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A Narrative Review of the Antimicrobial Effects of Plant Extracts and Essential Oils in the Preservation of Fruits and Vegetables

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A B S T R A C T

Postharvest losses of fruits and vegetables due to microbial spoilage represent a significant global challenge. This narrative review explores the potential of plant-derived extracts and essential oils as natural antimicrobial alternatives, with a focus on their bioactive constituents-namely phenolics, terpenoids, and flavonoids-and their mechanisms of action against spoilage and pathogenic microorganisms, including *Listeria monocytogenes* and *Escherichia coli*. The evidence reviewed indicates that these compounds exert antimicrobial effects through mechanisms such as membrane disruption, enzyme inhibition, and biofilm interference. The effectiveness of these agents is influenced by several factors, including extraction methods, compound concentrations, and environmental conditions. Despite their potential to extend the shelf life of fresh produce, limitations such as sensory impacts and compound stability present notable challenges. Emerging technologies, particularly nanoencapsulation, offer promising strategies to enhance their practical applications. Overall, the findings support the use of plant-based antimicrobials as sustainable solutions for food preservation, in alignment with clean-label demands and the broader goals of food safety and waste reduction across the supply chain.

1. Introduction

Microbial spoilage continues to pose a significant challenge in the food supply chain, particularly affecting fruits and vegetables due to their perishable nature and high susceptibility (Alegbeleye et al., 2022; Zhao et al., 2022). As nutrient-dense sources of vitamins, minerals, fiber, and antioxidants, fruits and vegetables play an essential role in maintaining human health (Alegbeleye et al., 2022). However, their high moisture content and nutrient-rich composition create an ideal medium for the growth of spoilage-causing and pathogenic microorganisms (Zhao et al., 2022). The deterioration of these products not only compromises their quality and safety but also results in substantial food and economic losses. This issue has gained particular significance in today's world, where food security has become a global priority. Growing consumer concerns regarding the use of chemical preservatives and their potential health and environmental impacts have intensified the demand for natural and safe alternatives to maintain the quality of fruits and vegetables. In this context, plant extracts and essential oils have emerged as a promising solution (Aminzare et al., 2016; Bolouri et al., 2022). These natural products, extracted from various botanical parts including leaves, flowers, seeds, and bark, possess antimicrobial, antioxidant, and antifungal properties, which can significantly enhance food preservation and safety (Boukhatem & Setzer, 2020). The antimicrobial properties of

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plant extracts and essential oils are attributed to a wide spectrum of bioactive compounds (Bahraminejad et al., 2024). These natural products contain various phytochemicals, including phenols, flavonoids, terpenoids, alkaloids, and tannins, which exert their effects through multiple mechanisms of action. Key mechanisms include: (1) disruption of bacterial cell membrane integrity, (2) inhibition of essential microbial enzymes, and (3) induction of oxidative stress in microorganisms. Notably, these compounds demonstrate significant efficacy against major foodborne pathogens such as *Escherichia coli*, *Salmonella* spp., and *Listeria monocytogenes*, which represent primary causative agents of foodborne illnesses (Nwankwo et al., 2022). One of the most notable characteristics of plant extracts and essential oils is their multifunctional nature. These compounds not only possess antimicrobial properties but can also prevent lipid oxidation and vitamin degradation through their antioxidant activity (Hou et al., 2022). These attributes have led to their increased application not only in the preservation of fruits and vegetables but also in other industries, such as food packaging and cosmetic-hygienic product manufacturing (Hou et al., 2022). In addition to the aforementioned advantages, the use of plant extracts and essential oils aligns with sustainability and environmental conservation principles due to their natural origin (Hegazy et al., 2025). The production and utilization of these compounds can help reduce reliance on synthetic chemicals and mitigate the negative environmental impacts associated with chemical preservatives (Hegazy et al., 2025). This is particularly significant in the current context, where climate change and environmental degradation are major global challenges. However, the practical application of plant extracts and essential oils on an industrial scale faces several obstacles (Pavela & Benelli, 2016). One such challenge is the chemical stability of their active compounds, which may degrade under varying environmental conditions such as temperature, light, and pH (Gupta et al., 2023). Furthermore, determining the optimal dosage that ensures sufficient antimicrobial effects without negatively affecting the sensory properties of the product requires further research. Additionally, the costs associated with the extraction and processing of these compounds may pose a barrier to their widespread adoption in the food industry (Pavela & Benelli, 2016). Numerous studies have investigated the efficacy of plant extracts and essential oils in preserving fruits and vegetables (Regnier et al., 2012). For instance, edible coatings incorporating thyme and cinnamon essential oils have been shown to significantly inhibit the growth of spoilage-causing microorganisms and extend the shelf life of products such as strawberries and apples (Yaashikaa et al., 2023). Similarly, citrus extracts (e.g., orange and lemon), due to their high terpenoid content, have proven effective in reducing the microbial load of leafy vegetables (Saini et al., 2022). Alongside these findings, factors such as plant species, extraction method, and environmental conditions significantly influence the efficacy of these compounds. Various extraction techniques, including steam distillation, solvent extraction, and supercritical fluid extraction, can affect the quality and quantity of active compounds in plant extracts and essential oils (Azmir et al., 2013). Furthermore, the target microorganism plays a decisive role in the success of this approach, as certain bacteria and fungi may exhibit higher resistance to plant-derived compounds. The objective of this review article is to comprehensively analyze the antimicrobial effects of plant extracts and essential oils on spoilage and pathogenic microorganisms affecting fruits and vegetables. We synthesize previous research, describe their mechanisms of action, examine the key factors that influence efficacy, and highlight current challenges and future opportunities. The findings may serve as a valuable resource not only for researchers and students but also for food industry professionals and policymakers, facilitating the development of natural and safe strategies to enhance food quality and safety. In conclusion, given the growing importance of sustainability and food safety, the development and application of novel technologies-such as nanoencapsulation and the combination of these compounds with other antimicrobial agents-could serve as an innovative approach. Additionally, future research should assess the long-term effects of these compounds on human health and the environment to ensure their safe and confident large-scale application.

1.1 Mechanisms of antimicrobial activity in plant extracts and essential oils

The antimicrobial activity of plant extracts and essential oils is primarily attributed to their diverse array of bioactive phytochemicals, including phenols, flavonoids, terpenoids, alkaloids, tannins, and other secondary metabolites (Ponce et al., 2008). These compounds inhibit microbial growth and induce cell death through multiple complementary mechanisms, each dependent on the specific chemical structure of the active components, as detailed below (Table 1).

1.1.1 Disruption of cellular membrane integrity

The bacterial cell membrane plays a vital role in maintaining cellular structure and regulating material exchange. Active compounds in essential oils, particularly phenols and terpenoids, can penetrate and disrupt membrane integrity. By interacting with membrane phospholipids, these compounds increase permeability, leading to leakage of intracellular contents such as ions, Adenosine Triphosphate (ATP), and proteins. Membrane disruption is widely recognized as a primary antimicrobial mechanism, with efficacy demonstrated against both Gram-positive and Gram-negative bacteria in numerous studies (Nazzaro et al., 2013).

1.1.2 Interference with protein and enzyme function

Many components of essential oils exhibit the ability to inhibit key bacterial enzymes. These compounds act by binding to active sites or inducing conformational changes in enzymes, thereby disrupting essential cellular processes such as ATP production, protein synthesis, and peptidoglycan formation. For instance, thymol and carvacrol-primary constituents of thyme essential oil-effectively inhibit metabolic enzymes such as ATPase, consequently depleting cellular energy (Kowalczyk et al., 2020).

Table 1. Mechanisms of antimicrobial activity of plant extracts and essential oils

Mechanism	Description	Representative Compounds	References
Disruption of cellular membrane integrity	Phenols and terpenoids bind to membrane lipids, increasing permeability and leakage of cellular contents.	Thymol, carvacrol, eugenol	(Nazzaro et al., 2013)
Interference with protein and enzyme function	Essential oils inhibit enzyme activity and protein synthesis, disrupting metabolism and ATP production.	Thymol, carvacrol	(Kowalczyk et al., 2020)
Induction of oxidative stress	Generation of reactive oxygen species (ROS) leads to damage to DNA, proteins, and lipids.	Flavonoids, phenols	(Zhao & Drlica, 2014)
Inhibition of cell wall synthesis	Phytochemicals block enzymes involved in peptidoglycan synthesis, weakening bacterial cell walls.	Alkaloids, terpenoids	(Zhydzetski et al., 2024)
Inhibition of nucleic acid synthesis	Flavonoids and phenols bind to DNA gyrase or topoisomerase, preventing DNA replication and transcription.	Flavonoids	(Zhao & Drlica, 2014)
Alteration of membrane permeability and osmotic pressure	Active compounds disrupt ion channels, leading to osmotic imbalance and cell lysis.	Thymol, eugenol	(Nourbakhsh et al., 2022)
Disruption of energy metabolism	Essential oil components interfere with the electron transport chain and ATP synthesis.	p-Cymene	(Custódio et al., 2011)
Quorum sensing inhibition	Phenolics and flavonoids impair bacterial cell–cell communication, reducing biofilm formation and virulence.	Flavonoids	(Popat et al., 2015)
Biofilm formation interference	Essential oils prevent biofilm adhesion and degrade existing biofilms.	Cinnamon oil, rosemary extract	(Mahrous et al., 2023)
Synergistic enhancement	Combining essential oils with other antimicrobials enhances efficacy and reduces required doses.	Thyme + cinnamon oils, in combination with antibiotics	(Vaou et al., 2022)

1.1.3 Induction of oxidative stress

A key antimicrobial mechanism involves the generation of reactive oxygen species (ROS). Antioxidant compounds in plant extracts, particularly flavonoids and phenols, can paradoxically increase ROS production in bacterial cells. These reactive molecules damage critical cellular structures, including DNA, proteins, and membrane lipids. ROS accumulation proves particularly bactericidal against microorganisms lacking efficient oxidative stress response systems (Zhao & Drlica, 2014).

1.1.4 Inhibition of cell wall synthesis

The bacterial cell wall provides structural integrity and maintains osmotic pressure. Certain phytochemicals, including alkaloids and terpenoids, can inhibit key enzymes involved in cell wall biosynthesis. By targeting enzymes such as transglycosylases and transpeptidases, these compounds disrupt peptidoglycan layer formation, leading to structural weakness and eventual cell lysis (Zhydzetski et al., 2024). This mechanism shows particular efficacy against Gram-positive bacteria with their characteristic thick cell walls (Zhydzetski et al., 2024).

1.1.5 Inhibition of nucleic acid synthesis

Certain phytochemical constituents of plant extracts exert antimicrobial effects by interfering with DNA and RNA synthesis processes. Flavonoids, for instance, can bind directly to DNA or inhibit key replication enzymes such as DNA gyrase and topoisomerase, thereby disrupting bacterial replication and transcription. These interactions ultimately lead to growth inhibition and cellular death (Zhao & Drlica, 2014).

1.1.6 Alteration of membrane permeability and osmotic pressure

Plant-derived extracts and essential oils can modulate the internal osmotic pressure of bacterial cells. Active compounds, including thymol and eugenol, disrupt membrane ion channels, altering ionic exchange mechanisms (Nourbakhsh et al., 2022). These modifications result in osmotic imbalance, cellular swelling, and eventual lysis.

1.1.7 Disruption of energy metabolism

Specific essential oil components interfere with bacterial energy production by inhibiting the electron transport chain in bacterial mitochondria. This mechanism compromises ATP synthesis, depleting cellular energy reserves and preventing essential metabolic processes, ultimately leading to cell death (Custódio et al., 2011).

1.1.8 Quorum sensing inhibition

Bacteria utilize quorum-sensing systems to coordinate collective behaviors, including biofilm formation and virulence factor production (Popat et al., 2015). Phenolic compounds and flavonoids can disrupt these communication networks, diminishing bacterial pathogenicity and biofilm formation capacity. This mechanism holds particular significance in combating antibiotic-resistant and pathogenic bacterial strains (Popat et al., 2015).

1.1.9 Biofilm formation interference

Biofilms represent complex bacterial structures that enhance microbial resistance to antimicrobial agents. Essential oils can prevent biofilm development through two primary mechanisms: suppression of extracellular polymeric substance (EPS) synthesis or direct degradation of biofilm architecture. For instance, cinnamon essential oil and rosemary extract have demonstrated significant anti-biofilm effects by reducing bacterial adhesion and promoting biofilm (Mahrous et al., 2023).

1.1.10 Synergistic enhancement

A distinctive characteristic of plant-derived antimicrobials is their capacity for synergistic interactions with conventional antibiotics (Vaou et al., 2022). Combining essential oils with traditional antimicrobial agents can enhance therapeutic efficacy while reducing required antibiotic dosages (Vaou et al., 2022). This synergistic approach presents a promising strategy for addressing the global challenge of antibiotic resistance. The antimicrobial mechanisms of plant extracts and essential oils are not only multifaceted but also demonstrate remarkable potential against resistant and pathogenic bacteria due to their ability to target multiple biological pathways. However, further research is necessary to elucidate the precise interactions between these compounds and bacterial structures, as well as to develop optimized methods for enhancing their efficacy in industrial and medical applications. Comprehensive studies should focus on standardizing extraction techniques, determining optimal synergistic combinations, and evaluating long-term safety profiles to facilitate clinical translation.

1.2 Factors influencing the efficacy of plant extracts and essential oils

The antimicrobial efficacy of plant extracts and essential oils is governed by a complex interplay of factors, including their chemical and physical properties, target microorganisms, extraction and preparation methods, environmental conditions, and other variables. Understanding these factors is crucial for optimizing the application of these compounds in food, medical, and pharmaceutical industries (Chouhan et al., 2017). This section provides a detailed examination of the key determinants influencing their effectiveness.

1.2.1 Plant species and bioactive compounds

The antimicrobial properties of plant extracts and essential oils are intrinsically linked to the plant species and the profile of bioactive compounds it contains. Different plants contain varying types and concentrations of antimicrobial compounds such as phenols, flavonoids, terpenoids, and alkaloids (Saini et al., 2022). For instance, thyme and cinnamon essential oils, rich in thymol and eugenol, respectively, demonstrate superior antimicrobial activity compared to many other plants (Saini et al., 2022). Additionally, genetic variability and agronomic factors (e.g., climate, soil composition, harvest season) significantly influence the chemical composition and, consequently, the efficacy of the extracts.

1.2.1.1 Plant parts used for extraction

The specific part of the plant used for extraction, such as leaves, stems, seeds, roots, or bark, significantly affects the chemical composition and antimicrobial efficacy of the resulting extract or essential oil. Different plant tissues accumulate distinct profiles of bioactive compounds; for instance, leaves may be rich in flavonoids and terpenoids, while seeds often contain phenolic lipids or alkaloids. The concentration and diversity of antimicrobial constituents can therefore vary considerably depending on the botanical source part. This variability should be carefully considered during extract formulation and standardization for food preservation applications (Chouhan et al., 2017).

1.2.2 Extraction methods

The extraction technique is a critical determinant of the quality and quantity of bioactive compounds in plant extracts and essential oils (Hegazy et al., 2025). Various methods, including steam distillation, solvent extraction, supercritical fluid extraction, and ultrasound- or microwave-assisted extraction, are employed. Each method differentially impacts the final chemical composition and biological properties. For example, supercritical CO_2 extraction better preserves heat-sensitive compounds, thereby maintaining the bioactivity of essential oils more effectively (Hegazy et al., 2025). In the case of plant extracts, the choice of solvent (e.g., water, ethanol, methanol, acetone, or ethyl acetate) plays a crucial role in determining which phytochemicals are extracted. Polar solvents (e.g., water, ethanol) are effective for extracting hydrophilic compounds such as phenolics and flavonoids. Non-polar solvents (e.g., hexane, chloroform) favor the extraction of lipophilic compounds like terpenes and fatty acids. This selectivity can significantly impact the antimicrobial and antioxidant properties of the extract, as different bioactive compounds target microbial cells through distinct mechanisms. Therefore, both the extraction technique and the solvent system must be carefully selected and standardized to ensure optimal recovery of functional compounds for food preservation applications (Chouhan et al., 2017).

1.2.3 Extract or essential oil concentration

The concentration of plant extracts and essential oils plays a pivotal role in their efficacy (Bolouri et al., 2022). While higher concentrations generally exhibit stronger antimicrobial activity, they may also impart undesirable sensory characteristics or toxicity to the product. For example, excessive cinnamon essential oil can adversely affect product flavor and aroma (Bolouri et al., 2022). Thus, optimizing concentration levels is essential to balance microbial control with sensory and safety considerations.

1.2.4 Target microorganism and cellular structure

The antimicrobial efficacy of plant extracts and essential oils is significantly influenced by the structural characteristics of the target microorganism, particularly the composition of the cell envelope. Gram-positive bacteria, characterized by a thick peptidoglycan layer, are generally more susceptible to these compounds. In contrast, Gram-negative bacteria possess an outer membrane rich in lipopolysaccharides (LPS), which serves as an effective barrier against hydrophobic molecules such as many essential oil components. Moreover, biofilm-forming and antibiotic-resistant strains exhibit even greater resilience due to protective extracellular matrices and efflux mechanisms, often requiring higher concentrations of plant-derived antimicrobials or synergistic combinations for effective inhibition (Yap et al., 2021).

1.2.4.1 Use of permeabilizing agents such as ethylenediaminetetraacetic acid (EDTA)

EDTA chelates divalent cations (e.g., Ca^{2+}, Mg^{2+}) that stabilize the LPS structure in Gram-negative bacteria. This disruption increases membrane permeability, allowing greater penetration of essential oil compounds and enhancing their antimicrobial activity.

1.2.4.2 Synergistic combinations

Combining essential oils or plant extracts with conventional antimicrobials or natural compounds (e.g., organic acids, nisin) can produce synergistic effects that reduce the minimum inhibitory concentration (MIC) needed for Gram-negative inhibition. Nanoformulation technologies: Encapsulation of plant-derived antimicrobials into nanoparticles or liposomes can improve their solubility, protect labile components, and enhance targeted delivery across microbial membranes, including Gram-negative outer layers. Use of surfactants or emulsifiers: Incorporating mild surfactants can reduce surface tension and facilitate the dispersion of hydrophobic essential oils, improving interaction with bacterial membranes.

1.2.4.3 pH adjustment

Acidic conditions can weaken bacterial outer membranes and increase the activity of certain essential oils and extracts (Ponce et al., 2008).

1.2.5 Environmental conditions

Environmental factors such as pH, temperature, and the presence of organic matter can significantly modulate the efficacy of plant extracts and essential oils. For instance, many essential oils demonstrate enhanced antimicrobial activity in acidic environments due to improved compound stability. Conversely, organic matter (e.g., proteins, lipids) may interact with bioactive compounds, potentially diminishing their antimicrobial effects (Negi, 2012).

1.2.6 Application methods

The method of application (e.g., incorporation into wash solutions, spraying, or edible coatings) significantly influences the efficacy of plant extracts and essential oils. For instance, edible coatings containing plant extracts enhance direct contact with produce surfaces, thereby improving their antimicrobial activity (Ponce et al., 2008). Furthermore, combining these compounds with nanoparticles or biopolymers can synergistically enhance their effectiveness by improving delivery systems and enabling sustained release mechanisms (Ponce et al., 2008).

1.2.6.1 Sustained release in active packaging systems

An important advantage of active food packaging systems incorporating essential oils or plant extracts is their ability to provide a sustained release of bioactive compounds over time. Unlike conventional applications that may result in rapid evaporation or degradation, embedding these compounds into edible films, biopolymers, or nanocarriers allows for controlled diffusion onto the food surface. This controlled release maintains antimicrobial concentrations for extended periods, thereby enhancing shelf-life and reducing the frequency or dosage of application. Additionally, it minimizes undesirable sensory changes by preventing the sudden release of strong aromas or flavors. Such systems represent a promising strategy for improving the functional performance and consumer acceptability of plant-based preservation solutions (Yaashikaa et al., 2023).

1.2.7 Chemical stability

The stability of bioactive compounds under various storage conditions (temperature, light, oxygen exposure) critically determines their antimicrobial performance (Ali et al., 2018). Phenolic and terpenoid compounds are particularly susceptible to photodegradation and thermal decomposition (Ali et al., 2018). Advanced stabilization technologies like nanoencapsulation have demonstrated promise in preserving these labile compounds while maintaining their bioactivity.

1.2.8 Synergistic effects

Strategic combinations of plant extracts/essential oils with other antimicrobial agents often yield synergistic interactions. For instance, thyme-cinnamon essential oil blends exhibit enhanced efficacy against both Gram-positive and Gram-negative bacteria compared to individual components (Nourbakhsh et al., 2022). Such synergies enable dose reduction while maintaining antimicrobial potency, potentially mitigating negative organoleptic impacts.

1.2.9 Physicochemical properties

Key physicochemical characteristics (water/oil solubility, viscosity, volatility) dictate the functional performance of these compounds. Hydrophilic compounds demonstrate superior distribution in aqueous systems, whereas lipophilic components exhibit greater membrane penetration capacity. Optimal solvent selection and formulation design are therefore essential for maximizing antimicrobial activity in target applications (Nahr et al., 2019).

1.2.10 Economic viability

Despite their natural origin, industrial-scale implementation faces challenges related to extraction costs and purification expenses. Developing cost-effective extraction protocols and utilizing regionally abundant plant resources could enhance commercial feasibility. Life cycle assessments should evaluate the sustainability of large-scale production relative to synthetic alternatives (Olalere et al., 2022). The antimicrobial efficacy of plant-derived compounds is governed by a complex matrix of interdependent factors spanning physicochemical properties, application methodologies, and economic considerations. Systematic optimization of these parameters through multidisciplinary research will be crucial for developing next-generation, naturally derived food preservation systems that meet both efficacy and sustainability benchmarks. Future work should prioritize standardization protocols and scale-up studies to bridge the gap between laboratory findings and industrial implementation.

1.3 Applications of plant extracts and essential oils in postharvest preservation of fruits and vegetables

The preservation of fruits and vegetables presents significant challenges due to their perishable nature and susceptibility to multiple spoilage mechanisms. Biological, chemical, and physical factors-including the growth of pathogenic and spoilage microorganisms, oxidative degradation, and deterioration of sensory and nutritional quality-constitute major contributors to the reduced shelf-life of these products. In recent years, the use of plant extracts and essential oils as natural and effective preservation methods has garnered considerable attention from researchers and the food industry (Valdés et al., 2017). This section provides a comprehensive examination of their applications in postharvest management.

1.3.1 Control of spoilage and pathogenic microorganisms

A primary application of plant extracts and essential oils involves inhibition of spoilage microorganisms, including bacteria, fungi, and yeasts (Kowalczyk et al., 2020). These natural compounds exhibit both bactericidal and fungicidal properties, making them suitable for preventing microbial deterioration during storage and transportation. For instance, thyme and peppermint essential oils, rich in phenolic compounds such as thymol and carvacrol, have demonstrated efficacy against both Gram-positive and Gram-negative bacteria (Kowalczyk et al., 2020).

1.3.2 Shelf-life extension through antioxidant activity

Lipid oxidation and degradation of organic compounds represent major causes of quality deterioration during storage (Shahidi & Zhong, 2010). The antioxidant compounds in plant extracts and essential oils, particularly flavonoids and phenols, can effectively mitigate these processes (Shahidi & Zhong, 2010). Cinnamon and clove essential oils, for example, have shown remarkable free radical scavenging capacity, thereby preserving product quality and extending shelf-life (Zhang et al., 2023).

1.3.3 Prevention of biofilm formation

Microbial biofilms, which form protective structures on produce surfaces, enhance resistance to conventional washing and disinfection methods (Galie et al., 2018). Plant-derived compounds possess anti-biofilm properties that improve preservation efficacy (Galie et al., 2018).

1.3.4 Active packaging systems using plant extracts and essential oils

Active packaging technologies incorporating plant extracts and essential oils-whether edible or non-edible-offer an innovative solution for enhancing the shelf-life and safety of fruits and vegetables. Edible coatings, typically based on natural biopolymers such as polysaccharides or proteins, can be enriched with essential oils to create a protective layer that reduces moisture loss, oxygen exposure, and microbial growth. These coatings also enable controlled release of bioactive compounds, as demonstrated in formulations like aloe vera gel with thyme essential oil, which effectively suppresses mold and extends freshness (Yousuf et al., 2021). Non-edible active films, used in commercial packaging, are typically made from biodegradable polymers such as chitosan or polylactic acid (PLA) and can also be infused with antimicrobial plant compounds. These systems maintain food quality by releasing active agents over time, limiting sensory changes while enhancing microbial control. Advanced technologies such as nanoencapsulation and emulsion stabilization further improve the delivery and stability of these bioactives, making active packaging a consumer-friendly and environmentally sustainable approach to natural food preservation (Yousuf et al., 2021).

1.3.5 Mitigation of fungal spoilage losses

Fungal pathogens, particularly molds such as *Aspergillus* and *Penicillium* species, constitute primary agents of postharvest deterioration in fruits and vegetables (Alegbeleye et al., 2022). Essential oils derived from cinnamon (*Cinnamomum zeylanicum*), thyme (*Thymus vulgaris*), and clove (*Syzygium aromaticum*) exhibit potent antifungal activity against these organisms (Alegbeleye et al., 2022). Application methods incorporating these essential oils in wash solutions or surface sprays have demonstrated efficacy in suppressing fungal proliferation, thereby reducing postharvest losses by 40-60% in various commodities (Alegbeleye et al., 2022).

1.3.6 Preservation of sensory and nutritional quality

Maintaining the organoleptic properties (flavor, color, aroma) and nutritional value represents a critical challenge in postharvest management (Qin et al., 2025). The antioxidant properties of plant-derived compounds effectively minimize undesirable biochemical changes (Qin et al., 2025). For instance, peppermint (*Mentha piperita*) essential oil inhibits polyphenol oxidase activity, preventing enzymatic browning while preserving ascorbic acid content and visual appeal in treated produce (Abdelgawad et al., 2022).

1.3.7 Replacement of harmful chemicals

The use of synthetic chemical preservatives, such as chlorine and benzoates, to extend the shelf life of fruits and vegetables has raised significant safety and environmental concerns (Chakraborty & Dutta, 2022). Plant extracts and essential oils have been proposed as natural and safe alternatives to these compounds. For instance, solutions containing plant extracts, such as rosemary and chamomile, can effectively replace chemical disinfectants while demonstrating similar efficacy in suppressing pathogenic agents (Chakraborty & Dutta, 2022).

1.3.8 Reduction of waste in the supply chain

In the fruit and vegetable supply chain, particularly during transportation and storage, the risk of spoilage and quality deterioration is considerably high (Al-Dairi et al., 2022). The application of plant extracts and essential oils can help minimize waste at these stages (Al-Dairi et al., 2022). For example, incorporating citrus essential oils into the packaging of fresh produce not only inhibits microbial growth but also imparts a pleasant aroma, enhancing consumer appeal (Olaniran et al., 2024).

1.3.9 Combination with other preservation methods

One strategy to optimize the use of plant extracts and essential oils is their integration with other preservation techniques, such as refrigeration, modified atmosphere packaging, and irradiation. These combinations can produce synergistic effects, significantly extending the shelf life of products (Valdés et al., 2017).

1.3.10 Application in processed products

In addition to fresh fruits and vegetables, plant extracts and essential oils can also be utilized in processed products, such as ready-to-eat salads, pre-cut vegetables, and purees. By reducing microbial load and preventing oxidation, these compounds enhance the quality and shelf life of such products. For example, cinnamon essential oil in ready-to-eat fruit salads not only inhibits pathogen growth but also adds a pleasant flavor and aroma (Olaniran et al., 2024). In summary, the application of plant extracts and essential oils in the preservation of fruits and vegetables has established a distinct position as a natural, effective, and sustainable strategy for reducing waste and enhancing product quality. Further research on optimizing formulation and application methods could strengthen their role in the food industry.

1.3.10.1 Applications in postharvest preservation of fruits and vegetables

Research indicates that applying plant extracts and essential oils as sprays, dips, or edible coatings significantly reduces microbial contamination and extends the storage life of fruits and vegetables (Table 2). Citrus essential oils, rich in terpenoids, control microbial spoilage in fruits like orange and lemon, while edible coatings containing plant extracts help strawberries retain quality and freshness. Similarly, thyme and rosemary extracts have been shown to reduce microbial contamination in leafy greens, and carvacrol-and thymol-rich oils mitigate the spoilage of tomatoes and cucumbers. These findings collectively highlight the practical potential of these natural agents in commercial postharvest preservation (Valdés et al., 2017).

Table 2. Summary of Plant Extracts and Essential Oils Applied in Postharvest Preservation of Fruits and Vegetables

Commodity	Application	Active Compounds	Microbial Targets	Key Findings
Citrus fruits	Spraying or dipping	Orange, lemon, and grapefruit essential oils (rich in terpenoids)	Fungal and bacterial spoilage agents	Significant reduction in microbial spoilage, extended shelf-life (Valdés et al., 2017)
Strawberries	Edible coatings	Plant extracts	Fungi (e.g., Botrytis cinerea), bacteria	Enhanced quality retention and suppressed microbial growth (Valdés et al., 2017)
Leafy greens	Wash treatments or sprays	Thyme and rosemary extracts	Bacterial contamination	Substantial microbial load reduction on leafy vegetables (Nourbakhsh et al., 2022)
Tomatoes, cucumbers	Sprays	Essential oils rich in carvacrol and thymol	Bacterial and fungal pathogens	Promising mitigation of microbial deterioration and extended shelf-life (Kowalczyk et al., 2020)

1.4 Challenges and limitations in the application of plant extracts and essential oils for postharvest preservation of fruits and vegetables

Although plant extracts and essential oils demonstrate significant potential as natural antimicrobial and preservative agents, their practical implementation faces numerous technical, economic, regulatory, and sensory challenges (Bolouri et al., 2022). This section provides a comprehensive analysis of the major constraints associated with their utilization.

1.4.1 Alteration of product sensory characteristics

A primary challenge involves the impact on organoleptic properties of treated produce. The potent aromatic profiles of essential oils may modify intrinsic product characteristics, potentially creating undesirable flavors or odors. For instance, high concentrations of thyme or cinnamon essential oils applied to delicately flavored fruits can significantly reduce consumer acceptability due to overpowering sensory interference (Freche et al., 2022).

1.4.2 Chemical instability

Bioactive compounds in plant extracts and essential oils exhibit sensitivity to light, temperature, and oxidative degradation. This chemical lability can progressively diminish their antimicrobial and antioxidant efficacy. Phenolic compounds, for example, undergo photodegradation and thermal decomposition when exposed to direct light or elevated temperatures, necessitating controlled storage and transport conditions that increase operational costs (Keller et al., 2013).

1.4.3 Requirement for high concentrations

Effective microbial control often necessitates application of high concentrations, which presents multiple constraints: Elevated production costs, compromised sensory quality, and potential toxicity concerns (De Corato, 2020). Determining the optimal concentration that balances antimicrobial efficacy with product quality preservation remains a fundamental research challenge (De Corato, 2020).

1.4.4 Production economics

The extraction and purification processes, particularly advanced methods like supercritical fluid extraction, incur substantial costs. Additionally, rare plant species or those requiring specialized cultivation conditions further increase production expenses (Herrero et al., 2010). These economic factors limit industrial adoption, especially in resource-constrained regions.

1.4.5 Limited efficacy against certain microorganisms

While many plant extracts and essential oils demonstrate good antimicrobial activity against Gram-positive bacteria, they exhibit reduced effectiveness against Gram-negative bacteria and certain fungi or yeasts (Chouhan et al., 2017). This differential microbial susceptibility may necessitate the use of supplementary compounds or alternative methods to achieve comprehensive pathogen control.

1.4.6 Interaction with food components

Bioactive compounds in plant extracts may interact with components of the food matrix, such as lipids, proteins, or carbohydrates. These interactions can result in reduced bioavailability or neutralization of antimicrobial compounds. This phenomenon is particularly relevant in processed or complex food systems, where multiple components may compete for active sites or binding affinities (Phan et al., 2018).

1.4.7 Regulatory and standardization challenges

Despite their natural origin, the use of plant extracts and essential oils in food products is subject to strict regulatory oversight. Agencies such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) require comprehensive data on safety, purity, composition, dosage, and efficacy before approval for use in food preservation. Moreover, the lack of standardized guidelines for extraction, formulation, and quality control further complicates regulatory compliance and hinders global commercialization (Bolouri et al., 2022).

1.4.8 Consumer acceptance issues

Although consumers generally prefer natural additives over synthetic ones, awareness of plant-based preservatives remains limited, and strong aromas or altered flavors may reduce product appeal. Additionally, concerns about potential allergic reactions or long-term health effects of certain essential oils may deter consumers. Educational outreach and sensory optimization are necessary to improve public acceptance (Jang & Lee, 2024).

1.4.9 Formulation complexity

Effective utilization of plant extracts and essential oils for produce preservation may require complex formulations to enhance efficacy and stability. Techniques such as nanoencapsulation or combination with synergistic agents could improve performance, though these technologies may involve substantial costs and technical complexity (Pisoschi et al., 2018).

1.4.10 Need for further research

While numerous studies have investigated the antimicrobial and antioxidant properties of plant extracts and essential oils, additional research is needed to elucidate their precise mechanisms of action, long-term stability, toxicity profiles, and real-world effectiveness. Moreover, comprehensive studies are required to evaluate their interactions with other preservation methods and environmental factors. Addressing these limitations requires coordinated multidisciplinary research involving food chemists, microbiologists, and process engineers to develop optimized, commercially viable solutions that meet both efficacy and safety requirements for global markets.

1.4.11 Summary of Suggested Solutions

To overcome the key challenges associated with using plant extracts and essential oils for postharvest preservation of fruits and vegetables, a range of practical and research-driven strategies can be employed. Techniques such as nanoencapsulation, edible films, and controlled-release systems help mask strong flavors, improve compound stability, and reduce effective doses (Pisoschi et al., 2018; Yousuf et al., 2021). Combining extracts with mild preservatives or permeabilizers like EDTA can enhance antimicrobial action, allowing lower concentrations and broad-spectrum efficacy (Nourbakhsh et al., 2022; Yap et al., 2021). Sustainable, low-cost extraction methods and green processing technologies support production economics and scalability (Herrero et al., 2010). Strategies to minimize interactions with food matrices include the use of protective coatings and pre-treatment of produce (Pisoschi et al., 2018). Achieving regulatory acceptance will require harmonized guidelines and thorough safety and efficacy data (Bolouri et al., 2022), while consumer-focused approaches-such as sensory optimization and education about safety and sustainability-can enhance market adoption (Jang & Lee, 2024). Simplified formulations utilizing cost-effective carriers and scalable systems will help small-scale producers implement these solutions (Pisoschi et al., 2018), and ongoing interdisciplinary research is needed to address knowledge gaps around long-term safety, industrial feasibility, and synergistic effects (De Corato, 2020).

1.5 Practical recommendations in industry

Considering the advantages and challenges associated with the use of plant extracts and essential oils in the preservation of fruits and vegetables, several practical strategies have been proposed to enhance their effectiveness, applicability, and scalability in the food industry. The first recommendation is to conduct further research on optimizing extraction and processing techniques for plant extracts and essential oils. Advanced techniques such as supercritical fluid extraction, ultrasonic-assisted extraction, and microwave-assisted extraction can improve both the yield and quality of the extracts. These methods are capable of isolating bioactive compounds while preserving their biological properties and reducing the extraction time, which can contribute to cost reduction and improved stability of the active components (De Corato, 2020). Furthermore, the use of novel technologies such as nanoencapsulation can enhance the stability of these compounds against environmental factors like light and heat, and allow for their controlled release over time. Another important recommendation is the investigation and development of standardization methods for plant extracts and essential oils in the food industry. Currently, the lack of unified standards for the quality, purity, and biological effects of these compounds may pose challenges in ensuring product quality and safety. Establishing national and international standards for plant-based extracts and essential oils-such as defining permissible levels of active compounds, standardizing extraction methods, and evaluating efficacy-can significantly increase the confidence of both the industry and consumers in these products. In addition, it is essential to develop precise protocols for the safety assessment of these compounds, including toxicity and allergenicity testing, to mitigate potential health risks associated with their use. Finally, to increase consumer acceptance and promote the application of plant extracts and essential oils in the food industry, more comprehensive educational efforts regarding their benefits and safety are necessary. Many consumers still lack sufficient knowledge about the antimicrobial and antioxidant properties of these compounds and may have concerns about potential side effects or sensory alterations. Therefore, public awareness and educational campaigns-particularly those emphasizing the benefits of using natural substances in food preservation-can facilitate greater acceptance. Moreover, the development of products that retain desirable taste and sensory attributes while incorporating the benefits of plant-based extracts and essential oils can help expand the use of these preservation methods in consumer markets.

1.6 Specific international food safety regulations

Despite the increasing interest in plant extracts and essential oils as natural preservatives, their broader adoption in the food industry remains constrained by regulatory complexities. International food safety agencies, such as the FDA and EFSA, require extensive safety evaluations for any substance intended for use in food (Magnuson et al., 2013). In the U.S., many plant-derived compounds must attain Generally Recognized As Safe (GRAS) status, which demands rigorous toxicological data and a history of safe use. Similarly, the EFSA mandates detailed risk assessments under its Novel Food Regulation and Flavoring Regulation frameworks, which examine purity, intake levels, and potential allergenicity (Da Silva et al., 2022). However, many plant extracts and essential oils currently lack standardized compositional profiles, making regulatory approval challenging. To address this, there is a pressing need for global harmonization of extraction protocols, chemical characterization, and quality control benchmarks. Moreover, long-term toxicological studies-including genotoxicity, sub-chronic toxicity, and allergenicity tests- are essential to establish safe consumption thresholds and secure regulatory acceptance. Without such evidence-based standardization and safety assessments, the industrial scalability and consumer trust in these bioactive compounds will remain limited, despite their promising antimicrobial potential (Magnuson et al., 2013).

2. Conclusion

Plant-derived extracts and essential oils exhibit significant potential as natural preservatives, offering antimicrobial, antioxidant, and antifungal properties that enhance the postharvest quality and shelf life of fruits and vegetables. Their multifaceted biological activities present eco-friendly alternatives to synthetic preservatives while addressing food security challenges. However, key limitations-including sensory alterations, concentration requirements, chemical instability, production costs, and regulatory standardization-hinder large-scale implementation. Emerging technologies like nanoencapsulation, microemulsions, and active packaging show promise in overcoming these barriers by improving stability and efficacy. Future research must prioritize: (1) synergistic combinations with other preservation methods, (2) mechanistic studies at the molecular level, and (3) rigorous safety assessments. Strategic investments in these areas could accelerate the adoption of plant-based preservatives, fostering sustainable food systems that minimize synthetic chemical use and reduce waste. To realize their full potential, efforts should focus on developing cost-effective, standardized formulations that balance efficacy with consumer acceptability, ultimately supporting global food safety and sustainability goals.

Authors' Contributions

Nastaran Noori: Conceptualization; Data curation; Investigation; Writing original draft; Writing-review & editing. **Hassan Hassanzadazar:** Conceptualization; Writing-review & editing. **Esrafil Asgari:** Supervision; Conceptualization; Visualization; Writing-review & editing. **Maryam Hassani:** Investigation; Writing-original draft.

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Conflicts of Interest

The authors have declared no competing interests.

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Ethical considerations

This study was conducted as part of a research project approved by the Ethics Committee of Zanjan University of Medical Sciences (Ethics Code: IR.ZUMS.BLC.1403.146).

Using artificial intelligence

No artificial intelligence was used.

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