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Garlic extract as a dual-action antimicrobial agent: pharmacological and pharmaceutical evaluations for foodborne pathogens

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Abstract
For instance, studies have shown garlic extract achieves up to a 70% reduction in biofilm formation and MICs ranging from 2 to 16 µg/mL against *Salmonella* and *E. coli*. These findings underscore its potent antibacterial capabilities.
The alarming rise of antimicrobial resistance (AMR) in foodborne pathogens has led to significant challenges in food safety and public health. Conventional antibiotics are becoming less effective, necessitating innovative alternatives to control and mitigate the spread of resistant pathogens. Garlic (*Allium sativum*) is a widely studied natural antimicrobial agent, known for its rich array of bioactive compounds, including allicin, ajoene, and diallyl sulfides, which have shown potent antibacterial activity. This study explores the dual-action antimicrobial properties of garlic extract, emphasizing its pharmacological mechanisms such as bacterial membrane disruption, quorum sensing inhibition, and efflux pump modulation. Furthermore, the paper evaluates garlic extract's pharmaceutical applications, including its use in pre-harvest and post-harvest food safety interventions, as well as in advanced delivery systems for stability and efficacy. Challenges in standardization, sensory acceptability, and scalability are addressed, alongside recommendations for future research and innovations. The findings underscore garlic extract's potential as a sustainable, natural antimicrobial agent capable of combating multidrug-resistant foodborne pathogens.

Keywords: Garlic extract, Antimicrobial resistance (AMR), foodborne pathogens, biofilm formation, Minimum inhibitory concentration (MIC)

1. Introduction

According to WHO estimates, antimicrobial-resistant foodborne pathogens cause over 700,000 deaths annually, with economic losses exceeding $1 trillion globally. Such statistics highlight the urgent need for alternative antimicrobial strategies.

Antimicrobial resistance (AMR) has become a critical issue globally, with foodborne pathogens such as *Salmonella*, *Escherichia coli*, and *Listeria monocytogenes* exhibiting alarming levels of resistance to commonly used antibiotics. These pathogens are responsible for millions of foodborne illnesses each year, leading to significant public health and economic burdens [1]. Antibiotic use in agriculture, particularly as growth promoters in livestock, has been identified as a major contributor to the spread of AMR [2]. As conventional antibiotics lose their efficacy, there is an urgent need for alternative strategies to ensure food safety and prevent disease outbreaks. Among natural alternatives, garlic has emerged as a leading candidate due to its broad-spectrum antimicrobial activity and lack of toxicity to humans when used appropriately [3]. The bioactive compounds in garlic, especially allicin, have been shown to effectively target bacterial pathogens through multiple mechanisms, making it a promising tool in addressing AMR [4]. This study aims to investigate garlic extract's dual-action capabilities, focusing on its pharmacological mechanisms and practical applications in food safety systems.

2. Reviews of Literature

For example, variations in the antimicrobial efficacy of garlic extracts have been noted, with ethanol extracts consistently showing higher allicin concentrations compared to aqueous methods. Such discrepancies emphasize the need for standardized extraction protocols.

Numerous studies have highlighted the antimicrobial properties of garlic extract and its potential to combat AMR. Ankri and Mirelman [5] demonstrated that allicin, a sulfur compound in garlic, exhibits bactericidal activity against *Salmonella* and *E. coli*. Borlinghaus *et al.* [6] reviewed the chemical properties of garlic compounds, emphasizing their ability to disrupt bacterial membranes and inhibit quorum sensing. Harun-Or-Rashid *et al*. [7] explored the biofilm inhibitory effects of garlic on multidrug-resistant bacterial strains, reporting a 70% reduction in biofilm mass. Similarly, Ried and Fakler [8] analyzed the synergistic effects of garlic and antibiotics, showing enhanced efficacy against resistant pathogens. These studies provide a solid foundation for understanding garlic extract's dual-action antimicrobial potential and its applications in food safety.

3. Main Objective

The primary objective of this study is to explore the dual-action antimicrobial properties of garlic extract, focusing on:

1. Evaluating its pharmacological mechanisms, including bacterial membrane disruption, quorum sensing inhibition, and efflux pump modulation.
2. Investigating its pharmaceutical applications in food safety, particularly in pre-harvest and post-harvest interventions.
3. Addressing challenges in the standardization, formulation, and delivery of garlic-based antimicrobials for sustainable use in combating multidrug-resistant foodborne pathogens.

4. Phytochemical Profile of Garlic Extract

Garlic's antimicrobial efficacy is rooted in its complex phytochemical composition. The most prominent bioactive compound is allicin, a sulfur-containing molecule formed enzymatically from alliin through the action of alliinase when garlic is crushed or chopped [9]. Allicin is highly reactive and exhibits both bactericidal and bacteriostatic properties, targeting a wide range of Gram-positive and Gram-negative pathogens [10]. In addition to allicin, garlic contains secondary sulfur compounds such as ajoene, diallyl sulfides, and S-allyl cysteine, each contributing uniquely to its antimicrobial activity [11]. These compounds disrupt bacterial metabolism, inhibit biofilm formation, and modulate resistance mechanisms [12]. Advanced analytical techniques such as gas chromatography-mass spectrometry (GC-MS) and high-performance liquid chromatography (HPLC) have identified over 200 phytochemicals in garlic extract [13]. Ethanol and methanol extractions consistently yield higher allicin concentrations compared to aqueous methods, with ethanol extracts showing enhanced stability and antimicrobial potency [14].

5. Mechanisms of Action against Foodborne Pathogens

Studies reported that garlic extract reduces bacterial viability by 80% within 6 hours at sublethal concentrations and decreases biofilm density by up to 70%. These findings provide quantitative evidence of its potent activity.

5.1 Membrane Disruption

One of the primary antimicrobial mechanisms of garlic compounds is their ability to disrupt bacterial membranes. Allicin interacts with membrane phospholipids, increasing permeability and leading to leakage of intracellular contents such as ions, proteins, and metabolites [15]. This disruption compromises the structural integrity of bacterial cells, ultimately resulting in cell lysis [16].

5.2 Inhibition of Quorum Sensing and Biofilm Formation

Quorum sensing is a bacterial communication system that regulates virulence factors and biofilm formation. Garlic-derived compounds, particularly ajoene and allicin, have been shown to inhibit quorum sensing pathways, reducing the pathogenicity of bacteria [17].

5.3. Efflux Pump Modulation

Efflux pumps are a common mechanism employed by bacteria to expel antibiotics, reducing their intracellular concentrations and effectiveness. Garlic compounds inhibit the activity of efflux pumps, enhancing the accumulation of antimicrobial agents within bacterial cells [18].

6. Pharmacological Efficacy

In poultry models, a daily dose of 0.5% garlic extract in feed resulted in a 60% reduction in *Salmonella* gut colonization within 14 days. Such findings demonstrate its practical applicability in animal husbandry.

Laboratory studies have shown that garlic extract exhibits minimum inhibitory concentrations (MICs) as low as 4 µg/mL against *Salmonella*, *E. coli*, and *Listeria* [19]. Chickens supplemented with garlic extract in their feed showed a 60% reduction in gut colonization by *Salmonella* [20].

7. Pharmaceutical Applications in Food Safety

7.1. Pre-Harvest Interventions

Garlic extract reduces pathogen load in livestock while enhancing gut health and immunity [21].

7.2. Post-Harvest Applications

A case study involving garlic-based antimicrobial sprays demonstrated a 65% reduction in microbial loads on treated poultry meat compared to untreated controls. This highlights its effectiveness in real-world food safety interventions.

Post-harvest applications include garlic-based antimicrobial washes, reducing surface contamination on poultry, meat, and fresh produce by up to 65% [22].

7.3. Pharmaceutical Formulations

Encapsulation technologies have been developed to enhance the stability and delivery of garlic compounds [23].

8. Challenges and Limitations

Ongoing research into nanoencapsulation techniques has shown promise in stabilizing allicin, with encapsulated formulations retaining bioactivity for up to 6 months under optimal conditions.

Despite its promising antimicrobial properties, garlic extract faces several challenges and limitations that must be addressed to maximize its potential in combating multidrug-resistant foodborne pathogens. One significant challenge lies in the variability of its phytochemical composition. Factors such as garlic cultivar, cultivation practices, climate, and extraction methods can influence the concentration of bioactive compounds like allicin and ajoene. This variability complicates the standardization of garlic-based formulations, which is critical for ensuring consistent efficacy in both pharmacological and food safety applications. Another major limitation is the instability of allicin, the primary antimicrobial compound in garlic. Allicin is highly reactive and degrades rapidly into other sulfur-containing compounds, which, while still active, may not possess the same level of potency. This instability poses a challenge for storage, formulation, and delivery, particularly in industrial and pharmaceutical settings. Developing techniques to stabilize allicin without compromising its bioactivity remains a critical area of research. Sensory attributes of garlic, particularly its strong odor and pungent taste, also limit its applicability in certain contexts. While these attributes are acceptable in some food safety interventions, they can pose significant barriers in pharmaceutical applications and consumer acceptance. Effective strategies to neutralize or mask the odor without reducing the antimicrobial efficacy are essential for its broader adoption.

Economic and logistical challenges further complicate the large-scale production and application of garlic-based antimicrobial agents. Cultivation, extraction, and processing require significant resources, and the scalability of such operations can be a limiting factor. Additionally, the cost of advanced formulations, such as encapsulation or nanoparticle delivery systems, may hinder widespread use, particularly in low-resource settings where antimicrobial resistance is most prevalent.

Regulatory hurdles also present a challenge for the adoption of garlic extract in food safety and pharmaceutical markets. Establishing comprehensive safety, efficacy, and quality standards is essential for gaining regulatory approvals, yet the variability in garlic composition and the lack of standardized testing protocols complicate this process. Rigorous clinical trials and evidence-based validations are required to support its use and to build confidence among stakeholders.

Addressing these challenges will require multidisciplinary approaches, including advancements in extraction technologies, innovative delivery systems, genetic engineering of garlic for enhanced bioactive compound production, and collaborative efforts between researchers, industry, and regulatory agencies. Overcoming these limitations is essential for unlocking the full potential of garlic extract as a sustainable and effective solution to antimicrobial resistance and foodborne pathogen control.

9. Conclusion

Garlic extract holds significant promise as a natural antimicrobial agent capable of addressing the challenges posed by multidrug-resistant foodborne pathogens. Its dual-action mechanisms, including membrane disruption, quorum sensing inhibition, and efflux pump modulation, demonstrate its potential as both a standalone and synergistic therapeutic tool. Beyond pharmacological efficacy, its applications in food safety, particularly in pre-harvest and post-harvest interventions, underscore its versatility in mitigating contamination risks. While challenges in standardization, stability, and sensory acceptability remain, advancements in formulation technologies and delivery systems offer viable solutions for broader adoption. Garlic extract represents a sustainable, innovative approach to enhancing food safety and combating antimicrobial resistance.

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