Antimicrobial Efficacy of Herbal Extracts and Essential Oils for the Inactivation of Foodborne Pathogens in Food and Food Products

Jannat Mazhar[1,*]

[1]National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan
*Corresponding author: mazharjannato@gmail.com

Abstract

Microbial contamination in food leads to foodborne illnesses which is a substantial global health concern, thus the development of effective food preservation methods is important. Synthetic preservatives despite their broad antimicrobial activity have drawn concerns over their potential toxicity. Consequently, herbal extracts and essential oils (EOs) have surfaced as alternatives based on their broad spectrum antimicrobial activity and safety. The chapter focuses on the antimicrobial properties of EOs and herbal extracts for the inactivation of foodborne pathogens and discusses their mechanisms of action, relative effectiveness, application in food preservation and future prospects. They exert antimicrobial effects via cell membrane disruption, inhibition of bacterial enzymes, interference of a quorum sensing mechanism and induction of oxidative stress. Their applications in food safety strategies as well as in edible coatings and active packaging technologies has shown versatility. Despite its promising potential, practical application of EOs and herbal extracts faces challenges including stability limitation, sensory activity alteration, compositional variability, legal limits and costs. Nonetheless, improvements by means of nano-encapsulation and intelligent antimicrobial packaging could provide solutions to the issues which currently limit their efficacy within a food contact system. As consumer preference for natural preservatives continues to rise, these offer the potential to change the landscape of food safety and preservation. They now need to be standardized, undergo regulatory approval and be implemented on a large scale as commercial applications to drive them into sustainable and health honoring food systems.

Keywords: Herbal extracts, Essential oils, Antimicrobial efficacy, Foodborne pathogens, Food preservation, Natural preservatives, Food safety, Antimicrobial mechanisms, Nano-encapsulation, Active packaging

Cite this Article as: Mazhar J, 2025. Antimicrobial efficacy of herbal extracts and essential oils for the inactivation of foodborne pathogens in food and food products. In: Khan A, Hussain R, Tahir S and Ghafoor N (eds), Medicinal Plants and Aromatics: A Holistic Health Perspective. Unique Scientific Publishers, Faisalabad, Pakistan, pp: 38-46. https://doi.org/10.47278/book.HH/2025.272

A Publication of Unique Scientific Publishers	**Chapter No:** 25-006	**Received:** 27-Feb-2025 **Revised:** 16-Apr-2025 **Accepted:** 22-May-2025

Introduction

Foodborne illnesses are a serious public health issue all over the world, sickening millions of people annually. These diseases occur due to the consumption of contaminated food containing bacteria, viruses, fungi or parasites that can lead to infection or toxin based diseases (Chouhan et al., 2017). Due to the compromised quality and safety of food products, foodborne outbreaks have become more common which has driven researchers to investigate antimicrobial strategies to help prevent contamination and improve the shelf life of food (Bukvicki et al., 2023). The food industry has traditionally used chemical preservatives such as sodium benzoate, nitrates, sorbic acid and others for preventing spoilage through the inhibition of microbial growth. Consumer reservations about health risks related to the use of synthetic additives (alkylates, epoxidized fatty acids) such as their links to the development of cancer, allergic reactions and the emergence of antibiotic resistance have steered the trend towards natural alternatives for food preservation (Calo et al., 2015). In this frame of work, herbal drugs and EO's have drawn attention due to their broad spectrum antimicrobial capability, a natural supply and possible health benefits (Martins et al., 2024). The bioactive compounds in herbal medicine such as polyphenols, flavonoids, tannins and alkaloids obtained from different plant sources exhibit antimicrobial activities against microbial food hazards (Batiha et al., 2021). Likewise, the EOs sourced from aromatic plants such as clove, oregano, thyme and cinnamon possess potent antimicrobial activity due to the phenolic compounds such as terpenes and aldehydes (Ju et al., 2019).

These antimicrobial agents exert their effects by damaging microbial cell membranes, blocking enzyme functions and colluding with quorum sensing mechanisms that regulate bacterial virulence. Besides their antimicrobial capacity, herbal extracts and EOs have shown to exert antioxidant, anti-inflammatory and immunomodulatory impacts which render them appealing candidates for food preservation and human health improvement (Mishra et al., 2020). New technologies for nanoencapsulation of EOs have demonstrated promise for improving *O. majorana* oil stability, efficacy and controlled release when applied in food (Ribeiro-Santos et al., 2017). Although herbal antimicrobials and EOs show great potential, some challenges still exist that could influence the application of these substances in the food industry. For example, composition of EOs is subject to variability based on the source of plant, stability issues due to volatility and oxidation as well as sensorial effects on food products (Pérez-Santa Escolástica et al., 2022). However, new research gives rise to new technologies that provide ways to optimize the use of plant based antimicrobials on food safety and preservation. This chapter will give an overview of the antimicrobial activity of herbal extracts and EOs against foodborne pathogens in food and food products. We will focus on the specific mechanisms of action, evaluate their efficacy compared to synthetic preservatives and investigate the role of natural preservatives in the food industry. The chapter will also describe challenges as well as future directions for the incorporation of these natural antimicrobials into commercial food preservation systems.

Common Foodborne Pathogens & Their Impact

Foodborne pathogens are microbes such as bacteria, viruses, parasites and fungi that infect food and lead to illness in humans. These pathogens are mainly spread via contaminated food, drink or contact with infected patients or surfaces. According to the World Health Organization (WHO, 2022), people fall ill from eating contaminated food around the globe 600 million times a year leading to 42000 deaths. Children under age five are among the most vulnerable, with an estimated 125,000 deaths from foodborne diseases per year (CDC, 2021). There are six ways a foodborne illness can affect a person, ranging from mild gastrointestinal illness to severe and sometimes fatal infections. These infections affect public health negatively and also exert pressure on the healthcare systems and lead to economic losses as a result of food recalls and reduced productivity. Economically, billions of dollars are lost owing to healthcare costs, reduced productivity relapse and expensive food removes (Batiha et al., 2021). Foodborne disease related healthcare costs in the United States alone are estimated to be $15.6 billion each year (CDC, 2021). These diseases also pose big problems in the food industry since recurrent recalls hurt brand image and lead to a loss of consumer confidence. Moreover, a rise in regulatory requirements increases the cost of compliance for businesses, making it difficult for the industry to function optimally.

Major Bacterial Foodborne Pathogens

i. *Salmonella spp*

Salmonella is among the most common foodborne pathogens globally. It is responsible for salmonellosis, one of the most prevalent infectious diseases caused by contaminated poultry, eggs and dairy products (Martins et al., 2024). The infection induces gastroenteritis and symptoms (diarrhea, fever and abdominal cramps) that occur 6 to 72 hours after ingestion (CDC, 2020). In more severe cases, it can lead to infections in the bloodstream, particularly in the immunocompromised populations (Calo et al., 2015).

ii. *Escherichia coli* (*E. coli* O157:H7)

Some strains of Shiga toxin producing *E. coli*, especially *E. coli* O157:H7, induce hemorrhagic colitis and hemolytic uremic syndrome (HUS) (Ju et al., 2019). The pathogen is passed through undercooked beef, unpasteurized dairy and tainted water. In its most severe form, HUS can result in a loss of kidney function necessitating dialysis and is associated with a significantly high mortality rate, particularly in children and the elderly (Mishra et al., 2020).

iii. *Listeria monocytogenes*

Listeria monocytogenes can multiply at refrigeration temperatures unlike other types of bacteria. It is present in ready-to-eat meats, dairy and fresh produce. Listeriosis is especially fatal for pregnant women, newborns and immunocompromised individuals and can also cause miscarriages, meningitis or septicemia (Pérez-Santa Escolástica et al., 2022).

iv. *Campylobacter spp*

Campylobacteriosis is a leading bacterial cause of gastroenteritis globally. The germ is present in contaminated water, undercooked poultry and raw milk. It produces fever, abdominal pain and diarrhea and may lead to a neurological illness known as Guillain-Barré syndrome (Chouhan et al., 2017).

v. *Clostridium botulinum*

C. botulinum produces botulinum, a toxin known to be one of the most potent neurotoxins known. It poisons canned foods, fermented fish and honey. Botulism symptoms include muscle paralysis followed by respiratory failure and potential death in untreated patients (Ribeiro-Santos et al., 2017).

vi. *Staphylococcus aureus*

S. aureus is commonly found in dairy, meat and baked goods. It creates thermally stable enterotoxins resulting in vomiting, cramps and diarrhea 2 to 6 hours post ingestion. While symptoms are self-limiting, they can be severe in vulnerable populations (Mishra et al., 2020).

Viral Foodborne Pathogens

i. Norovirus

Norovirus, the most common cause of viral gastroenteritis spreads through contaminated water, shellfish and direct contact with the infected person. It is extremely transmissible and can prompt intense diarrhea and vomiting beginning 12-to-48-hour post-infection (Ju et al., 2019).

ii. Hepatitis A Virus

Hepatitis A is a liver infection that occurs through consumption of contaminated food or water. It leads to jaundice, nausea and liver inflammation. Severe cases may lead to long term complications (Seo et al., 2017).

Herbal Extracts as Antimicrobial Agents

From centuries herbal extracts has played crucial role in treatment of infections and maintaining health. Numerous bioactive compounds (alkaloids, flavonoids, tannins, polyphenols and EOs) characterized by an antimicrobial activity towards foodborne pathogens are obtained from medicinal plants (Chouhan et al., 2017). Researchers are increasingly exploring plant based antimicrobials as safe and effective alternatives to synthetic preservatives, especially amid growing concerns over antibiotic resistance and the toxicity of synthetic preservatives (Martins et al., 2024). These natural antimicrobial agents perform their function through pathways such as disruption of cell membrane, interruption of enzyme activity and suppression of bacterial virulence factors (Batiha et al, 2021). Herbs also have antioxidant, anti-inflammatory and immuno-stimulatory effects on top of their role in food safety and human health.

Essential Oils as Antimicrobial Agents

EOs are volatile and highly potent aromatic compounds obtained from the roots, seeds, flowers, leaves and bark of medicinal plants. These oils are also known for their antifungal and antimicrobial effect and have long been used as food preservatives in both pharmaceuticals and traditional medicine (Panda et al. 2019). Many EOs have been evaluated as potential suitable replacement for synthetic antimicrobials in order to meet the growing marketplace for the natural food preservatives (Ju Jian et al., 2019). Phenols, terpenes, aldehydes and flavonoids present in the chemically complex composition of EOs helps them to be effective antimicrobial agents. EOs are very promising candidates for their use in food safety as they are generally recognised as safe (GRAS) by regulatory organizations like the U.S. Food and Drug Administration unlike the artificial preservatives (Falcó et al., 2024).

Mechanisms of Antimicrobial Action

The bioactive compounds of herbal medicines and EOs responsible for their antimicrobial and antifungal activity have been reported to be efficacious against food hazards. They exert various antibacterial mechanisms including cell membrane disruption, enzyme inhibition, metabolic interference, DNA damage and interference of quorum sensing (Chouhan et al., 2017). However, the principles behind these mechanisms must be well understood for the practical applications of these methods in food preservation and enhancing the overall safety of food and food products.

i. Cell Membrane Disruption

Among the various antimicrobial mechanisms, disruption of microbial cell membrane is one of the most important mechanisms for the leakage of cytoplasmic contents and cell breakdown which ultimately leads to cell death. Numerous components in EOs are hydrophobic, enabling them to cross bacterial lipid bilayers and thus modifying the permeability and integrity of the membranes (Calo et al., 2015). Some EOs such as thymol, carvacrol or eugenol penetrate bacterial membranes which leads to structural destabilization and dysfunction. Such disturbance causes leakage of ions (K^+, Na^+), drainage of ATP and depletion of critical metabolites which finally leads to cell lysis (Martins et al., 2024). The cell wall of bacteria has different susceptibility to the components of the EOs due to its structure. Gram-positive bacteria like *Staphylococcus aureus* are more susceptible due to their relatively simplified cell wall (mainly made of peptidoglycan) which does not include a peripheral membrane (Batiha et al., 2021). Similarly, gram-negative bacteria such as *Salmonella* and *E. coli* are more resistant due to their protective outer membrane. Nevertheless, some EOs including cinnamon and oregano can cross this barrier and imply antimicrobial impact (Ju et al., 2019). These results suggest the effectiveness of EOs as natural antimicrobials for the control of foodborne microorganisms and enhancing food product safety. Lipophilic bioactive compounds in herbal extracts penetrate and destabilize the bacterial cell membrane which results in the leakage of vital cellular components and cell death (Figure 1) (Mishra et al., 2020).

ii. Enzyme Inhibition

Some herbal extracts and EOs block bacterial enzymes that are critical for metabolism thereby preventing bacterial growth and reproduction. Phenolic compounds such as thymol and carvacrol attach to vital metabolic enzymes such as ATPases and dehydrogenases, impairing the bacteria energy metabolism and viability (Mishra et al., 2020). Eugenol, the primary compound of clove oil inhibits certain enzymes such as amylase and protease that aids in the absorption of nutrients by bacteria thus restricting their growth capacity (Pérez-Santa Escolástica et al., 2022). Moreover, certain green tea and turmeric polyphenols blocks DNA gyrase, a critical enzyme in bacterial replication thereby hindering their reproduction capacity to a certain extent (Ju et al., 2019). These natural antimicrobials target these enzymatic pathways, compromising the defenses of bacteria and demonstrating the ability to improve food safety and preservation. Certain plant compounds such as allicin (derived from garlic) or curcumin (derived from turmeric) bind to bacterial enzymes and inhibit metabolic pathways essential for bacterial growth (Ju et al., 2019).

iii. Interference with Metabolism and Nutrient Uptake

Many herbal extracts and EOs affect metabolic pathways of bacteria and inhibit their critical biomolecules such as proteins, fatty acids and nucleotides. Lemongrass and cinnamon EOs have been shown to inhibit fatty acid biosynthesis, a vital pathway for bacterial membrane repair and energy generation (Chouhan et al., 2017). Allicin, the main compound in garlic interacts with sulfur containing amino acids which results in the disruption of protein synthesis in bacterial cells (Calo et al., 2015). Moreover, green tea flavonoids have been found to hinder bacteria by altering iron absorption which is a key factor for their survival and replication (Martins et al., 2024). Metabolic inhibitors exert a potent effect on foodborne pathogens such as *E. coli* and *Salmonella* that rely on the rapid acquisition of nutrients to growth. EOs and phenolic compounds have proven to be valuable natural antimicrobials since they hinder various metabolic pathways of *Listeria monocytogenes* and its adaptation to food environments (Batiha et al., 2021).

iv. Bacterial DNA Damage and Replication Inhibition

Some natural compounds show antimicrobial effects directly associated with bacterial DNA that inhibits pivotal cellular schemes. The polyphenols from tea, turmeric and rosemary produces reactive oxygen species (ROS) that results in the breakage of the bacterial DNA strands, leading to cell damage and ultimately cell death (Mishra et al., 2020). Berberine, a bioactive compound obtained from the Goldenseal herb intercalates into bacterial DNA (Ju et al., 2019) thereby inhibiting transcription and translation. Recent advances in food safety research have shown that nanoencapsulated EOs significantly cause greater DNA damage making it more effective compared to their standard counterparts. They produce reactive oxygen species (ROS) which induces oxidative stress and DNA fragmentation in bacteria (Mishra et al., 2020). Lemongrass and cinnamon oils cause DNA damage in *Listeria* and *Clostridium* through nucleotide oxidation (Martínez-Graciá et al., 2015). Curcumin (from turmeric) and catechins (from green tea) have been reported to induce bacterial DNA fragmentation through the generation of ROS causing oxidative stress (Calo et al., 2015). Polyphenols from neem inhibits bacterial protein synthesis which leads to pathogen death (Ribeiro-Santos et al. 2017).

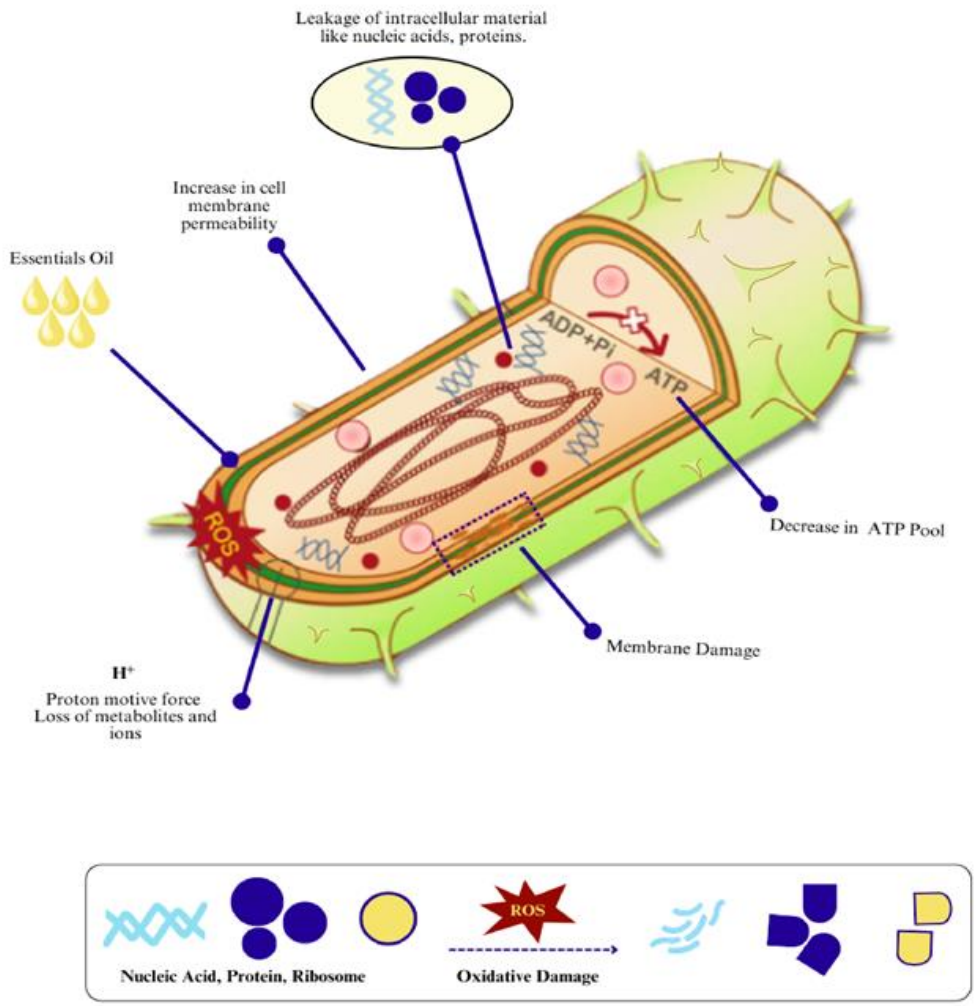

Fig. 1: Mechanism of Cell Membrane Disruption by EOs

v. Quorum Sensing Inhibitors (Anti-virulence approach)

Quorum sensing (QS) is a communication mechanism by which bacterial populations coordinate virulence factors, biofilm formation and resistance genes. Herbal extracts and EOs are known to suppress virulence of bacteria without killing them, acting as quorum sensing inhibitors (QSIs) (Batiha et al., 2021). Small natural compounds can interfere with bacterial QS and inhibit toxin production and biofilm formation. Another approach is utilizing furanones derived from garlic and cinnamon which serve as QS signalling competitors and inhibit the effective coordination of antibiotic toxin production (Martins et al., 2024). Thymol and carvacrol are equally important for the reduction of biofilm formation, making pathogens like *Listeria* and *Salmonella* more susceptible to being eliminated (Ju et al., 2019). Furthermore, a vital part of clove oil, eugenol inhibits the LuxR receptor which is a major QS integral receptor found in *E. coli* and *Pseudomonas aeruginosa* (Mishra et al., 2020). QS inhibition is a strategy to disarm the defensive capabilities of bacterial pathogens which results in enhanced susceptibility to immune responses and antimicrobial therapies. Additionally, by inhibiting biofilm development, these compounds can further minimize the risks of contamination in food processing facilities thereby enhancing food safety (Chouhan et al., 2017).

Antimicrobial Impact and Chemical Composition of EOs

Table 1 summarizes some potential efficacious EOs along with their major compounds and mechanisms of action against foodborne pathogens.

Table 1: Major Essential Oils with Antimicrobial Properties, Source: (Batiha et al., 2021)

Essential Oil	Major Compounds	Target Pathogens	Mode of Action
Oregano (*Origanum vulgare*)	Carvacrol, Thymol	*E. coli, Salmonella, Listeria*	Disrupts cell membranes, inhibits ATP production
Clove (*Syzygium aromaticum*)	Eugenol	*Staphylococcus aureus, Listeria*	Denatures proteins, damages bacterial DNA
Cinnamon (*Cinnamomum zeylanicum*)	Cinnamaldehyde	*Salmonella, E. coli, Listeria*	Disrupts membrane integrity, interferes with quorum sensing
Thyme (*Thymus vulgaris*)	Thymol, Carvacrol	*Listeria, Bacillus cereus*	Alters permeability of bacterial membrane
Tea Tree (*Melaleuca alternifolia*)	Terpinen-4-ol	*E. coli, Campylobacter jejuni*	Inhibits respiration, damages bacterial proteins
Lemongrass (*Cymbopogon citratus*)	Citral, Geraniol	*Clostridium botulinum, Staphylococcus*	Induces oxidative stress, inhibits bacterial replication

Comparative Effectiveness of Herbal & Essential Oils vs. Synthetic Preservatives

Food preservation is at the core of food safety and longevity. Chemical preservatives such as nitrites, sodium benzoate, sorbic acid and sulfites have traditionally been utilized in the food industry due to their strong antioxidant and antimicrobial properties (Panda et al., 2019). However lower health risk concerns and consumer preference for natural food additives have sparked greater interest in herbal antimicrobials and EOs as natural alternatives (Batiha et al., 2021). Herbal extracts and EOs demonstrate a broad spectrum of antimicrobial activity against fungi, bacteria and viruses through different mechanisms including cell membrane disruption, inhibition of metabolic enzymes and suppression of quorum sensing (Calo et al., 2015). On the contrary, synthetic preservatives prevent microbial growth via direct enzymatic inhibition or acidification which may also result in toxic effects and antimicrobial resistance over time (Martínez-Graciá et al., 2015). The table 2 shows the comparative effectiveness of herbal extracts, EOs and Synthetic Preservatives.

Table 2: Comparative Analysis of Natural vs. Synthetic Preservatives, Sources: (Batiha et al., 2021)

Feature	Herbal Extracts & Essential Oils	Synthetic Preservatives
Source	Natural plant extracts	Chemically synthesized
Mechanism of Action	Disrupts cell membranes, inhibits enzymes, damages DNA	Lowers pH, inhibits enzymes, prevents oxidation
Antimicrobial Spectrum	Broad (bacteria, fungi, viruses)	Target-specific (mainly bacteria)
Health Concerns	Low toxicity, antioxidant properties	Potential toxicity (linked to allergies, cancer and gut microbiome disruption)
Antibiotic Resistance Risk	No resistance development	Contributes to antimicrobial resistance
Shelf Life	Can degrade over time (volatile)	Stable for longer periods
Consumer Preference	High (natural, organic trend)	Low (chemophobia, artificial additives)
Regulatory Approval	Some restrictions (GRAS approved in food)	Strict FDA/EU food regulations

Application of Herbal Extracts and EOs in the Food Industry

The food industry faces a constant challenge in mitigating food contamination and decomposition which leads to the use of preservatives to boost longevity and improve the safety of the product. Bacterial growth inhibition, potential shelf life extension and maintenance of food quality can be achieved through the application of herbal extracts (Figure 2) and EOs without the health hazards associated with chemical preservatives (Martínez-Graciá et al., 2015). They exhibit potent antimicrobial, antioxidant and bioactive properties rendering them highly effective in food applications including meats, dairy, beverage, bakery products and food packaging (Batiha et al., 2021).

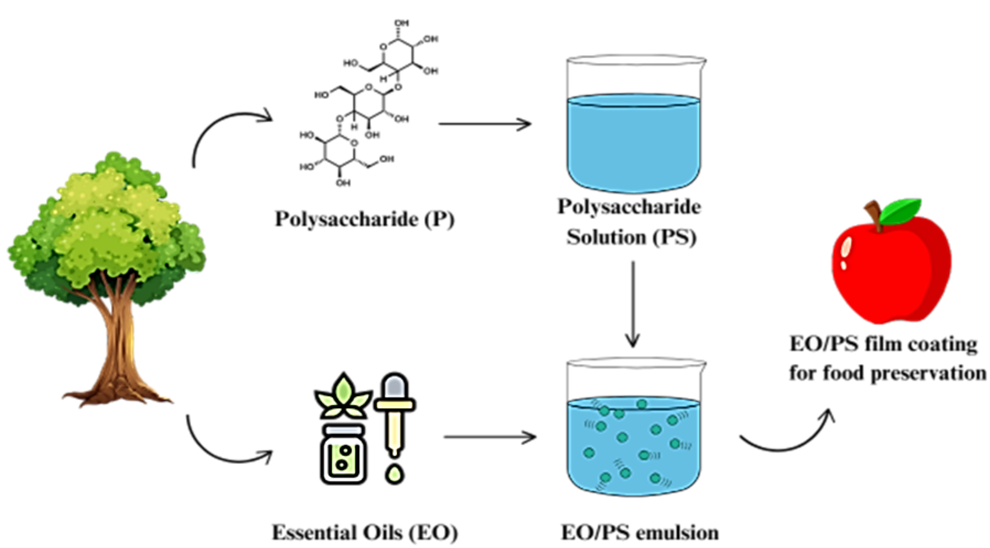

Fig. 2: Essential Oils Infused Edible Films and Coatings

Direct Application of Herbal Extracts and EOs in Food Products

Due to the antimicrobial and antioxidant properties of the plant based herbal extracts and EOs, these can be incorporated in the food products to prevent spoilage, flavor and enrich nutritional properties.

i. **Meat and Poultry Preservation**

Meat products are perishable products and easily spoiled by microbial contaminants. EOs from oregano, rosemary and thyme (Ju et al., 2019) are used for spoilage prevention and to inhibit *Salmonella*, *Listeria* and *E. coli* in processed meats. For example, thyme and oregano EOs extended the storage life of ground beef for an additional 10 days at refrigerator temperatures (Mishra et al., 2020). Chitosan nanoparticles and ginger (*Zingiber officinale*) EO coating on the chicken fillet showed to significantly restrict microbial growth and improve the refrigerated storage life from 4 days to 28 days (Musalem et al., 2024). In another study, impact of chitosan coating enriched with *Artemisia fragrans* EO was assessed on the chicken fillet shelf life during refrigeration. It indicated that until day 12 of storage the counts of molds and yeasts, TVC (total viable counts) and total coliforms were considerably lower (Yaghoubi et al., 2023). Packaging enriched with oregano and cinnamon oil inhibited growth rate of *Listeria monocytogenes* and enhanced the microbiological shelf life and stability of vacuum packaged chicken (Ju et al., 2019). Therefore, incorporation of EOs in edible coatings indicates a promising technology for improvement of the meat quality and stability.

ii. **Fruits and vegetables**

EOs can also be incorporated into biodegradable films which helps to protect fresh fruits, vegetables, meat and dairy from microbial contamination (Pateiro et al., 2021). For instance, cinnamon oil and chitosan films inhibited mold growth on strawberries by as much as 85% (Hochma et al., 2021). In another study, citral and eugenol enriched pectin and alginate coatings on fresh raspberries were proved to be effective in maintaining fruit quality and extending shelf life (Guerreiro et al., 2015). Nanoemulsion coatings of hydroxypropyl methylcellulose, beeswax and EOs (clove, thyme, cinnamon and peppermint) exhibited potent antimicrobial activity against *E. coli* and *A. niger* and maintained quality attributes in sweet cherries (Iqbal et al., 2022). The wax coating containing EOs of lemongrass and eucalyptus were shown to prevent fungal and bacterial growth in fresh produce (Martínez-Graciá et al., 2015). These bio-based biopolymers such as chitosan or alginate, may be functionalized with antimicrobial EOs for further protecting coatings added to fruits and vegetables against microbial contamination.

iii. **Dairy (Milk, Cheese, Yogurt)**

Dairy products have a short period of optimal quality and are particularly liable to microbiotic pollution and spoilage by bacteria and fungi. Some pathogens such as *Escherichia coli, Listeria monocytogenes*, *Salmonella* and other spoilage fungi can considerably shorten shelf life and cause serious health problems. The antimicrobial properties of EOs have made them effective natural preservatives in the dairy industry. Several EOs including rosemary, cinnamon, thyme, oregano and clove oils have been studied extensively for their antimicrobial mechanism of action in food while preserving sensory quality (Batiha et al., 2021). EOs obtained from clove, cinnamon and oregano have been shown to hinder growth of *Listeria monocytogene*s and other spoilage microorganisms without inducing undesirable alterations in texture or flavour (Ju et al. 2019). In a study by (Batiha et al., 2021), it was shown that clove and thyme oils reduce fungal contamination of cheese, potentially increasing its shelf life without altering its taste and odor. EO-based edible coatings have been developed to act as food antimicrobial agents in various types of cheese, thereby improving food safety and enhancing the storage stability of these food products (Ribeiro-Santos et al., 2017).

Eucalyptus, lemongrass and tea tree EOs showed potent antibacterial activity against *Salmonella* and *E. coli* in both raw and pasteurized milk (Mishra et al., 2020). Nanoencapsulation of EOs improves solubility in dairy products and provides controlled release and sustained antimicrobial activity (Martins et al., 2024). EOs can also extend the lifetime of yogurt. Adding oregano, peppermint and thyme oils to yogurt formulations has been shown to effectively inhibit spoilage bacteria and yeast in increasing its shelf life (Martínez-Graciá et al., 2015).

iv. **Bakery and Cereal Products**

Baked goods are a high moisture food making them more susceptible to spoilage by developing moulds and bacteria. Fungi in baked goods include *Aspergillus, Penicillium* and *Rhizopus* specie as well as spoilage bacteria shorten the shelf life and safety of these products. EOs serve as natural preservatives that can inhibit microbial growth, prolonging the freshness of bakery products without affecting their sensory features. Some EOs like ginger, clove and cinnamon exert a high antifungal activity on baked products thus restricting the growth of molds on bread, cakes and pastries (Martínez-Graciá et al., 2015). It has been shown in studies that the incorporation of clove and cinnamon essential oils have significant antifungal activity and thus enhancing the shelf life of bread by reducing the rate of fungal contamination. Common antifungal compounds found in EOs such as eugenol and cinnamaldehyde prevent the growth of spoilage fungi and thus may be used as an substitute to synthetic preservatives (Ribeiro-Santos et al., 2017).

EO infused edible coatings and bioactive packaging can also be beneficial for bakery products. Thyme oil, cinnamon or oregano within edible films decreased mold growth while extending shelf life without harming the quality of the bread (Ju et al., 2019). The addition of plant based phenolic compounds such as rosemary and green tea has shown to enhance the oxidative stability of bakery products. Natural antioxidants suppress rancidity and spoilage due to lipid oxidation, a common problem in cereal based foods (Martins et al., 2024).

v. **Beverages and Fruit Juices**

Antioxidants such as green tea polyphenols and ginger oil are added to fruit juices to prevent oxidative and microbial spoilage (Ju et al., 2019). Lemongrass oil proved effective in preserving the orange juice with little alteration in flavour (Mishra et al., 2020).

The table 3 summarizes direct applications of EOs and herbal extracts in food commodities along with their effectiveness.

Table 3: Direct Application of Herbal Extracts and EOs in Food Products

Herbal Medicine/Essential Oil	Target Foodborne Pathogen	Food/Food Product	Mode of Application	Efficacy	References
Oregano, Rosemary, and Thyme EOs	*Salmonella spp.*, *Listeria monocytogenes*, *E. coli*	Processed Meats	Direct application	Extended shelf life by 10 days	(Ju et al., 2019; Mishra et al., 2020)
Chitosan Nanoparticles +Ginger Essential Oil	Various microbial contaminants	Chicken Fillet	Coating treatment	Extended refrigerated storage from 4 to 28 days	(Musalem et al., 2024)
Artemisia fragrans Essential Oil + Chitosan Coating	TVC, Coliforms, Molds and Yeasts	Chicken Fillet	Edible coating	Significant reduction in microbial load until day 12	(Yaghoubi et al., 2023)
Cinnamon Oil	Mold Spoilage	Strawberries	Chitosan film	Inhibited mold growth by 85%	(Hochma et al., 2021)
Citral & Eugenol	Microbial Contaminants	Raspberries	Pectin & alginate coatings	Extended shelf life	(Guerreiro et al., 2015)
Thyme, Cinnamon, Clove, and Peppermint EOs	*E. coli*, *Aspergillus niger*	Sweet Cherries	Nanoemulsion coating	Maintained fruit quality	(Iqbal et al., 2022)
Lemongrass & Eucalyptus Oils	Bacterial & Fungal Growth	Fresh Produce	Wax Coating	Prevention of microbial contamination	(Martínez-Graciá et al., 2015)
Clove, Cinnamon, Oregano, and Thyme Oils	*Listeria monocytogenes*, Spoilage Fungi	Dairy Products	Edible Coating	Inhibited fungal growth & prolonged shelf life	(Ju et al., 2019; Batiha et al., 2021)
Lemongrass, Eucalyptus, Tea Tree Oils	*E. coli*, *Salmonella*	Raw & Pasteurized Milk	Direct application	Significant antibacterial activity	(Mishra et al., 2020)
Oregano, Peppermint, Thyme Oils	Spoilage Bacteria & Yeast	Yogurt	Direct application	Increased shelf life	(Martínez-Graciá et al., 2015)
Ginger, Clove, Cinnamon Oils	Fungal Contamination	Baked Goods	Direct application	Inhibited mold growth	(Martínez-Graciá et al., 2015)
Clove & Cinnamon Oils	Spoilage Fungi	Bread	Edible Coating	Enhanced shelf life	(Ribeiro-Santos et al., 2017)
Rosemary & Green Tea Extracts	Lipid Oxidation	Bakery Products	Direct application	Improved oxidative stability	(Martins et al., 2024)
Oregano & Cinnamon Oils	*Listeria monocytogenes*	Vacuum-Packed Chicken	Active Packaging	Suppressed microbial growth	(Ju et al., 2019)

Active Packaging Technology

Active packaging technologies are developed based on the incorporation of herbal extracts and EOs which releases antimicrobial vapors for the control of spoilage and contamination (Batiha et al., 2021). The nanoencapsulation of these oils protects them from degradation thereby permitting a gradual release (Figure 3) (Ribeiro-Santos et al., 2017). This technology facilitates a controlled release of bioactive compounds, making an antimicrobial food packaging to prevent spoilage and contamination. Essential oils like oregano, cinnamon, thyme and clove have potent antimicrobial action against various food bacteria including *Escherichia coli, Salmonella* and *Listeria monocytogenes* (Batiha et al., 2021). Due to their reactivity and volatility, EOs are prone to degradation and the nanoencapsulation of these compounds are important in active packaging systems to protect them and provide a controlled release (Ribeiro-Santos et al., 2017).

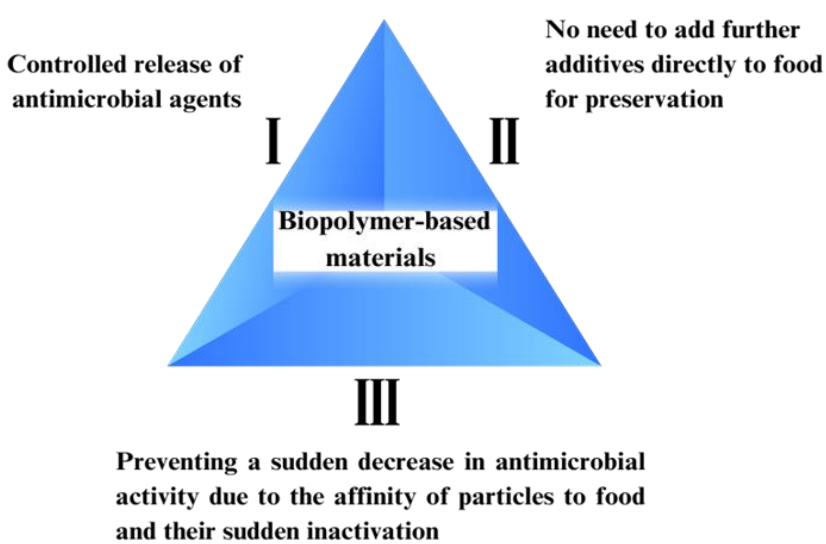

Fig. 3: Antimicrobial Food Packaging with Essential Oils

Challenges and Future Directions of Herbal Medicine and Essential Oils in Foodborne Pathogen Control

- EOs are extremely volatile and can easily go through oxidation, heat degradation or exposure to UV light hence decreasing their application in food preservation (Mishra et al., 2020). Most herbal extracts are prone to degradation which leads to the limited shelf life of herbal containing food products (Ju et al., 2019).
- Some EOs (e.g., garlic, oregano and clove oil) contain strong flavors and odors which may modify the aroma and taste of food products (Martínez-Graciá et al., 2015). The presence of EOs beyond their sensory threshold on food formulations results in products with low consumer acceptance.
- The need for their regulatory approval restricts the commercialization of many EOs as food preservatives (Prakash et al., 2015). Other plant derived substances such as thujone in sage (sage oil) or estragole in basil (basil oil) in high concentrations can also be toxic (Ju Jian et al., 2019).
- Since the large scale and high quality production of EOs is very resource demanding, they result in a higher cost than synthetic preservatives (Prakash et al., 2015). Seasonal variations in plant availability are also challenging the production cost and supply stability (Batiha et al., 2021).

Future Directions

- Bioavailability and antimicrobial efficiency of EOs can be enhanced by using nanotechnology based delivery systems (nanoemulsions, liposomes and polymeric nanoparticles). These systems improve the stability of EOs incorporated in food matrices. They enable a controlled release hence extending their antimicrobial action and reducing their impact on sensory perception (Martínez-Graciá et al., 2015)
- Antimicrobial activity can be increased by combining EOs with probiotics, organic acids or plant polyphenols (Panda et al., 2019). The addition of lactic acid to oregano oil remarkably enhanced its bacterial inhibition ability in meat preservation (Ju et al., 2019).
- Active packaging systems with EOs emit antimicrobial vapors which can inhibit pathogens in the packaged foods (Zhu et al., 2021). Cinnamon oil infused biodegradable packaging improved the shelf life of bread by 7 days (Ribeiro-Santos et al., 2017).

Conclusion

The rising incidence of foodborne diseases is caused by microbial contamination leading to an urgent demand for safe and reliable preservation of food. Synthetic preservatives are being utilized extensively which has led to issues with human health, chemical residues and antimicrobial resistance. Consequently, natural antimicrobial alternatives like herbal medicine and EOs are receiving much interest as a sustainable and customer accepted approach for inactivation of foodborne pathogens and extension of food storage duration. This chapter has explored the antimicrobial activities of herbal medicine and EOs, their action mechanism, comparison with synthetic preservatives and food industry applications. The challenges and the future perspectives to optimally use these natural antimicrobials were also discussed.

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