant and antibacterial qualities, positioning it as a potential substitute for synthetic preservatives, especially in meat products. However, consumer acceptability remains a significant concern (Batiha et al., 2020). The importance of certain spice and herb extracts in preserving product quality and minimizing deterioration has been emphasized by scholars (Aziz and Karboune, 2018; Khan et al., 2020; Azizun et al., 2021; Rajput et al., 2023). These bio-preservatives play a crucial role in addressing bacterial resistance concerns associated with chemical antimicrobials while ensuring the safety of food products without adverse effects on consumers. Given these attributes, extracts from spices and herbs present a promising alternative to synthetic additives currently prevalent in the market (Batiha et al., 2020).

3.3 Plant antimicrobial peptides

Since their discovery in 1942, anti-microbial peptides have been produced by organisms as diverse as bacteria, animals, and plants to combat pathogens (Omidbakhsh Amiri et al., 2021). They are amphiphilic and mostly positively charged. Anti-microbial peptides play a significant role in a plant's protection against infection, both in the defense reflex and the preexisting defense barrier (Baindara and Mandal, 2022) (Figure 3). Research has shown that a peptide plays a defensive role against the pathogen. It can be shown if peptide-sensitive bacterial variants display lower pathogenicity in plant tissues expressing the peptide or overexpression of the peptide increases plant resistance to the pathogen. Most peptides inhibit both Gram-negative and Gram-positive bacteria. Majorly, various plant varieties and their tissues have released cysteine-rich plant pAMPs. A recent study (Omidbakhsh Amiri et al., 2021) identified over 20 pAMPs from plant tissues. Although the number of pAMPs families is subject to debate, separate protein families can be identified based on structure and amino acid sequence features.

Plant antimicrobial peptides (pAMPs) play crucial roles in the immune system, the enzymatic pathway required for metabolism, as a food and a storage molecule, and are found in a wide variety of plant and plant parts (Shwaiki et al., 2022). Over the past two decades, 1,500 anti-microbial peptides have been reported from insects, plants, microbes, amphibians, and mammals. Anti-microbial peptides have antioxidant, antithrombotic, antihypertensive, and immunomodulatory properties. Anti-microbial peptides are classified according to the metabolic pathway. Bacitracin and glycopeptides are in the first group, while ribosomally produced peptides in the organism's innate defence mechanism are categorized in the second group. Anti-microbial peptides can alter the porosity of bacterial membranes due to their amphiphilic property and the availability of positively charged residues. pAMPs inhibit fungal cell wall chitin production and membrane permeability by attacking peptides (Omidbakhsh Amiri et al., 2021). The cationic lactoferrin peptide demonstrates that pAMPs bind glycosaminoglycan on cell membranes, preventing virus-cell interaction.

3.4 Antioxidants

Antioxidants are naturally occurring molecules that prevent food damage caused by an oxidative environment. These oxidative damages cause alterations in food's nutritional and sensory characteristics (Embuscado, 2015; Aziz and Karboune, 2018; Bajpai et al., 2019). Antioxidants are found in fruits, vegetables, nuts, and seeds. They are also helpful in preventing various diseases that happen due to oxidative stress. Carotenoids, ascorbic acid, phenolic compounds, and tocopherol (also known as vitamin E) are all-natural antioxidants in foods. When it comes to naturally occurring antioxidants, phenolic compounds are by far the most well-known and influential. This is because phenolic compounds have a powerful effect on scavenging free radicals and have good anticancer and antidiabetic actions (Embuscado, 2015). Green tea, ginger, turmeric, strawberries, blackberries, blueberries, saffron, rosemary, and chili are widely acceptable and utilize natural antioxidant sources as additives (Suvarna et al., 2022). In addition to regulating the immune system, antioxidants have a preventative action on cardiovascular and neurological disorders. Some EOs have good antioxidant activities and can potentially replace the chemical antioxidants now utilized as food preservatives.

4 Animal sources as natural anti-microbial resources

In animals, proteins and enzymes are the prominent naturally produced anti-microbial compounds. The enzyme lactoperoxidase, the protein lactoferrin, and the enzyme lysozyme are all examples of natural substances (Kasimanickam et al., 2021; Njoga et al., 2021; Pessoa et al., 2021). Because of their anti-bacterial properties, many of these compounds are primarily used by animals as a defensive mechanism against various types of predation. They are effective for Gram-positive and Gram-negative bacteria because they disrupt the integrity of their respective cell membranes, thereby killing off the bacteria.

4.1 Lysozymes

Lysozymes are another type of naturally occurring compound that can be found in animals and are decisive against the germs that cause spoiling. They are considered GRAS and can be added to food matrices without additional processing. Lysozymes have attracted much attention due to their remarkable stability across a broad pH (2–10) range and temperatures (4°C to 95°C). Studies have been done on the effectiveness of lysozymes in combating various bacteria that cause disease and food spoilage (Agazzi et al., 2023; Naveed et al., 2023). *Listeria monocytogenes*, *Bacillus stearothermophilus*, *Clostridium tyrobutyricum*, and *Micrococcus* spp. are bacteria that are particularly susceptible to the effects of lysozymes (Davidson et al., 2012). The antimicrobial effect of lysozyme was traced back to its ability to break the bacterial cell-wall peptidoglycan layer by the hydrolysis of N-acetyl muramic acid and N-acetyl glucosamine cross bonds (Zhang et al., 2022). However, it has been observed that the effectiveness of lysozyme in suppressing Gram-negative bacteria is restricted by the presence of the lipopolysaccharides layer, which limits the access of these bacteria to the site where lysozyme is most effective. Several research-level strategies that could increase the activity of lysozymes against Gram-negative bacteria have been proposed with the hope of expanding the applications of lysozymes in the food industry. Proteins can be modified in many different ways, including by glycosylation, chelation, lysine attachment to saturated fatty-acids, temperature denaturation, disulfide bond reduction, and denaturation (Masschalck and Michiels, 2003). Kerkaert and De Meulenaer (2007) reported that lysozyme was employed in semi-hard cheeses on a large scale to

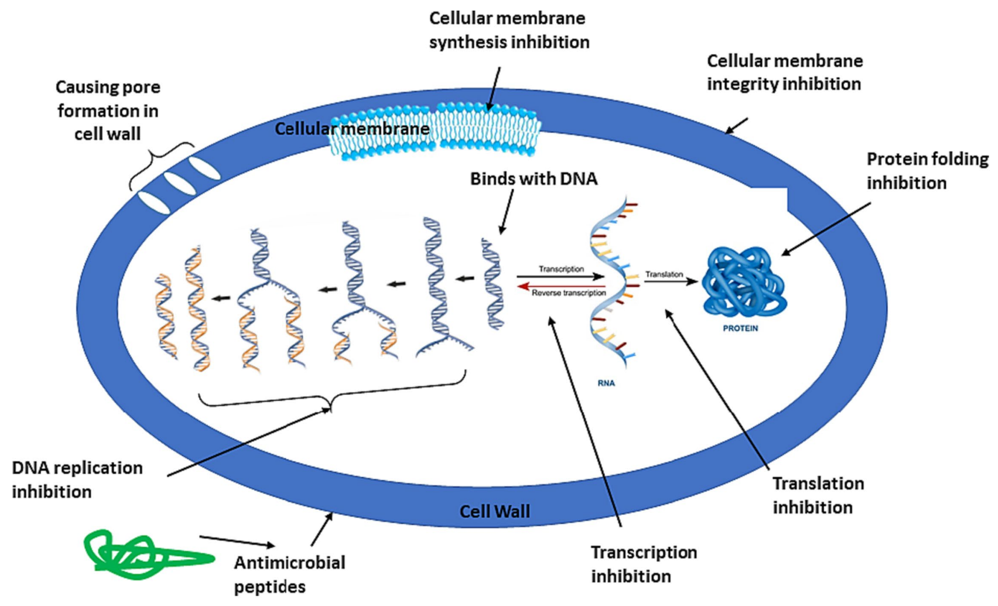

FIGURE 3
Various mechanisms used by anti-microbial peptides against bacteria cell.

suppress *C. tyrobutyricum* late-blowing. It has been demonstrated that lysozyme has a protective role in the human immune system, assisting it in fighting against many diseases (Masschalck and Michiels, 2003). As a result, they can be utilized to change and block the activities of bacteria undesired in food.

4.2 Chitosan

Chitin is a poly-cationic linear poly-saccharide primarily found in the exoskeletons of marine crustaceans. The process of partial deacetylation transforms chitin into chitosan, with glucosamine polymers and N-acetyl glucosamine being its principal constituents (Gumienna and Gorna, 2021). Chitosan can be derived from fungi and extracted from crustaceans such as crabs and shrimp through chemical and microbiological processes involving organisms like *A. niger*, *Mucor rouxii*, and *Penicillium notatum*. With regard to its potential as a natural food preservative against a broad spectrum of pathogens, chitosan exhibits non-toxicity, biodegradability, and high adaptability (Wronska et al., 2021). Its antimicrobial properties render it effective against various microorganisms, including molds, yeast, and both Gram-positive and Gram-negative bacteria.

4.3 Lactoferrin

In addition to LPS, lactoferrin is another naturally occurring anti-bacterial molecule that may be found in milk. It is used in the food industry to prevent the growth of pathogenic and spoilage-causing microbes (Al-Nabulsi and Holley, 2005). In addition to its anti-bacterial properties, the globular glycoprotein found in milk also possesses anti-obesity, anti-carcinogenic, and anti-carcinogenic properties, making it a multifunctional substance. In Japan and a number of other countries, lactoferrin is applied in yogurt and other foods as a bio-preservative (El-Fakharany, 2020). Edible anti-microbial coatings were produced in limited quantities to restrict the development of pathogenic microorganisms on the surfaces of ready-to-eat foods. Lactoferrins are found in the respiratory, reproductive, and digestive secretions of animals and humans. They are present in large amounts in cow's colostrum and have powerful anti-microbial effects against both Gram-positive and Gram-negative bacteria and fungi (El-Fakharany, 2020). In addition, they exert a potent inhibitory effect on bacteriostatic organisms. Bacteriostatic organisms prevent deterioration and the proliferation of pathogenic germs without necessarily eliminating them. The powerful antibacterial characteristics of lactoferrin against various food-borne pathogens such as *E. coli*, *Klebsiella*, *Carnobacterium*, and *L. monocytogenes* are observed (Hogendorf et al., 2013; Zhang et al., 2017; El-Fakharany, 2020). It has been observed that lactoferrin can reduce the *Cronobacter* spp. initial population by 10^4 CFU/mL at 37°C incubation temperature for 4 h (Martins et al., 2016).

When lactoferrin (1 mg/mL) was added to an *L. monocytogenes* culture and cultured at 37°C for 8 h, the bacterial population dropped from 10^9 to 10^4 CFU/mL (Ripolles et al., 2015). Its antibacterial action was due to its iron chelation property, which reduced microorganisms' proximity to nutrients and led to the breakdown of the outer membrane of Gram-negative bacteria. It was only because iron chelation was present that this was possible (Ripolles et al., 2015). Because lactoferrins have a low inhibitory effect on the growth of pathogens in fermented meat, they cannot be employed in this context. In addition, lactoferrins coupled with lysozyme as film coatings are effective against many salmon fish fillet microorganisms.

4.4 Lactoperoxidase

Another type of anti-bacterial substance derived from animals is known as lactoperoxidase (LPS). The epithelial cells of the mammary gland secrete an enzyme that is present in cow's milk in high concentrations (Cissé et al., 2015). The level of LPS in cow's milk is 20 times higher than that found in human breast milk. LPS is an effective agent that can suppress the growth of bacteria, including Coliforms, *Pseudomonas*, *Shigella*, and *Salmonellae*, and destroy them (Arqués et al., 2008). There is currently a paucity of knowledge regarding the use of this enzyme as an anti-bacterial agent on chicken and other animal foods. However, further research needs to be done on their potential usage in meat products as this enzyme is abundant in cow-milk and has a cost advantage over synthetically made additives currently available in the market.

5 Natural antimicrobials in food preservation: trends, challenges, and future directions

The field of food preservation is experiencing a paradigm shift, with a pronounced emphasis on harnessing natural antimicrobial compounds to ensure food safety and quality (Angane et al., 2022). In this section, we elaborated the most important trends in the utilization of natural antimicrobials in the realm of food preservation, shedding light on their significance, challenges, and potential future directions.

5.1 Rising interest in natural antimicrobials

There is a discernible surge in interest surrounding the use of natural antimicrobial compounds derived from plants, bacteria, and enzymes. Researchers are increasingly exploring these naturally occurring substances as alternatives to synthetic counterparts, driven by a growing awareness of the environmental and health implications associated with artificial additives (Njoga et al., 2021; Ahmed et al., 2022).

5.2 Safety and health considerations

Natural antimicrobials offer a distinct advantage in terms of safety. Unlike synthetic chemicals, these compounds pose minimal health risks for consumers (Njoga et al., 2021). This aspect is gaining paramount importance in an era where consumers are becoming more discerning about the quality and safety of the food they consume. The shift towards natural antimicrobials aligns with the broader trend of clean label preferences among consumers (Pessoa et al., 2021).

5.3 Underexplored potential of naturally derived molecules

Despite the increasing focus on natural antimicrobials, a substantial portion of these compounds remains underexplored. This presents an intriguing area for further research and discovery. Unlocking the full potential of naturally derived molecules holds the key to developing innovative and effective solutions for food preservation (Riešutė et al., 2022).

5.4 Replacement of synthetic chemicals in the food sector

The demand for sustainable and environmentally friendly practices has led to a reevaluation of synthetic chemicals in the food sector. Natural antimicrobials provide an opportunity to replace hazardous synthetic additives, aligning with the global movement towards greener and more sustainable food production practices (Njoga et al., 2021; Han et al., 2022).

5.5 Challenges in sensory quality preservation

While the adoption of natural antimicrobials is on the rise, there exists a potential challenge related to the preservation of sensory qualities in food products (Davidson et al., 2012; Njoga et al., 2021). The incorporation of these additives may impact the taste, aroma, and overall sensory experience of the final product. Striking a balance between effective antimicrobial action and minimal impact on sensory attributes remains a critical area for optimization.

5.6 Optimization of effective quantities

Advancements in research have led to the identification of numerous natural antimicrobial compounds; however, further investigation is necessary to determine the optimal quantities for inhibiting pathogenic microorganisms effectively. Achieving the right balance is crucial to ensure both the safety of the product and the preservation of its sensory qualities (Han et al., 2022).

The current trends in natural antimicrobials for food preservation reflect a dynamic landscape marked by a shift towards sustainability, safety, and consumer preference for natural ingredients (Njoga et al., 2021). While significant strides have been made in exploring the potential of these compounds, there remains untapped potential and challenges, particularly in preserving sensory qualities (Zhao et al., 2023). Future research endeavors should focus on unlocking the full potential of underexplored molecules, optimizing effective quantities, and addressing challenges associated with sensory quality preservation. As the food industry continues to evolve, the judicious use of natural antimicrobials holds promise for revolutionizing food preservation practices on a global scale.

6 Use of naturally occurring anti-microbials in edible coatings

Edible coatings are produced by biological actions. These coatings are thin layers of biologically formed polymer molecules. They've been employed on food surfaces by electrostatic coatings, sprinkling, brushing, or soaking. The characteristics of edible coatings rely on coating attributes such as degree of crosslinking, viscosity of coating solutions, coating thickness, structure, composition, chemical processing conditions like concentration, temperature, pH, and the solvent type and additives plasticizers emulsifiers, and crosslinking agents (Bouarab Chibane et al., 2019). These coatings are improved by adding physiologically active compounds with anti-bacterial and antioxidant properties to food. Edible coatings are more environmentally friendly than synthetic counterparts. Edible coatings can be made from polysaccharides, lipids, and proteins from food manufacturing leftovers and sustainable agricultural materials. The effectiveness of edible coating in preserving food quality and prolonging shelf-life is determined by the coating material's chemical composition and structure, the coated object's qualities, and even the handling and storage environment (Bouarab Chibane et al., 2019). Directly adding natural anti-microbials to food systems has reduced microbiological contamination. However, the regulated diffusion of anti-microbial substances through edible coatings into large volumes of food products and their reactions with food items can reduce their anti-microbial potency during preservation and prevent their practical usage in food manufacturing practices. Thus, as carriers for natural anti-microbials, edible coatings can be employed to improve food quality, and safety is slowly growing in the packaging industry for food items.

Park et al. (2004) applied chitosan (2%) and lysozyme (10%) to develop a lysozyme-chitosan polymer film as an anti-bacterial coating film. There have been reports of the effectiveness of various plant extracts and essential oils in suppressing food-borne pathogens, including *E. coli* O157: H7, *L. monocytogenes*, and *Salmonella* spp. (Torres Dominguez et al., 2019; Fu and Dudley, 2021). These extracts and EOs have been integrated into these edible coatings. Furthermore, other researchers have developed a grape-fruit seed extract containing edible film for strawberries. The edible strawberry film apparently suppressed the proliferation of *E. coli* O157: H7 and *L. monocytogenes*, and after 14 days of storage, the population of mold, yeast, and aerobic bacteria was drastically reduced (Batiha et al., 2020). Further researchers found that edible lemon grass oil films inhibited *Listeria monocytogenes* and *Escherichia coli* strain ATCC-25922 development in liquid-food. Numerous research studies suggest that edible-coated anti-microbial compounds can suppress food-borne microbial metabolites in food (Bouarab Chibane et al., 2019; Torres Dominguez et al., 2019).

In contrast to direct applications, this method can provide foods with a relatively localized functional benefit while maintaining their organoleptic and sensory attributes. Edible coatings can also act as semipermeable barriers to protect food against respiration, oxidative reactions, moisture loss, solute migration, and gas exchange. Food ingredients like fat and protein may produce a coating around microorganisms or absorb the anti-bacterial ingredient, reducing the amount and potency in aqueous environments (Cissé et al., 2015). Therefore, the addition of natural anti-bacterial solutions into packaging technologies, also known as "bioactive packaging," has made it feasible to improve the safety of foodstuffs and extend their shelf-life. Edible coatings can also reduce the exchange of gases across foodstuffs and their surroundings, slowing metabolism and delaying fresh product maturation and deterioration. Polysaccharide coatings have been found to preserve natural anti-microbials and enhance the stability of freshly and minimally processed fruits such as blueberry, grape, mango, orange, fresh cut apple, fresh cut pineapple, and moderately processed papaya (Figueroa-Lopez et al., 2020).

In addition, incorporating various naturally occurring anti-microbial compounds, in particular, essential oils (EOs), into edible coatings has been demonstrated to have excellent outcomes in terms of increasing the shelf-life of sea-foods and chicken meat (Fu and Dudley, 2021). Contrarily, they effectively maintain quality and improve the shelf life of a variety of food products; their application as the anti-microbials carrier in the manufacturing industries is limited due to the formation of weak-bonds with hydrophilic molecules that cause carrier materials to degrade or desorb anti-microbials quickly. Polysaccharides such as sodium alginate (NaAlg) and hydroxyl propyl methyl cellulose (HPMC) have been used in edible coating preparations for fresh items due to their strong coating-forming characteristics and preferential permeability (Aloui et al., 2014). Chitosan is a positively charged high-molecular weight chemical ranging from 50 to 2000 kDa. It is soluble in water and can form films and gels. These properties have made chitosan a primary applicant to be used widely in food coatings and edible anti-microbial coatings, and it has various benefits over alternative bio-based packaging materials for food. Several different types of chitosan-based anti-microbial coatings for foodstuffs have been researched. When used in conjunction with lauric alginate and nisin, Chitosan has been successfully applied as coatings and wrapping film to salami and coating to reduce the number of *Listeria monocytogenes* in chopped turkey deli meat, as well as seafood and fish (Cissé et al., 2015). When applied with 0.7% oregano EOs, chitosan coatings also kill *Pseudomonas* spp. and *Brochothrix thermosphacta*. Gelatin films with nisaplin at concentrations ranging from 0.025–0.5% w/v (nisin) have been used to kill *L. monocytogenes* in turkey bologna (Petrou et al., 2012). EOs and whey protein isolate-based edible coatings were tested for anti-bacterial activity. In meat sausages with 1% sorbic acid, they killed *L. monocytogenes*, *S. enterica typhimurium*, and *E. coli* O157:H7. In beef milk protein coatings with oregano EOs, prevent *E. coli* and *Pseudomonas* (Moreira et al., 2014). A novel film production technology called layer-by-layer (LbL) coating is becoming popular for coating perishable goods, notably fresh-cut fruits like fresh-cut melons, watermelons, and pineapples (Torres Dominguez et al., 2019; Rollini et al., 2020).

7 Anti-microbial packaging of food products

Ongoing investigations focus on the incorporation of antimicrobial agents into active packaging, presenting researchers with various challenges. The mobilization of food additives, including spices, fortified nutrients, flavors, colorants, antimicrobials, and antioxidants, within active packaging has been extensively studied (Amor et al., 2021; Maresca and Mauriello, 2022; Shwaiki et al., 2022). These antimicrobial solutions are integrated into edible coatings or films within active packaging, with controlled release onto food surfaces. This method offers a potentially superior alternative to the direct application of antibacterial agents onto food surfaces, allowing for regulated diffusion into the interior.

Numerous studies have explored the utilization of natural antimicrobials in active packaging solutions (Ahmed et al., 2022; Gulin-Sarfraz et al., 2022). Chitosan, essential oils, enzymes, and other naturally occurring antimicrobial compounds discussed previously are employed as inclusions in active packaging solutions. The combined application of active packaging solutions in foods has demonstrated efficacy in preventing the growth and activity of harmful bacteria, including pathogenic *E. coli*, *S. aureus*, and *L. monocytogenes* (Bouarab Chibane et al., 2019; Figueroa-Lopez et al., 2020; Wronska et al., 2021).

Recent research has focused on more integrated antimicrobial inclusions in food packaging, exploring their broad-spectrum actions against spoilage and pathogenic microbes. However, limitations persist in the commercial preservation of liquid foods using active packaging solutions. These constraints encompass food safety regulatory issues, the absence of suitable antimicrobials for liquid foods, and compatibility challenges with emerging polymer packaging materials. Despite similar limitations in the commercial preservation of solid foods against microorganisms, active packaging solutions are still subject to certain restrictions in the context of liquid food preservation.

8 The application of nanoparticles in the process of preserving food

Nanotechnology is a relatively new science that plays an increasingly important role in food production (Guidotti-Takeuchi et al., 2022). In recent years, numerous investigations on the application of nanotechnology in the food manufacturing business have been carried out. Recent research has shown that this method is superior for improving the efficiency of naturally occurring anti-bacterial compounds and the functionality and quality of food products (Suvarna et al., 2022). This was fulfilled using the development of nano-encapsulating and nano-laminate delivery systems. Nano-encapsulated delivery methods used for anti-microbial chemicals increase stability and solubility and prevent direct reactivity of anti-microbials with food ingredients during food preparation and refrigeration. Nanocarriers are effective as delivery systems for anti-microbials; however, their usage and incorporation into food systems are complicated and underexploited. Despite this, the use of anti-microbial substances that are based on nanotechnology is a promising avenue for the prevention of the spoilage of food (Rollini et al., 2020; Babaei-Ghazvini et al., 2021).

The use of nano-encapsulation technology in food preservation, i.e., nano-emulsions, is gaining focus in the food business at present. They can be added to food as ingredients with processing techniques that are less complicated in the industry and entail vigorous mixing (Babaei-Ghazvini et al., 2021). They preserve the food's sensorial and organoleptic qualities and are effective as anti-microbials to control food-borne pathogens and other contaminants. However, there are challenges linked with utilizing nano-droplets as an inhibitory agent against pathogenic and food spoilage bacteria on food surfaces and as a preservative for some qualitative characteristics of various foods, especially when applied to solid food like fruits and meat products. They are also appropriate for inclusion in food products that lack specific functional features, such as optical properties, because they do not contribute to those properties themselves (Guidotti-Takeuchi et al., 2022). Recent developments have been made in manufacturing *in-situ* nano-emulsions from edible coatings based on biopolymers. These nano-emulsions have been examined and proven to be an efficient method of placing anti-microbial compounds on the surface of solid items (Gulin-Sarfraz et al., 2022). The findings of these investigations appear to hold promise for enhancing the quality and safety of goods based on meat, fresh fruits, and vegetables.

8.1 Nanoparticles and nano-vesicles

Natural chemicals can minimize the impact of some food ingredients, which adds another layer of complexity and creates a challenge in using anti-microbials in the food system. Nanoparticles and nano-vesicles have been produced since they have much-untapped potential, preserve food effectively, and regulate food quality intact (Azizun et al., 2021). Investigations have shown that egg white lysozyme catalyzes the formation of silver nanoparticles, which preserve the hydrolase functionality of lysozymes (Agazzi et al., 2023). When employed, the produced nanoparticles are efficient against *Candida albicans*, *Staphylococcus aureus*, *Escherichia coli*, and *Bacillus anthracis* (Rollini et al., 2020). At the same time as it was effective against antibiotic-resistant *E. coli* strains, the substance that was produced also showed substantial activity against *Proteus mirabilis*, which is resistant to silver. Silver nanoparticles are harmless in human epidermal keratinocyte research when the correct quantities are employed to inhibit the growth of microorganisms. Nisin nanoparticles have shown positive and encouraging results in tests conducted against *Staphylococcus aureus* and *Listeria monocytogenes* (Chatzidaki et al., 2019). It has also been observed that nanoparticles and nano-vesicles containing bacteriocin have a powerful effect against various harmful microorganisms. Although this technology has the potential to be helpful, some consumers are worried about its impact on their safety. As a result, additional research on the topic of safety is required to assuage consumers' concerns and identify the nanoparticle concentrations that are most effective as anti-microbial agents.

8.2 Anti-microbial coatings made of many layers with nanoparticles

Utilizing anti-microbial multi-layer coatings has been proposed as an effective strategy to retain anti-microbial compounds adequately, incorporating a controlled release mechanism (Ansari, 2023). This technique involves integrating anti-microbial chemicals into multi-layered and nanolaminate systems (control-layer, matrix-layer, and barrier-layer) through the electrostatic deposition of layer-by-layer (LbL) techniques (Babaei-Ghazvini et al., 2021). The process entails immersing solid substrates in film-forming solutions of oppositely charged polyelectrolytes, with surplus solutions removed after each immersion phase. The inner and protective layers of multi-layer coatings restrict the dispersion of anti-microbial substances within the food matrix layer, creating an efficient delivery mechanism (Chatzidaki et al., 2019; Manikandan et al., 2023). The design of the multi-layered packaging influences the dispersion of anti-microbials, considering factors such as packaging thickness, diffusion pathway fluctuations, and the interaction between the anti-microbial solution and the polymer. The LbL assembly approach is gaining attention for coating anti-bacterial solutions in perishable products like fresh meat and fruit (Moreira et al., 2014). This method enhances coated food stability and quality by producing multi-layer coatings with specified properties, thicknesses, and performance. Multi-layered edible coatings, consisting of pectin, sodium alginate, calcium chloride, and anti-microbials in nano-emulsion form, have shown promise in extending the shelf life of fresh-cut fruits, preserving sensory characteristics, and reducing weight loss (Mantilla et al., 2013; Sipahi et al., 2013). Additionally, research by Moreira et al. (2014) highlighted the effectiveness of anti-microbial multi-layered edible coatings against a broad spectrum of microbes.

8.3 Unfavourable effects of nanoparticles

Nanoscale anti-microbial edible coatings can preserve food quality, extend shelf-life, and prevent microorganism-induced deterioration. There is a possibility that the usage of this technology in foods will harm the human body (El-Fakharany, 2020). Although the structure of nanoparticles might not directly influence human health, the nanoscale features of nanoparticles might result in side effects that are unavoidable when they are directly exposed to humans. Nanoparticles and other nanomaterials that have been created can enter the human body through the lungs, the digestive system, or through dermal holes (El-Fakharany, 2020; Suvarna et al., 2022). The degree to which many of these nanoparticles are toxic is dependent not only on their properties but also on how they enter the human body, the concentration of the nanoparticles that they are exposed to, how long they are exposed to them, and the individual's immune system, which may have a significant bearing on the matter. When relatively high doses of nano-silver particles were used, the outcomes of the oral mode of administration revealed signs of toxicity (Aschberger et al., 2011).

9 Natural anti-microbials: regulation for food application

Global regulations impose strict limitations on food additives, yet there is a lack of consensus among nations regarding the safety, permissible quantities, and legal parameters for consuming food (Juneja et al., 2012). Only a select few European chemicals, such as organic acids, have gained approval as food preservatives, subject to a rigorous process overseen by the European Commission. Individuals proposing new food additives must formally request approval, providing crucial information on the product's scientific safety. Upon approval, the European Commission tasks the European Food Safety Authority (EFSA) with assessing the substance's safety for its intended use, ensuring compliance with EU standards (Hintz et al., 2015).

In the United States, the Food and Drug Administration (FDA) possesses the authority to approve various food additives for use. The FDA evaluates the risks associated with unapproved additives, considering consumption levels, short- and long-term health effects, and safety factors. Approved additives are governed by regulations in Title 21 of the Code of Federal Regulations, specifying allowable quantities, permitted food categories, and accurate labeling (Torres Dominguez et al., 2019; Samtiya et al., 2022).

Conversely, the Environmental Protection Agency (EPA) establishes standards guiding the FDA in regulating pesticide presence in food. Antimicrobials in food packaging, excluded from the "pesticide chemical" definition, fall under FDA oversight as food additives.

10 Advantages and disadvantages of natural antimicrobials in food preservation

Food preservation is a critical aspect of the food industry, aiming to extend the shelf life of products while maintaining their safety and quality (Gottardi et al., 2016). In recent years, there has been a growing interest in the use of natural antimicrobials as alternatives to synthetic additives for preserving food. These natural compounds, derived from plants, bacteria, and enzymes, offer a range of advantages and disadvantages that impact their effectiveness in food preservation (El-Saber Batiha et al., 2021).

10.1 Advantages

10.1.1 Enhanced safety

One of the primary advantages of natural antimicrobials is their enhanced safety profile compared to synthetic counterparts. Synthetic additives may sometimes pose health risks to consumers, and the shift towards natural alternatives aligns with the increasing demand for safer and healthier food options (El-Saber Batiha et al., 2021). Consumers are becoming more conscious of the potential adverse effects of synthetic chemicals, driving the food industry to explore safer alternatives (Gottardi et al., 2016).

10.1.2 Antimicrobial and antioxidant properties

Natural antimicrobials often exhibit dual functionality by acting as both antimicrobial and antioxidant agents (Zhang et al., 2023). These compounds not only inhibit the growth of pathogenic microorganisms but also prevent oxidative deterioration of food, contributing to the overall quality and stability of the product. This dual action is particularly beneficial in preserving the sensory attributes and nutritional content of the food.

10.1.3 Environmental sustainability

The use of natural antimicrobials aligns with the growing emphasis on environmental sustainability. Synthetic additives may have environmental implications during production, use, and disposal. Natural antimicrobials, being derived from renewable resources, offer a more sustainable alternative, reducing the ecological footprint associated with food preservation practices (Sharma et al., 2023).

10.1.4 Consumer preference

As consumers become more informed about the origin and composition of their food, there is a rising preference for natural and minimally processed products (Zhang et al., 2023). The use of natural antimicrobials caters to this demand, as it aligns with the trend towards clean-label and natural food products. Manufacturers leveraging natural antimicrobials can capitalize on consumer preferences for products perceived as healthier and more environmentally friendly (El-Saber Batiha et al., 2021).

10.1.5 Potential health benefits

Some natural antimicrobials may possess additional health benefits beyond their preservative properties. For instance, certain plant-derived compounds have been studied for their potential anti-inflammatory, anti-cancer, and immune-modulating effects (Setiarto and Anshory, 2024). Integrating such bioactive compounds into food preservation may contribute to functional foods that promote health and wellness (Gottardi et al., 2016; Papadochristopoulos et al., 2021).

10.2 Disadvantages

10.2.1 Variable efficacy

The effectiveness of natural antimicrobials can vary depending on factors such as source, concentration, and the specific microorganisms targeted. Achieving consistent and reliable antimicrobial activity across different food matrices and storage conditions can be challenging. This variability may limit the widespread adoption of natural antimicrobials in certain applications (Papadochristopoulos et al., 2021).

10.2.2 Impact on sensory qualities

While natural antimicrobials are generally considered safe, they can sometimes affect the sensory qualities of food products. Changes in taste, color, and texture may occur, especially when these compounds are used at higher concentrations (Angane et al., 2022; Coimbra et al., 2022). Striking a balance between effective antimicrobial activity and minimal impact on sensory attributes requires careful optimization in product development.

10.2.3 Cost considerations

The production and extraction of natural antimicrobials can be more expensive than their synthetic counterparts. This cost factor may influence the feasibility of large-scale implementation, especially for smaller food producers with tighter budget constraints. Research and innovation are needed to develop cost-effective methods for extracting and utilizing natural antimicrobials in food preservation (Manikandan et al., 2023).

10.2.4 Limited understanding of mechanisms

Despite advancements in research, the mechanisms of action of many natural antimicrobials remain incompletely understood (Elshafie et al., 2022). This lack of detailed understanding can hinder the precise control and optimization of these compounds for specific applications. Further research is needed to unravel the complex interactions between natural antimicrobials and different types of microorganisms (Papadochristopoulos et al., 2021).

10.2.5 Regulatory challenges

Regulatory approval for the use of natural antimicrobials in food products can be complex and time-consuming. Establishing safety and efficacy profiles, as well as determining acceptable usage levels, requires rigorous testing and documentation. The regulatory landscape is evolving, but navigating the approval process remains a challenge for food manufacturers seeking to incorporate natural antimicrobials into their products (Samtiya et al., 2022).

The use of natural antimicrobials in food preservation presents a promising avenue for addressing consumer concerns about synthetic additives while promoting sustainability and safety. The advantages of enhanced safety, dual functionality, environmental sustainability, consumer preference, and potential health benefits make natural antimicrobials an attractive option for the food industry (Torres Dominguez et al., 2019). However, challenges related to variable efficacy, impact on sensory qualities, cost considerations, limited mechanistic understanding, and regulatory hurdles must be carefully addressed to maximize the benefits of these compounds. As research and innovation continue, the optimization of natural antimicrobials in food preservation holds the potential to revolutionize the way we approach food safety and quality.

11 Emerging trends in the future of natural antimicrobials for food preservation

The utilization of natural antimicrobials in the food industry has witnessed a notable surge in recent years, driven by a growing awareness of health and sustainability issues associated with synthetic alternatives (Aziz and Karboune, 2018). As we look ahead, several trends are expected to shape the future landscape of using natural antimicrobials in food preservation. This section, explores these anticipated trends, shedding light on innovations, challenges, and the transformative potential of harnessing nature's antimicrobial compounds.

11.1 Increased demand for natural and clean label products

Consumers are becoming increasingly conscious of the impact of their food choices on health and the environment (Choudhary et al., 2022). As a result, there is a rising demand for natural and clean label products, prompting food manufacturers to explore natural antimicrobials as alternatives to synthetic preservatives. The shift towards clean labels aligns with consumers' desire for transparency and a clearer understanding of the ingredients present in their food (Bouarab Chibane et al., 2019).

11.2 Diversity in antimicrobial sources

While traditional sources such as plants, bacteria, and enzymes have been extensively studied for their antimicrobial properties, the future holds promise for exploring new and unconventional sources. Marine organisms, fungi, and even insects are emerging as potential reservoirs of novel antimicrobial compounds (El-Saber Batiha et al., 2021). The exploration of these untapped resources may lead to the discovery of compounds with unique properties and enhanced efficacy in food preservation.

11.3 Advancements in extraction and formulation techniques

The extraction and formulation of natural antimicrobials are critical aspects of their successful integration into the food industry. In the near future, we can anticipate advancements in extraction techniques, such as green extraction methods that minimize environmental impact (Balasubramanian et al., 2022). Additionally, innovative formulation strategies will be developed to improve the stability and bioavailability of these natural compounds, ensuring their effectiveness in diverse food matrices (Bagheri et al., 2020).

11.4 Synergistic combinations for enhanced efficacy

To overcome challenges such as limited solubility and stability of certain natural antimicrobials, researchers are exploring the concept of synergistic combinations (Choudhary et al., 2022). Combining multiple natural antimicrobial agents can result in enhanced efficacy, potentially allowing for lower concentrations to achieve the same level of microbial inhibition. These synergistic approaches may also contribute to overcoming potential sensory challenges associated with the use of natural antimicrobials in food products (Baraza et al., 2016; Berteli et al., 2022).

11.5 Focus on targeted applications

As research progresses, there will likely be a shift towards targeted applications of natural antimicrobials based on specific food types and preservation requirements. Tailoring these antimicrobials to address the unique challenges posed by different food matrices will be crucial. For instance, the preservation needs of dairy products may differ from those of fresh produce, leading to customized approaches for optimal effectiveness (Cör et al., 2018; Coimbra et al., 2022).

11.6 Integration of nanotechnology

Nanotechnology holds significant promise in the future of food preservation. Researchers are exploring the incorporation of natural antimicrobials into nanostructures to improve their stability and controlled release (Davidson et al., 2012). Nanoencapsulation, for example, can protect antimicrobial compounds from environmental factors, enhance solubility, and facilitate targeted delivery, thereby maximizing their impact on microbial control in food products (Babaei-Ghazvini et al., 2021).

11.7 Regulatory developments and standardization

As the use of natural antimicrobials becomes more prevalent in the food industry, regulatory bodies are likely to adapt and establish clear guidelines for their inclusion. Standardization of extraction methods, dosage, and labeling requirements will be essential to ensure product safety and consistency. The development of regulatory frameworks will provide a foundation for the responsible and widespread adoption of natural antimicrobials (Njoga et al., 2021; Samtiya et al., 2022).

11.8 Consumer education and acceptance

Educating consumers about the benefits and safety of natural antimicrobials will be crucial for fostering acceptance. Transparent communication regarding the science behind these compounds, their efficacy, and their role in sustainable food production will help build trust and enhance consumer confidence. Manufacturers and regulatory bodies play a pivotal role in disseminating accurate information to dispel any misconceptions.

The future of using natural antimicrobials in food preservation is poised for exciting developments, driven by a confluence of consumer preferences, technological advancements, and sustainability imperatives. The trends discussed highlight the potential for a paradigm shift in the way we approach food preservation, with a greater emphasis on harnessing the power of nature to ensure the safety and longevity of our food supply. As research continues to unveil new possibilities, the integration of natural antimicrobials into mainstream food production holds the promise of not only enhancing food safety but also contributing to a more sustainable and health-conscious food industry.

12 Conclusion

This article explores the potential applications of bio-preservatives in the food industry's system to extend the shelf-life of food products safely. Given that the usage of chemical additives is associated with some hazards to the health and safety of consumers, it has been suggested that natural anti-microbials could serve as a suitable and risk-free replacement for chemical preservatives generated synthetically. Despite the significant progress that has been made, research should continue to concentrate on the role that natural food anti-microbials play in the preparation and formulation of food products, as well as their relation with the intrinsic food properties that have been formulated and the extrinsic characteristics that can influence how effectively these food-products can be stored in food systems. In addition, more research should be conducted on combining natural anti-microbials for particular foods because some studies have suggested that these anti-microbials might not always be effective, i.e., two or more natural EOs might not result in positive synergistic effects. Since incorporating natural anti-microbials into foods via edible film, multi-layer coating, and nanotechnology is a relatively new phenomenon, it is important to analyze customer opinion to understand how they will react to the trend.

Author contributions

AK: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. TM: Conceptualization, Resources, Writing – review & editing.

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Conflict of interest

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