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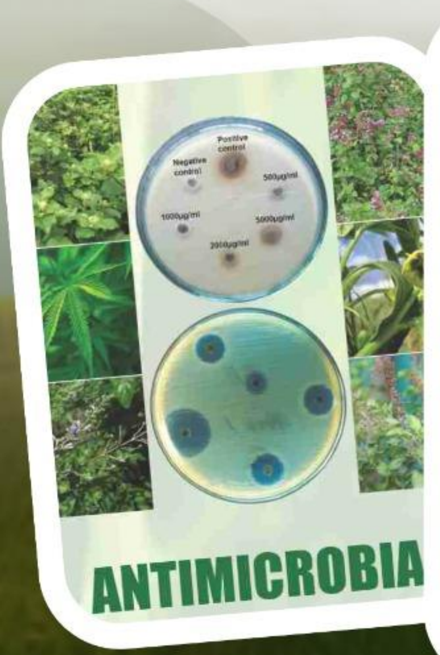

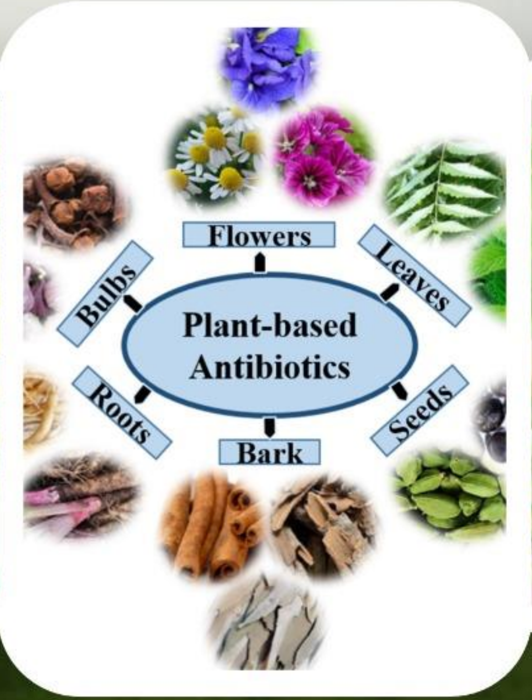

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EFFICACY AND LIMITATIONS OF PLANT-DERIVED ANTIMICROBIALS IN FOOD PRESERVATION

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ABSTRACT

Plant-derived antimicrobials (PDAs) are increasingly regarded as promising alternatives to synthetic preservatives due to their natural origin, safety, and multifunctional properties. This review synthesizes current knowledge on the efficacy and limitations of PDAs in food preservation, drawing upon various classes such as essential oils, polyphenols, alkaloids, and glucosinolates. The paper explores their antimicrobial mechanisms, effectiveness across different food matrices, sensory and technological challenges, and strategies to overcome existing limitations. Furthermore, it discusses the outlook and necessary innovations for integrating PDAs into mainstream food systems. By offering a comprehensive analysis of the literature, this review aims to support the development of sustainable and consumer-acceptable antimicrobial strategies for the food industry.

KEYWORDS:

plant antimicrobials, food preservation, essential oils, polyphenols, natural preservatives, food safety, hurdle technology, edible coatings.

1. INTRODUCTION

In the past few decades, the food industry has witnessed a change in basic assumptions driven by rising consumer awareness regarding food safety, health, and environmental sustainability. Traditional synthetic preservatives, although effective, are increasingly scrutinized due to their potential toxicity, allergenicity, and long-term health effects, including carcinogenic and teratogenic risks. Moreover, the growing prevalence of antimicrobial resistance in pathogenic and spoilage microorganisms necessitates alternative solutions that are both effective and safe.

Plant-derived antimicrobials (PDAs), encompassing a wide range of bioactive compounds from herbs, spices, fruits, and vegetables, have emerged as viable alternatives. These natural agents exhibit broad-spectrum antimicrobial activity, including bactericidal, fungicidal, and antiviral effects. They also contribute antioxidant benefits, which are vital for preventing lipid oxidation in food systems. Despite their promising features, the successful application of PDAs in food preservation is challenged by issues such as flavor alterations, stability loss, poor solubility, and regulatory uncertainty.1

This review aims to provide a critical evaluation of the role of PDAs in enhancing food safety and shelf life. It focuses on their sources, mechanisms of action, application in diverse food categories, and the technological and regulatory hurdles impeding their widespread use. Furthermore, it presents innovative strategies like nanoencapsulation, active packaging, and hurdle technology that can enhance the performance and acceptability of these natural compounds.

2. CLASSIFICATION AND SOURCES OF PLANT-DERIVED ANTIMICROBIALS

2.1 ESSENTIAL OILS: Essential oils (EOs) are among the most extensively studied PDAs due to their potent antimicrobial and antioxidant activities. They are complex mixtures of volatile compounds, primarily terpenoids and phenylpropenes, extracted from various plant parts. Their mode of action includes disruption of microbial membranes, inhibition of enzyme activity, and leakage of cell contents. Oregano oil (rich in carvacrol), thyme oil (thymol), clove oil (eugenol), and cinnamon oil (cinnamaldehyde) are notable examples.

Numerous studies have demonstrated the efficacy of EOs against pathogens such as *Listeria monocytogenes*, *Escherichia coli*, *Salmonella enterica*, and *Staphylococcus aureus*. For instance, oregano oil at concentrations as low as 0.1% has been found to significantly reduce microbial counts in ground meat and ready-to-eat salads. Their GRAS (Generally Recognized as Safe) status by the FDA further supports their use in food systems. However, their strong aroma and volatility require careful formulation and application.3

2.2 POLYPHENOLS: Polyphenols are widely distributed in plant foods and are known for their diverse structures and functionalities. These include phenolic acids (e.g., gallic, ferulic), flavonoids (e.g., quercetin, catechins), stilbenes (e.g., resveratrol), and tannins. Their antimicrobial mechanisms include inhibition of cell wall synthesis, membrane disruption, and interference with nucleic acid and energy metabolism.

For example, gallic acid exhibits MIC values of 1000–2000 µg/mL against common pathogens. Resveratrol has shown efficacy at lower concentrations, particularly against Gram-positive bacteria. Combinations of polyphenols and EOs have shown synergistic effects, improved antimicrobial potency while reducing the required dose.

2.3 ALKALOIDS: Alkaloids such as berberine, quinine, and capsaicin represent another class of PDAs with potential in food preservation. They interfere with microbial DNA replication and protein synthesis. Berberine, extracted from *Berberis* species, has shown inhibitory effects against *Candida albicans*, *E. coli*, and *S. aureus*. While not as widely researched in food applications, their pharmacological background indicates significant promise.

2.4 GUCOSINOLATES AND OTHER COMPOUNDS: Glucosinolates, found in cruciferous vegetables like broccoli and mustard, hydrolyze to form isothiocyanates—compounds with demonstrated antimicrobial properties. Allyl-isothiocyanate is particularly effective against *Salmonella*, *Listeria*, and spoilage fungi. Other natural compounds like saponins, thiols, and plant peptides also show potential but require further exploration.

3. MECHANISM OF MICROBIAL ACTION

The antimicrobial action of PDAs involves a complex array of biochemical and biophysical processes that lead to microbial cell damage or death. These mechanisms can vary based on the compound class and target microorganism but include:

- **Disruption of Cell Membranes:** Many PDAs, especially essential oils and terpenes, integrate into microbial lipid bilayers, increasing membrane permeability and causing leakage of cellular contents. For instance, thymol and carvacrol have been shown to disrupt membrane integrity in *E. coli* and *S. aureus*.
- **Denaturation of Proteins and Enzymes:** Phenolic compounds can bind to microbial proteins, leading to enzyme inactivation and interference with metabolic processes. Tannins, for instance, form complexes with proteins, reducing their functionality.
- **Inhibition of Nucleic Acid Synthesis:** Certain alkaloids and flavonoids can intercalate with DNA or inhibit topoisomerases, thus preventing DNA replication and transcription.
- **Disruption of ATP Synthesis and Metabolic Pathways:** Some PDAs act by targeting the energy-producing pathways of microbes, leading to ATP depletion and cell death.

The multi-targeted nature of PDAs is especially beneficial in reducing the risk of resistance development, as microbes find it more difficult to adapt simultaneously to multiple modes of attack.

4. APPLICATIONS IN FOOD PRESERVATION

4.1 MEAT AND POULTRY PRODUCTS: PDAs have shown significant potential in preserving meat and poultry products, which are highly perishable and prone to microbial contamination. Essential oils from oregano, rosemary, and thyme have been incorporated into marinades, coatings, and packaging films to inhibit spoilage bacteria such as *Pseudomonas spp.* and pathogens like *Listeria monocytogenes*. Studies have demonstrated that the addition of 0.5% rosemary oil can extend the shelf life of refrigerated chicken breasts by up to 5 days.

Polyphenols like catechins and tannic acid have also been applied in processed meats, including sausages and patties. These compounds not only suppress microbial growth but also retard lipid oxidation, thereby preserving flavor and nutritional quality.

4.2 DAIRY PRODUCTS: In dairy systems, PDAs are applied to control spoilage organisms and pathogens such as *Lactobacillus*, *Penicillium*, and *Staphylococcus aureus*. Incorporating essential oils into cheese wax coatings or integrating polyphenol extracts into milk formulations has shown promising results in reducing microbial load without significantly affecting sensory attributes.

For example, the use of thyme oil in cheese coatings has been reported to reduce surface mold growth by over 70% during aging. Similarly, the incorporation of green tea polyphenols into yogurt has shown effective inhibition of spoilage yeasts without compromising consumer acceptance.

4.3 FRUITS AND VEGETABLES: Fresh produce is often contaminated through handling, irrigation water, or postharvest processes. PDAs, especially when formulated into edible coatings, can serve as an effective barrier to microbial contamination. Aloe vera gel enriched with lemongrass oil, for instance, has been shown to extend the shelf life of strawberries by 7–10 days (about 1 and a half weeks).

Citrus-based oils and grape seed extracts are also popular in preserving minimally processed fruits and vegetables. Their application via dipping, spraying, or packaging films has yielded significant reductions in microbial counts while maintaining color, texture, and taste.

4.4 READY-TO-EAT AND MINIMALLY PROCESSED FOODS: In ready-to-eat products like salads, sandwiches, and dips, PDAs have been used in wash solutions, antimicrobial sachets, and biopolymer films. For example, washing leafy greens with a 0.2% oregano oil solution has shown to reduce *E. coli* and *Salmonella* counts by over 2 log CFU/g.

Encapsulation of PDAs into biodegradable films allows for controlled release of antimicrobial agents, thus maintaining a consistent inhibitory effect throughout storage. Such strategies are particularly useful in convenience foods, where traditional preservatives are often avoided.

5. LIMITATIONS AND CHALLENGES

Despite their potential benefits, the application of plant-derived antimicrobials in food preservation is accompanied by several limitations and challenges that must be addressed to enable their widespread use in commercial food products.

5.1 SENSORY IMPACT: Many PDAs, particularly essential oils, possess strong aromas and flavors that can alter the sensory characteristics of food. While consumers may associate natural preservatives with health and sustainability, any negative change in taste, smell, or appearance can lead to product rejection. For example, cinnamon oil may impart a pungent taste when used at higher concentrations, limiting its application in mildly flavored foods like dairy or beverages. This necessitates careful optimization of concentration levels and formulation strategies, such as encapsulation or selective blending, to maintain sensory acceptability.

5.2 STABILITY AND FOOD MATRIX INTERACTIONS: Many PDAs are sensitive to environmental conditions such as heat, light, pH, and oxygen. During food processing and storage, these factors can degrade active components, diminishing their antimicrobial effectiveness. Essential oils, for instance, are volatile and can evaporate or degrade over time if not properly protected. Furthermore, interactions with food matrix components such as fats, proteins, and carbohydrates can sequester active compounds and reduce their bioavailability.

In emulsified or high-fat foods, lipophilic compounds like terpenes may preferentially partition into the lipid phase, limiting their accessibility to water-phase microorganisms. This necessitates tailored delivery systems such as emulsions, microencapsulation, or nano formulations to maintain stability and targeted release.

5.3 REGULATORY AND SAFETY CONCERNS: Although many plant extracts are recognized as safe, their use in food systems is not universally regulated. Differences in regulatory frameworks across countries and regions create challenges for global commercialization. For example, a compound approved for use in the EU may still be under evaluation in the United States or Asia.

Moreover, concerns regarding allergenicity, toxicity at higher doses, and potential accumulation of secondary metabolites necessitate rigorous safety assessments. Without well-defined maximum usage limits and standardized toxicological data, food manufacturers may hesitate to adopt PDAs widely.

5.4 COST AND SCALIBILITY: Extraction and purification of bioactive compounds from plants can be labor-intensive and costly, particularly for high-purity essential oils and phenolics. This can be a barrier for small and medium enterprises (SMEs) seeking affordable preservative solutions. Additionally, the availability of raw plant material in sufficient quantities may be affected by seasonal variation, climate change, or agricultural constraints.

5.5 RISK OF MICROBIAL RESISTANCE: Although PDAs often employ multiple mechanisms of action, which reduces the likelihood of resistance development, emerging studies have reported potential adaptive responses in some microorganisms. Sub-lethal doses or prolonged exposure to low concentrations may lead to tolerance, necessitating cautious application and dose optimization.

These challenges highlight the need for further research and innovation to optimize PDA formulations, enhance their stability, mitigate sensory impacts, and establish robust regulatory frameworks.

6. STRATEGIES TO OVERCOME LIMITATIONS

To enhance the feasibility and effectiveness of PDAs in food preservation, several strategies have been developed and tested. These include formulation improvements, advanced delivery systems, combination approaches, and innovative packaging technologies.

6.1 NANOENCAPSULATION AND MICROENCAPSULATION: Encapsulation techniques are widely employed to protect bioactive compounds from environmental degradation and control their release in food systems. Microencapsulation involves enclosing the active compound within a protective matrix, while nanoencapsulation achieves this at a nanometric scale, offering greater stability and bioavailability.

Materials such as chitosan, alginate, starch, and lipids are commonly used as encapsulating agents. For example, nanoemulsions of thyme and oregano essential oils have been shown to provide sustained antimicrobial activity and reduce the required concentration, thereby minimizing sensory impact.

Encapsulation also enables targeted delivery, allowing the antimicrobial agent to be released at the site of microbial contamination, which is particularly advantageous in multilayered or complex food matrices.

6.2 SYNERGISTIC COMBINATIONS AND HURDLE TECHNOLOGY: One promising approach to overcoming the limitations of individual PDAs is their use in combination with other natural or conventional preservation methods. This concept, known as hurdle technology, involves applying multiple preservation factors (e.g., low pH, modified atmosphere packaging, mild heat treatment, or refrigeration) to achieve microbial control without compromising food quality.

Synergistic effects have been observed between essential oils and polyphenols, where the combined antimicrobial action is greater than the sum of their individual effects. Additionally, combining PDAs with bacteriocins like nisin or organic acids can enhance their spectrum and potency against resistant strains.

6.3 SMART AND ACTIVE PACKAGING: Active packaging systems are designed to release antimicrobial compounds over time or in response to environmental triggers. These systems extend shelf life while maintaining food quality by controlling microbial growth during storage and distribution.

Incorporating PDAs into biopolymer-based films (e.g., PLA, gelatin, cellulose) allows for gradual diffusion of the active agents. For instance, incorporating cinnamon or clove essential oils into edible coatings has proven effective in controlling mold growth on bakery products and fruits.

Smart packaging, which includes indicators and sensors, can be integrated with antimicrobial systems to monitor food freshness and signal spoilage, further enhancing safety.

6.4 SENSORY MARKING AND REFORMULATION: To mitigate the undesirable sensory attributes of some PDAs, flavor-masking agents or reformulation strategies can be employed. Techniques such as microemulsions and cyclodextrin inclusion complexes can reduce volatility and aroma intensity without compromising antimicrobial activity.

Moreover, selecting less pungent but equally effective compounds (e.g., rosmarinic acid instead of whole rosemary extract) may offer functional benefits while ensuring consumer acceptance.

6.5 REGULATORY HARMONIZATION AND RESEARCH SUPPORT: Efforts should also be directed toward establishing clear and harmonized regulatory frameworks for the approval and labeling of PDAs. This includes setting acceptable daily intake (ADI) levels, conducting comprehensive risk assessments, and promoting global alignment of food safety standards.

Public and private investment in research and development is essential to bridge knowledge gaps, particularly regarding toxicity, interactions with food matrices, and consumer perception. Collaborative projects among academia, industry, and regulatory bodies can facilitate innovation and translation into practical applications.

7. FUTURE PERSPECTIVES

The future of plant-derived antimicrobials (PDAs) in food preservation is promising but requires a strategic and interdisciplinary approach to overcome current limitations and unlock their full potential. As the global demand for clean-label, sustainable, and safe food products continues to grow, PDAs are expected to play a vital role in reshaping preservation technologies.

7.1 ADVANCED FORMULATION AND DELIVERY SYSTEM: The development of next-generation delivery systems—including nanostructured lipid carriers, multilayered films, and hybrid encapsulation technologies—will be crucial to improve the solubility, stability, and targeted release of PDAs. Precision delivery that adapts to specific food matrices and microbial profiles will become increasingly important.

Moreover, intelligent packaging systems that integrate sensors and controlled-release antimicrobial agents could transform how spoilage and contamination are managed throughout the food supply chain.

7.2 INTEGRATED PRESERVATION STRATEGIES: There is increasing recognition that no single preservation method is universally effective. As such, combining PDAs with non-thermal technologies such as pulsed electric fields (PEF), cold plasma, high-pressure processing (HPP), and ultraviolet (UV-C) treatment holds significant promise. These integrated approaches can achieve synergistic antimicrobial effects while maintaining food quality.

7.3 EXPANSION OF ANTIMICROBIAL SOURCES: Research is also expanding to include underutilized plant species and agricultural by-products (e.g., grape pomace, olive leaves, pomegranate peel) as cost-effective and sustainable sources of antimicrobial compounds. Such valorization of food waste aligns with circular economy principles and reduces the environmental impact of food production.

7.4 CONSUMER AWARENESS AND MARKET ACCEPTANCE: Educating consumers about the benefits, safety, and scientific basis of PDAs is essential for broader market acceptance. Transparent labeling, certification programs, and sustainability claims supported by credible evidence can build trust and preference for PDA-enriched food products.

7.5 INDUSTRY COLLABORATION AND INNOVATION ECOSYSTEMS: Strong collaboration between academia, regulatory agencies, ingredient manufacturers, and food producers will accelerate innovation and commercialization. Public-private partnerships and funding initiatives can support translational research, pilot testing, and scale-up of novel PDA-based solutions.

The establishment of innovation hubs and consortia focused on natural food preservation technologies will further catalyze progress.

8. CONCLUSION

Plant-derived antimicrobials (PDAs) represent a compelling alternative to synthetic preservatives in the pursuit of safer, more natural, and sustainable food systems. Their broad-spectrum antimicrobial properties, antioxidant activity, and compatibility with consumer preferences for clean-label products position them as key players in modern food preservation.

This review has highlighted the diversity of PDAs, including essential oils, polyphenols, alkaloids, and glucosinolates, as well as their mechanisms of action and proven applications across a range of food categories. From meat and dairy products to fruits, vegetables, and ready-to-eat meals, PDAs have demonstrated efficacy in inhibiting spoilage organisms and foodborne pathogens.

However, several challenges still hinder their widespread adoption. Sensory issues, variability in composition, limited stability, and regulatory ambiguities remain critical barriers. These limitations necessitate the development of innovative delivery systems, synergistic preservation strategies, standardized safety protocols, and global regulatory harmonization.

Future progress will depend on continued interdisciplinary research, technological innovation, industry partnerships, and proactive consumer education. By addressing these challenges and building on their strengths, PDAs can help drive a transformative shift toward natural, effective, and resilient food preservation methods.

In summary, PDAs hold significant promise as part of a broader toolkit for ensuring food safety, reducing food waste, and meeting the demands of health-conscious consumers in a rapidly evolving global food landscape.

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AUTHOR CREDIT STATEMENT

The sole author was responsible for the conceptualization, literature review, data analysis, writing, and final editing of the manuscript. All sources have been appropriately acknowledged, and the content reflects the author's independent synthesis and critical evaluation of the existing literature.

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