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Review Article

A comprehensive review of spices: Use of prevalent preservative techniques and bio-preservatives for enhancing shelf life of spices

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Abstract

Spices, renowned for flavor enhancement, also act as natural preservatives, prompting exploration into non-thermal preservation methods due to drawbacks of traditional techniques. Antimicrobial properties of herbs and spices, like cloves and black pepper, contribute to food preservation and offer health benefits. Traditional preservation methods like thermal treatment, drying, canning, freezing, and salt-based techniques are employed for preservation of spices. Bio-preservation techniques, including natural antimicrobials, fermentation, probiotics, and competitive exclusion, enhance spice safety and shelf life. Challenges such as strain selection, regulatory compliance, and consumer acceptance highlight the need for thorough screening and education for successful implementation. This review paper entails the use of traditional preservation methods as well as the importance of bio-preservatives for the preservation of different spices to enhance shelf life.

Introduction

Spices are used to make food delicious and more appealing. Examination of plant micro remains found on grinding stone tools, believed to be of South Asian descent, has revealed the presence of cooking spices such as turmeric, ginger, fingerroot, sand ginger, galangal, clove, nutmeg, and cinnamon. These spices are essential components in the preparation of curry in present-day South Asia (Wang et al., 2023). The U.S. Food and Drug Administration (FDA) defines spices as "aromatic vegetable substances that are used in whole, broken, or ground form, primarily to add flavor to food rather than for nutritional value," and they should not have any volatile oil or flavoring principle removed from them (Gottardiz et al., 2016). Spices can also be used as a preservative for food. The primary benefit of incorporating herbs and spices into food as preservatives stem from their 'generally recognized as safe' (GRAS) status, as their historical use in the human diet has stood the test of time. Moreover, they are typically devoid of chemical residues, making them promising substitutes for chemical additives (Jhandai et al., 2019).

Heat or thermal treatment is regarded as a noble and traditional method for preserving food. Over the years, this technique has been successfully utilized in a variety of food industries, ranging from bakery and dairy products to fruits and vegetables (Wurlitzer et al., 2019; Gharibi et al., 2020; Christiansen et al., 2020). Certain drawbacks have been identified in heat treatment and freezing techniques, including food shrinkage, texture deterioration, nutrient loss, and changes in organic properties, resulting in significant overall food product losses (Jayasena et al., 2015). However, in the past few decades, the thermal processing of food has been discouraged. Non-thermal processing involves processing food at temperatures close to room temperature, which ensures that heat-sensitive nutrients remain intact and prevent damage to the food, unlike thermal food processing (Jadhav et al., 2021).

In the past decade, the food industry has been searching for new natural bio-preservatives that not only serve as food preservatives but also promote human health (Burt, 2004). The need for sustainable food processing technologies to tackle the global food safety concerns is pressing. However, introducing new methods may pose certain risks due to changes in microorganisms, production techniques, environmental factors, and global trade. Thus, a careful evaluation is imperative to ensure the production of safe and top-quality food products (Zhou et al., 2022). Fermentation process is also quite significant in preservation of food which generates numerous beneficial products through the action of bacteria, which helps to reduce food spoilage and eliminate pathogenic microorganisms and metabolites, thereby rendering the food safe for consumption (Singh, 2018).

Salt and sugar both function in the same way when it comes to food preservation. When added to food products, they absorb water and limit the availability of water, which, in turn, inhibits the growth of microorganisms and helps in preserving the food (Dwivedi, 2017). Acidic food products are often treated with organic acids, like ascorbic acid, acetic acid, and benzoic acid, to hinder the growth of microorganisms and to prevent the growth of Clostridium botulinum and stabilize the color of cured meat products, nitrites and nitrates are commonly added (Branen et al., 2001). To prevent browning and control microbial activity in dried fruits, wines, and juices, sulfites are a common preservative used (Yang & Purchase, 1985). Products that contain fats and oils are often treated with antioxidants, such as butylated hydroxy anisole (BHA) and butylated hydroxytoluene (BHT), to prolong their shelf life (Gupta & Yadav, 2021).

Nisin and natamycin are types of antibiotics that are frequently used to preserve various food products (Silva & Lidon, 2016). The importance of spices and herbs has been growing recently as they are being recognized as potential sources of natural food preservatives. This interest has arisen due to the increasing emphasis on exploring methods of preserving food naturally that are both safe and efficient (Martinez-Gracia et al., 2015).

When herbs and spices are added to food products, their antimicrobial properties make them capable of preventing food spoilage and maintaining food safety by controlling the growth of spoilage and pathogenic microorganisms (Jack et al., 1995). A study evaluated 25 different types of spices for their natural antimicrobial properties and their effectiveness in preventing the growth of different foodborne microorganisms. It also recommends further research into their potential use as natural food preservatives to provide safer and more sustainable ways to prolong shelf life (Sulieman et al., 2023).

Spices have also exhibited pharmacological importance. S. aromaticum has been studied pharmacologically for its effects on a range of harmful parasites and microorganisms, such as pathogenic bacteria, Plasmodium, Babesia, Herpes simplex, and hepatitis C viruses. Numerous studies have shown that eugenol, found in S. aromaticum, possesses analgesic, antioxidant, anticancer, antiseptic, anti-depressant, antispasmodic, anti-inflammatory, antiviral, antifungal, and antibacterial properties (Batiha et al., 2020). They also observed that these properties have been observed against various pathogenic bacteria, including methicillin-resistant Staphylococcus epidermidis and S. aureus. Black pepper contains piperine in a range of 2-7.4%, which varies based on the pepper plant. Piperine has been found to have a wide range of pharmacological effects, including anti-proliferative, anti-tumor, anti-angiogenesis, antioxidant, anti-diabetic, anti-obesity, cardioprotective, antimicrobial, anti-aging, and immunomodulatory effects in both laboratory and animal experiments (Haq et al., 2021). Additionally, piperine has been noted for its hepatoprotective, anti-allergic, anti-inflammatory, and neuroprotective properties.

Prevalent Preservation methods

Bio preservation is the latest or modern method of preservation of food. Some traditional or prevalent methods other than bio preservation are also there that have been used over decades for the preservation of food and spices in homes at smaller scale as well as on the commercial level.

Thermal treatment

The typical procedure includes heating food at a temperature ranging from 75 to 90 degrees Celsius or above, with a holding period of 25 to 30 seconds. Research on improving the preservation of apple juice through pasteurization and thermal treatment of maize demonstrated significant effects on flavor, digestibility, glycemic index, aroma, color, and sensory characteristics (Charles-Rodriguez et al., 2020; Zou et al., 2020). Heating food decreases the presence of harmful microorganisms. However, extensive research has demonstrated that it can also result in energy inefficiencies, flavor changes, structural modifications, and nutritional depletion (Rosello-Soto et al., 2018).
By causing gelatinization and browning processes, liquid foods, juices, and drinks can potentially have negative impacts (Codina-Torrella et al., 2017; De Souza et al., 2020). These days, heating food is not a highly valued preservation technique because it may lower its nutritional benefits; instead, methods that preserve the food's natural characteristics and nutrients are recommended.

Drying and dehydration

For thousands of years, drying which entails taking liquid out of a substance has been an essential unit activity in a variety of commodities, including food, waste, paper, coal, wood, and biomass. The main and often applied drying methods are examined in this section. In order to explain the simultaneous heat and mass transfer processes inside the drying material's internal layers and at its interface with the surrounding space, drying kinetics takes the place of complex mathematical models (Michailidis & Krokida, 2014).

In order to improve the process' efficiency in terms of food quality and energy consumption, the evolution of drying techniques which can be divided into four stages is thoroughly investigated (Vega-Mercado et al., 2001). Tray drying is the first step, followed by the integration of different drying techniques (the hurdle technology concept in drying). Producing high-quality dehydrated products requires an economical drying system since it cuts down on drying time and minimizes product damage.

In order to decrease energy usage and operational costs, new drying techniques have now been introduced. Osmotic dehydration, vacuum drying, freeze drying, superheated steam drying, heat pump drying, and spray drying are all promising technologies for producing high-quality dried products and powders (Sagar & Suresh Kumar, 2010). A widely utilized, reliable, and reasonably priced method of preserving foods and spices throughout time is drying and dehydration. For long-term storage, spices are especially ground and sealed in vacuum canisters.

Canning and bottling

There are various methods of thermal processing, but commercial sterilization or canning is one of the most well-known. The purpose of this chapter is to provide an introduction to food canning. According to Owusu-Apenten & Vieira, (2023), there are following typical points of canning that should be taken under consideration:

1. Introduction to unconventional canning methods, 2. Commercial sterilization or canning, can sealing, 3. Conventional heat processing, 4. Cooling of heat-processed foods; canning of acidic foods, 5. Other heat processing methods: continuous agitating retort, hydrostatic cooker, aseptic fill method, cooking under pressure, and microwave processing, 6. Containers, such as cans, flexible pouches, and glass containers; microwavable containers; plastic containers and flexible containers, 7. Warehouse storage of canned foods, 8. FDA regulations and safety, 9. Basic principles of thermal processing, including temperature and heat, heat capacity, heat transfer, cooking and cooking methods, pasteurization of liquid foods, and blanching fresh fruits and vegetables, 10. Microbial death rate.

Freezing and refrigeration

Preserving leafy vegetables, spices, and milk products often involves using cooling and freezing methods to maintain their sensory qualities and nutritional content. Freezing techniques commonly used are air blast, cryogenic, direct contact, and immersion freezing, while more advanced methods include high-pressure freezing, ultrasound-assisted freezing, electromagnetic disturbance freezing, and dehydration freezing (Cheng et al., 2017; Brbosa de Lima et al., 2020). The process of cooling and freezing relies on heat transfer mechanisms, where heat energy is transferred from the food and its container to the surrounding environment, resulting in a cooling effect.

Hence, thermal conductivity and thermal diffusivity play a significant role in influencing the speed of cooling or freezing. There has been an increasing focus on storage methods, particularly with the growing popularity of ready-to-eat foods to meet consumer needs. When properly packaged and stored at low temperatures, foods can be shielded from the entry of microorganisms, ensuring food safety. Although cooling and freezing are reliable techniques, concerns such as cooling duration, uneven formation of ice crystals, storage expenses, and the requirement for specialized environments need to be addressed (Sridhar et al., 2021).

To tackle these challenges, we have evaluated technological tools like three-dimensional mathematical models and computational fluid dynamics models. These tools aid in comprehending heat transfer and fluid flow patterns in various food compositions, providing a way to address the issues (Zhu et al., 2019; Barbosa de Lima et al., 2020; Branda et al., 2020; Stebel et al., 2020). Freezing (approximately -15 degrees Celsius) and refrigeration (around 4 degrees Celsius) are effective methods for preserving food, preventing microbial contamination and growth for many years.

Vacuum packing

The oxidation and spoilage of many dairy products are triggered by the presence of air. However, packaging these food items with plastic films and vacuum sealing extends their shelf life (Singh et al., 2019). It has long been recognized that Modified-Atmosphere Packaging (MAP) can increase the shelf life of various food products. Initially, researchers found that MAP or vacuum packing could slow down the ripening process of fruits and vegetables (Xu et al., 2022).
Since this discovery in 1995, there has been a significant rise in the range of products now packaged in modified atmospheres because it is considered more effective than vacuum packing (Domingues Galli et al., 2024). At the moment, a variety of food products including vegetables, fruits, cheese, pasta, baked goods, ready-to-eat meals, tea, coffee, potato chips, and an expanded range of fresh and cooked fish and meats are being sold in modified atmospheres (Davies, 2003; Hur et al., 2013). The research indicated that chilies stored in cold conditions and vacuum-sealed packaging experienced the smallest decrease in quality

parameters. Furthermore, chilies with 12% moisture content, stored in vacuum-sealed bags, exhibited superior quality parameters compared to those with 10% moisture content (Chetti et al., 2014).
The application of vacuum packaging was successful in lessening the development of some types of biogenic amines (BAs). On the other hand, they also stimulated the growth of other types of BAs like spermine and tyramine (Doeun et al., 2016). So, the vacuum packing is a helpful technique for conservation of food but there are methods that are more efficient than simple vacuum packing.

Salt as a Preservative in various spices

Salt Curing: Certain spices, such as whole peppercorns or mustard seeds, can be preserved by curing them with salt. The salt removes moisture from the spices, creating an environment that discourages the growth of bacteria and molds. This method, commonly employed for olives and capers, helps in their preservation (Sebranek, 2009).

Salt Brining: Spices can also be preserved by soaking them in a saltwater solution, a process known as brining. This technique is often used for preserving vegetables like cucumbers (pickles) and cabbage (sauerkraut), with added spices such as dill, garlic, and mustard seeds for flavor enhancement (Kanagaraj & Babu, 2002; Brás & Costa, 2010).

Salt Packing: Preserving herbs like basil or rosemary can be achieved by coating them with salt or layering them with salt. This method draws out moisture and creates a protective barrier against microbial growth, aiding in their preservation (King, 2006).

Salt Blending: Mixing spices with salt not only enhances their flavor but also aids in preservation. Seasoned salts or spice rubs, which combine spices with salt, are commonly used to flavor and preserve meats, vegetables, and other foods.

Salt Encrusting: Spices can be encrusted with a layer of salt to form a protective barrier against moisture and microbes. This technique, often utilized in preserving fish or meat, helps in retaining moisture and flavor while preventing spoilage (Raghavan, 2006).

Salt Fermentation: Fermenting spices with salt not only preserves them but also enhances their flavor through the fermentation process. This method is popularly employed in fermenting chili peppers for hot sauces or making kimchi, a Korean fermented cabbage dish (Nout, 2014).

Salt Drying: Drying spices with salt aids in their preservation by removing moisture and inhibiting microbial growth. This method is commonly used for preserving herbs like sage or thyme, where salt helps in retaining their flavor and color during the drying process (Raghavan, 2006).

Bio-preservation Techniques

Bio-preservation techniques play an important role in increasing the shelf life of food goods while maintaining quality and safety. In this review, we will look at the many approaches used in bio-preservation, with a focus on natural antimicrobials, fermentation and pickling, the use of probiotics, and microbial inhibition via competitive exclusion (Jhandai et al., 2019).
Because spices are susceptible to microbial contamination and deterioration, utilizing the antibacterial characteristics of natural antimicrobials becomes extremely important in the bio-preservation process (Nazir et al., 2017). Spices, which are frequently exposed to changing environmental conditions during cultivation, harvesting, processing, and storage, are vulnerable to contamination from a variety of spoilage and pathogenic bacteria, fungus, and yeasts (Rawat, 2015). As a result, the use of natural antimicrobials provides an effective technique for reducing microbial development and maintaining spice quality throughout the supply chain (Shelef, 1984).

Use of Natural antimicrobials

Natural antimicrobials, such as bacteriocins produced by lactic acid bacteria (LAB), are critical in ensuring the safety and purity of spices (Rendueles et al., 2022). LABs are naturally present in many fermented foods and have the ability to create a wide range of antibacterial chemicals, including bacteriocins such as nisin (Yusuf, 2018). These bacteriocins have broad-spectrum antibacterial activity against Gram-positive bacteria found in spices, including Bacillus and Clostridium species, as well as foodborne pathogens including Salmonella and Listeria (Gautam & Sharma, 2009).

When added to spices, natural antimicrobials such as nisin can effectively limit the growth of spoilage and harmful bacteria, extending the shelf life of these important culinary items. Natural antimicrobials aid to avoid undesired changes in color, flavor, and scent, ensuring that spices retain their characteristic sensory properties over time (Nisa et al., 2023).

Furthermore, the bio-preservation of spices through the application of natural antimicrobials is in line with customer aspirations for minimally processed and clean-label goods. With people looking for more natural options than artificial additives and preservatives, adding natural antimicrobials to spices provides an open, sustainable way to keep them fresh without sacrificing flavor or nutritional content (Tiwari et al., 2009).

Natural antimicrobials not only have antibacterial qualities but also have the ability to improve the sensory qualities of spices, which adds to their allure in culinary applications. Some antimicrobial chemicals, such thymol in thyme and cinnamaldehyde in cinnamon, are generated from herbs and spices themselves. These compounds not only prevent the growth of microorganisms but also give the spices their unique smells and fragrances (Moghadam et al., 2019). These natural flavorings work in concert to preserve and improve the quality of spices, especially when paired with the antibacterial action of bacteriocins generated by LAB, such as nisin (Retnaningrum et al., 2020).

All things considered, the use of natural antimicrobials is a viable method for bio-preserving spices, providing strong defense against microbial deterioration without sacrificing their distinct flavor profile (Batiha et al., 2021). The use of natural antimicrobials into spice preservation techniques offers a chance to satisfy customer demands for safe, tasty, and sustainable culinary ingredients as the market for clean-label and natural food items grows (Ayala-Zavala et al., 2008).

Fermentation and pickling

Traditional techniques for preserving spices that add distinct aromas and increase their shelf life by using beneficial microbes include pickling and fermentation (Sultana et al., 2014).

Lactic acid bacteria (LAB) and yeast are two examples of the specific microorganisms whose growth and metabolism are controlled during fermentation, changing the biochemical makeup of spices (Guizani & Mothershaw, 2007). Fermentation can happen naturally in the context of preserving spices or with the inclusion of starter cultures containing particular strains of yeast or LAB. These microbes break down the sugars and other carbohydrates found in spices to produce organic acids, alcohols, and other substances that help to build flavor and stop the growth of germs that cause spoiling (Mani A., 2018).

In the fermentation of spices, lactic acid bacteria—including species like Lactobacillus and Pediococcus—are essential. As a metabolic byproduct, these bacteria produce lactic acid, which lowers the pH of the fermentation medium and creates an acidic environment that prevents the formation of mold and harmful bacteria (Nout, 2014). Furthermore, by inhibiting the growth of spoilage organisms, LAB may produce antimicrobial chemicals such bacteriocins, which further aid in the preservation of spices.

A particular type of fermentation called pickling is frequently used to preserve spices, especially whole or chopped spices that are submerged in a brine solution (Peréz-Dıaz et al., 2013). Pickling preserves spices and adds a distinct tangy flavor because the acidic environment produced by the addition of vinegar or brine prevents the growth of spoilage and pathogenic germs. The pickling solution's acidity helps preserve the texture and color of the spices over time in addition to halting the growth of microorganisms (Behera et al., 2020).

Furthermore, by utilizing a variety of metabolic pathways and enzymatic processes, pickling and fermentation help produce varied flavor profiles in spices. Fermented spices get their distinct flavor and scent from a wide range of flavor compounds that are produced by yeast and LAB during fermentation. These compounds include volatile organic acids, esters, and alcohols (Reina et al., 2005). Furthermore, the pickling solutions' acidic environment facilitates the better extraction of flavor components from spices, enhancing their sensory qualities (Srivastava, 2018).

Application of probiotics

A new method for improving the nutritional content and safety of these culinary components is the use of probiotics in the preservation of spices.

Owing to their capacity to withstand the acidic environment of the stomach and establish themselves in the intestines, specific strains of lactobacilli, bifidobacteria, and other lactic acid bacteria are frequently utilized as probiotics (Illupapalayam et al., 2014). These probiotic microbes can prevent pathogenic bacteria and spoilage while encouraging good microbial populations, which is important for spice preservation (Mahmoudi et al., 2017).

Probiotics lower the danger of microbial contamination and spoiling by competing with harmful bacteria for resources and colonization sites when added to spice preparations. Probiotics also generate antimicrobial compounds that stop the growth of pathogens and spoilage organisms, like hydrogen peroxide, organic acids, and bacteriocin (Barak & Mudgil, 2022). By stopping microbial growth and preserving product quality over time, its antimicrobial action contributes to the shelf life extension of spices.

Furthermore, consuming spices that contain probiotics may help consumers' health in ways other than just preserving food (Song et al., 2012). Probiotic-spiced foods may aid in the development of a healthy gut microbiota, which is crucial for immune system function, digestive health, and general well-being, by adding advantageous microbes into the diet (Rodgers, 2008). Probiotics are a beneficial addition to the diet since research indicates that they may improve nutritional absorption, lessen the risk of some infections, and relieve gastrointestinal issues.

Probiotics added to spice recipes also correspond with consumer demands for functional meals that support wellbeing and health (Dinkçi et al., 2019). Probiotic-enhanced products are in high demand as customers' interest in holistic approaches to nutrition and illness prevention grows. Probiotic-spiced foods provide a quick and tasty method to add probiotics to your diet, letting you get the advantages of these healthy bacteria while also improving the taste and nutritional value of your favorite meals (Sridhar et al., 2021).

Microbial inhibition through competitive exclusion

Microbial inhibition through competitive exclusion is a dynamic strategy employed in the preservation of spices, leveraging the natural antagonistic interactions between beneficial microorganisms and harmful pathogens to maintain product quality and safety.

- **Introduction of Beneficial Microorganisms:** Competitive exclusion is the intentional introduction of particular lactic acid bacteria (LAB) strains or other protective cultures into spice matrices (Leyva Salas et al., 2017). These helpful microorganisms have built-in antagonistic capabilities against spoilage and pathogenic bacteria, allowing them to outcompete and inhibit undesired microbial populations (de Souza et al., 2021).

- **Mechanisms of Competitive Exclusion:** Beneficial bacteria use a variety of strategies to prevent the spread of dangerous diseases and rotting organisms. One crucial process is the creation of antimicrobial chemicals such as organic acids, hydrogen peroxide, and bacteriocins, which make the environment unsuitable for harmful bacteria. Furthermore, competitive exclusion may involve the occupation of ecological niches, competition for nutrients, and colonization sites, limiting the availability of resources for pathogen multiplication (Kodape et al., 2024).

- **Selection of Protective Cultures:** The selection of appropriate LAB or other protective cultures is critical for successful competitive exclusion in spice preservation. Strains having demonstrated antibacterial activity, tolerance to spice matrix conditions, and compatibility with the intended flavor profile are usually favored. Furthermore, the safety and regulatory implications of using protective cultures must be carefully considered in order to maintain consumer confidence and comply with food safety regulations (Vignolo et al., 2014).
- **Application Methods:** Protective cultures can be introduced into spice matrices using a variety of application methods, including direct inoculation, fermentation, and coating (Sharma et al., 2017). Direct inoculation adds live microbial cultures to spice compounds, whereas fermentation uses the natural fermentation process to spread beneficial microbes and suppress infections (Rodgers, 2008). Coating techniques, such as encapsulation or microencapsulation, can also be used to safeguard microbial cultures during processing and storage, assuring their viability and effectiveness (Gottardi et al., 2016).

- **Extension of Shelf Life:** Microbial inhibition by competitive exclusion helps to extend spice shelf life by actively reducing the growth of spoilage and pathogenic microorganisms (Teshome et al., 2022). The presence of helpful microorganisms helps to preserve product freshness, color, fragrance, and flavor throughout time, lowering the danger of microbial spoilage and deterioration. This not only increases the economic value of spices, but it also reduces food waste and improves consumer pleasure (Katiyar & Jain, 2018).

- **Targeted Applications:** Competitive exclusion tactics can be adjusted to specific spice products and processing circumstances to maximize effectiveness. For example, protective cultures may be chosen based on the most common microbial contaminants linked with specific spice kinds or processing processes (Sulieman et al., 2023). Furthermore, including protective cultures into spice blends or seasoning mixes enables for targeted prevention of spoilage organisms while maintaining the desirable sensory characteristics of the finished product (Castellano et al., 2017).

Enhancing Shelf Life with Bio-preservatives

Bio-preservation is a promising and eco-friendly approach to improving the safety and shelf life of food products (Maurya et al., 2021). By harnessing the power of antagonistic microorganisms or their metabolic products, bio-preservatives can inhibit or destroy undesired microorganisms in foods, thereby extending their shelf life and enhancing their safety (Ali et al., 2022). This review article will delve into the mechanisms of action of bio-preservatives and explore the challenges and limitations associated with their use.

Mechanisms of action of bio-preservatives:

The mechanisms of action employed by bio-preservatives play a crucial role in inhibiting or destroying undesired microorganisms in spices, thereby extending their shelf life and enhancing their safety. Here's a detailed exploration of the mechanisms mentioned.

- **Production of Antimicrobial Compounds**
  Bio-preservatives, specifically lactic acid bacteria (LAB), are well-known for their capacity to create a wide range of antibacterial chemicals. Bacteriocins, organic acids, and hydrogen peroxide are examples of chemicals with strong antibacterial activity against a wide spectrum of spoilage and pathogenic bacteria found in spices (Qbi et al., 2018). Bacteriocins are tiny heat-resistant peptides generated by LAB and other microbes. These chemicals can specifically target and destroy closely related bacterial species, making them useful against spoiling organisms and foodborne diseases (Khalil et al., 2021).

Notably, bacteriocins such as nisin have been widely researched and approved for use as bio-preservatives in a variety of food products due to their safety and efficacy. Organic acids, including lactic acid and acetic acid, are metabolic byproducts of LAB fermentation (Nimrat et al., 2021).

These organic acids reduce the pH of the spice environment, providing an acidic environment that inhibits the growth of bacteria and fungi. Organic acids operate as bacteriostatic or bactericidal agents by affecting microbial cell membranes and metabolic activities, hence reducing microbial proliferation and deterioration (Jamuna et al., 2005). Certain LAB bacteria create another antimicrobial chemical called hydrogen peroxide (H2O2). This oxidative chemical can damage microbial cell membranes and DNA, causing cell death and inhibiting microbial development.

However, hydrogen peroxide production is frequently closely managed to avoid oxidative harm to the producing organism, ensuring optimal preservation while maintaining cell viability (Sharif et al., 2017).

- **Competitive Exclusion**
  Bio-preservatives use competitive exclusion as a strategic strategy to prevent the growth of dangerous pathogens in spices. Beneficial microorganisms, such as LAB, can successfully prevent the expansion of spoilage organisms and maintain the microbial balance in the spice environment by competing with pathogenic bacteria for nutrients and colonization sites (Sherawat et al., 2021).
  Competitive exclusion is based on bio-preservatives' ability to fill ecological niches and consume nutrients, depriving pathogens of necessary resources for development and survival. Furthermore, bio-preservatives' ability to produce antimicrobial chemicals gives them a competitive advantage by making the environment unsuitable for spoilage and pathogenic microorganisms (Moses, 2018).

- **pH Reduction**
  The metabolic activity of bio-preservatives, particularly LAB, can cause a drop in pH in the spice environment. LAB ferment the sugars found in spices, producing lactic acid that accumulates and lowers the pH of the surrounding medium. This fall in pH generates an acidic environment that limits the growth of spoilage and pathogenic bacteria, which helps to preserve spices (Anees et al., 2015). Acidic pH reduces microbial enzyme activity and disturbs cellular processes, limiting bacterial and fungal growth and survival. Furthermore, the low pH of the spice environment might improve the stability of some bioactive chemicals and pigments, allowing the spices to retain their sensory attributes and nutritional value over time (Amiri et al., 2021).

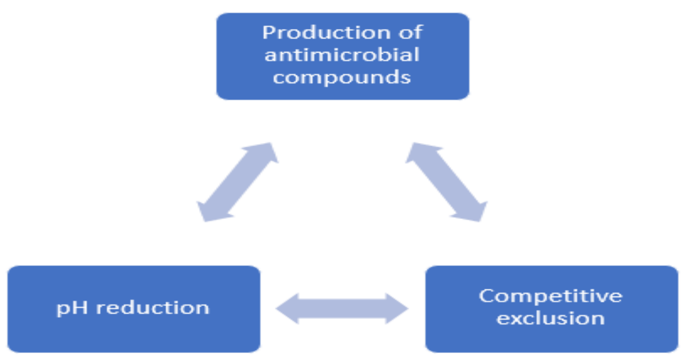

Figure 1. Mechanism of action of bio-preservatives

Challenges and limitations

Challenges and limitations associated with the use of bio-preservatives in spices pose hurdles to their widespread adoption in the food industry. Here's a detailed exploration of these challenges:

- **Strain Selection**
  It can be difficult to identify and choose the most effective bio-preservative strains for spice preservation. Different strains of lactic acid bacteria (LAB) or other helpful microbes may have varying antibacterial activity, compatibility with spice matrices, and capacity to tolerate processing and storage conditions. As a result, comprehensive screening and evaluation

are required to identify strains that demonstrate strong preservation efficacy while maintaining product quality and safety (Reina et al., 2005).

- **Optimization of Conditions**
  Temperature, pH, moisture content, and the presence of other microorganisms all have an impact on the performance of bio-preservatives used to preserve spices. To achieve the best preservation results, these conditions must be optimized for specific spice goods through thorough trial and tweaking (Ahmed et al., 2023). Furthermore, variations in processing methods and storage conditions may have an impact on bio-preservative performance, demanding constant monitoring and adjustment to ensure efficacy (Barcenilla et al., 2023).

- **Regulatory Compliance**
  The use of bio-preservatives in spice goods must adhere to the regulatory restrictions specified by food safety authorities, which vary by country and region. Regulatory compliance entails proving the safety and efficacy of bio-preservatives through extensive testing and validation (Oluk & Karaca, 2018). This procedure can be time-consuming and resource-intensive, necessitating significant expenditure in research and development to meet regulatory requirements and achieve commercial approval (Yildirim, 2011).

- **Consumer Acceptance**
  Manufacturers face considerable problems when it comes to consumer perception and adoption of bio-preservative-containing food items. Consumers may be unfamiliar with bio-preservatives or regard them as synthetic or unnatural ingredients, creating concerns about their safety and potential health consequences.
  Addressing these issues necessitates open communication, education, and outreach initiatives to educate consumers on the benefits of bio-preservatives and their role in improving food safety and shelf life. Furthermore, manufacturers may need to spend in product labeling and marketing initiatives to increase consumer trust and confidence in bio-preserved spice items.

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