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Review Article

BIOLOGICAL FUNCTIONS OF GARLIC (*ALLIUM SATIVUM* L.) AND ITS ACTIVE COMPOUNDS AGAINST PATHOGENS

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ABSTRACT

Garlic (*Allium sativum* L.), a globally cultivated plant with significant medicinal and culinary value, contains over 200 bioactive compounds, including allicin, organosulfur compounds, phenolic compounds, vitamins, and minerals. These components contribute to its diverse biological activities, such as antioxidant, cardio-protective, anti-cancer, anti-inflammatory, immunomodulatory, anti-diabetic, and antimicrobial properties. Allicin, the primary active compound, exhibits broad-spectrum antimicrobial activity by inhibiting essential enzymes and disrupting pathogen membranes through thiol group interactions. This study reviews antifungal, antibacterial, and antiviral effects of garlic against pathogens. Garlic extracts demonstrate efficacy against human pathogenic fungi like *Aspergillus*, *Candida*, and *Cryptococcus*, as well as plant pathogens such as *Fusarium oxysporum* and *Botrytis cinerea*. Its antibacterial activity targets both gram-positive (*Staphylococcus aureus*) and gram-negative bacteria (*Escherichia coli*), with differential susceptibility due to variations in bacterial membrane composition. Moreover, garlic shows potential in controlling postharvest diseases and seed-borne bacteria like *Ralstonia solanacearum*. The antiviral properties of garlic, particularly its ability to interact with viral phospholipids, highlight its role in combating infectious diseases. Modern extraction techniques, such as ultrasound-assisted extraction and supercritical fluid extraction, enhance the yield and stability of bioactive compounds. Overall, garlic represents a versatile natural resource with immense therapeutic and agricultural applications. Continued research into its bioactive compounds will further optimize its use in medicine and sustainable agriculture.

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INTRODUCTION

Overview of garlic (*Allium sativum* L.)

Historical significance and global cultivation

Garlic (*Allium sativum* L.) is one of the most important vegetables worldwide, with a history spanning thousands of years. It was first domesticated in Asia and later spread to various regions, becoming widely cultivated in temperate, dry, and hot climates (Jamal et al., 2023). Its historical significance can be traced back to ancient civilizations such as Egypt, where it was a staple food for workers building the pyramids. Biblical references also mention that the Hebrews consumed garlic as part of their diet. During World War I, garlic was widely used as an antiseptic to prevent gangrene, demonstrating its longstanding medicinal value (El-Saber et al., 2020). Today, garlic remains a globally significant crop, cultivated for both culinary and medicinal purposes.

Nutritional and medicinal value across cultures

Garlic is highly valued not only for its flavor but also for its well-documented health benefits. It is rich in various phytochemicals and bioactive compounds, making it a potent functional food. Garlic bulbs contain approximately 60% water, 32% carbohydrates, and 6.5% fiber, along with essential vitamins (particularly B-complex and vitamin C) and minerals such as phosphorus, potassium, selenium, and zinc. Furthermore, it is abundant in antioxidants and phenolic compounds, including flavonoids (Beato et al., 2011; Shang et al., 2019). These compounds work synergistically, contributing to antioxidant, anti-inflammatory, and immunomodulatory effects of garlic.

Garlic has been recognized for its medicinal value across various cultures, serving as a cornerstone of traditional medical systems such as Ayurveda, traditional Chinese medicine, and Mediterranean medicine (Bhandari, 2012).

Importance in traditional medicine and contemporary therapeutic uses

Garlic has long been used in traditional medicine to treat a wide range of ailments, from infections to cardiovascular diseases. Its bioactive compounds, particularly allicin, exhibit strong antimicrobial properties, including antifungal, antibacterial, and antiviral activities (Borlinghaus et al., 2014). Recent scientific studies have validated many of these traditional applications, emphasizing potential role of garlic in preventing and managing chronic diseases such as cancer, diabetes, obesity, and cardiovascular disorders (Amagase, 2006; El-Saber et al., 2020).

Antioxidant, anticancer, immunostimulatory, and cardioprotective properties of garlic have gathered significant attention in modern therapeutic research. Moreover, its broad-spectrum antimicrobial activity makes it a promising natural alternative to synthetic drugs, particularly in combating drug-resistant pathogens (Rouf et al., 2020). The dual role of garlic as both a culinary ingredient and a medicinal agent continues to inspire scientific exploration into its diverse biological functions.

Purpose of the Review

The primary objective of this review is to summarize the chemical composition, extraction methods, and biological activities of garlic, a medicinal herb of historical significance that is widely cultivated and utilized worldwide. Garlic is rich in bioactive compounds, including allicin, organosulfur compounds, phenolic compounds, and essential nutrients, all of which contribute to its diverse therapeutic properties.

Furthermore, this review aims to evaluate the antifungal, antibacterial, and antiviral activities of garlic and its active constituents against various pathogens. Although garlic is widely used as both a spice and a home remedy, its potential as a natural antimicrobial agent against human pathogens remains underexplored. This review will examine the mechanisms through which garlic exerts its antimicrobial effects, as well as its potential applications in human health and agriculture, based on recent research findings.

By assessing relevance of garlic as a natural alternative to synthetic drugs and pesticides, this review seeks to highlight its role in combating drug-resistant pathogens and emerging infectious diseases. Furthermore, it emphasizes essential contributions of garlic to health promotion and pathogen control while identifying critical research gaps that warrant further investigation.

A review of the biological functions of garlic and its active compounds against pathogens is provided below.

Chemical composition of garlic

Garlic is one of the richest sources of bioactive compounds, which are responsible for its various biological effects. It contains a range of therapeutic and protective substances, contributing to its significance in human health and agriculture.

Key bioactive compounds

Allicin: antibiotic properties and mechanism of action

Allicin (diallyl thiosulfinate) is one of the most well-known bioactive compounds in garlic. It is produced when fresh garlic tissue is disrupted, leading to the release of the enzyme alliinase, which converts alliin into allicin. Allicin exhibits broad-spectrum antimicrobial activity against gram-positive and gram-negative bacteria, viruses, and fungi (Borlinghaus et al., 2014). Its mechanism of action involves the inhibition of vital enzymes in pathogens by interacting with free thiol groups in proteins, thereby disrupting their function. Moreover, allicin is highly permeable to cell membranes, which enhances its ability to inhibit microbial growth (Miron et al., 2000; El-Saber et al., 2020). However, allicin is unstable at room temperature and loses its activity when heated to 80°C. Therefore, developing stable analogs of allicin or allicin-derived compounds (ACG) is essential for practical applications (Okada et al., 2005).

Organosulfur compounds (allyl trisulfide, allyl disulfide, etc.)

Organosulfur compounds are characteristic components of chemical profile of garlic and include derivatives such as allyl trisulfide, allyl disulfide, and diallyl sulfide. These compounds contribute to distinct aroma and taste of garlic while also exhibiting significant antimicrobial, antioxidant, and anti-inflammatory properties (Shang et al., 2019). One of the key active compounds derived from allicin, allyl sulfide, interacts with methylsulfide, viral phospholipids, and amino acids, preventing pathogens from attaching to host cells (Rouf et al., 2020).

Phenolic compounds: antioxidant properties and role in disease prevention

Garlic contains phenolic compounds, including flavonoids and hydroxylated phenols, which contribute to its strong antioxidant activity. These compounds neutralize free radicals and help prevent oxidative damage at the cellular level, reducing the risk of chronic diseases such as cancer, cardiovascular disease, and neurodegenerative conditions (Yilmaz and Toledo, 2005; Beato et al., 2011). Moreover, their anti-inflammatory and immunomodulatory properties further enhance their role in disease prevention (Hile et al., 2004; Zhou et al., 2017).

Minerals (manganese, potassium, calcium, phosphorus, selenium, etc.)

Garlic is rich in essential minerals, including manganese, potassium, calcium, phosphorus, selenium, zinc, and iron. These minerals play a crucial role in enzyme activation, bone health, immune function, and antioxidant activity (Bozin et al., 2008). Selenium, in particular, enhances antioxidant potential of garlic by supporting glutathione metabolism (Hasib et al., 2016).

Vitamins (vitamin b6, vitamin c, folic acid, niacin)

Garlic is a source of essential vitamins, including vitamin B6 (pyridoxine), vitamin C, folic acid, and niacin. Vitamin C is a powerful antioxidant that supports immune function and collagen synthesis, while vitamin B6 plays a key role in brain health and metabolism (Shang et al., 2019). Although present in trace amounts, niacin and folic acid are vital for DNA synthesis and cellular repair.

Other components (flavonoids, essential oils, and carbohydrates)

In addition to its bioactive effects, garlic contains flavonoids, essential oils, and carbohydrates. Flavonoids enhance antioxidant activity, while essential oils, rich in sulfur compounds, contribute to antimicrobial and aromatic properties of garlic. Carbohydrates in garlic, primarily in the form of fibers, aid in digestion and provide an energy source (Mardomi, 2017).

Biological significance

Contribution to antioxidant, anti-inflammatory, and immunomodulatory effects

The combination of bioactive compounds in garlic contributes to its potent antioxidant, anti-inflammatory, and immunomodulatory effects. Phenolic compounds and organosulfur derivatives help reduce free radicals and oxidative stress, while allicin regulates pro-inflammatory enzymes and cytokines (Amagase, 2006; Durazo, 2017), thereby controlling inflammatory pathways. These properties make garlic effective in preventing and managing chronic diseases such as diabetes, obesity, and cancer (Bhandari, 2012).

Role in protecting plants and humans from pathogens

Bioactive compounds in garlic play a crucial role in protecting both plants and humans from pathogens. In plants, these compounds defend against insects and diseases by inhibiting the growth of fungi, bacteria, and oomycetes (Alan et al., 2008). For humans, garlic extracts have demonstrated antimicrobial activity against a wide range of pathogens, including *Aspergillus*, *Candida*, *Staphylococcus aureus*, and *Escherichia coli* (Elshaer et al., 2019; Rauf et al., 2020). Moreover, its antiviral properties make it a promising candidate for combating emerging infectious diseases (Sahli et al., 2021). Researchers can harness these properties to develop natural alternatives to synthetic medicines and pesticides, addressing global health and agricultural challenges.

Extraction methods of bioactive compounds

The extraction of bioactive compounds from garlic is a critical step in utilizing its medicinal and antimicrobial properties. Both traditional and modern extraction methods have been employed to optimize the yield and activity of these compounds. The choice of extraction method significantly impacts the quality and efficacy of the bioactive substances obtained.

Traditional methods

Maceration using solvents

Maceration using solvents is a widely used method for extracting bioactive compounds from garlic. This process involves soaking crushed or powdered garlic in a chosen solvent for an extended period, allowing the active compounds to dissolve efficiently. Various solvents, including ethanol, methanol, petroleum ether, ethyl acetate, chloroform, and water, have been employed for this purpose (Abiola et al., 2017; Jiang et al., 2022). The choice of solvent significantly influences the yield and composition of the extracted bioactive compounds. Ethanol is often preferred due to its ability to extract higher concentrations of antioxidants compared to other solvents, making it a widely used option in many studies (Durairaj et al., 2009; Nagella et al., 2014). In contrast, water, being a universal solvent, is effective but may yield lower amounts of specific bioactive compounds, such as organosulfur derivatives. The maceration technique is particularly advantageous for heat-sensitive compounds like allicin, as it does not involve high temperatures that could lead to the degradation of labile molecules (Handa et al., 2008). This makes maceration a suitable method for preserving the bioactivity of garlic extracts while ensuring the efficient recovery of key phytochemicals.

Modern techniques

Ultrasound-assisted extraction

Ultrasound-assisted extraction (UAE) is one of the well-developed methods used in laboratories and industries, primarily due to its efficiency, speed, and environmental friendliness (Mathialagan et al., 2017). This technique utilizes ultrasound waves to disrupt plant cell walls, facilitating the release of bioactive compounds. One of the key advantages of UAE is that it does not require heating, making it particularly suitable for extracting heat-sensitive compounds such as allicin. Furthermore, water serves as the preferred solvent at 25°C for 90 min when extracting bioactive compounds from garlic slices (García-Marino et al., 2006). This method not only preserves the integrity of delicate compounds but also enhances extraction yield, making it a valuable tool in both research and industrial applications.

Supercritical fluid extraction and subcritical water extraction

With the goal of extracting bioactive compounds under high pressure and temperature conditions, supercritical fluid extraction (SFE) employs supercritical fluids, most commonly carbon dioxide. This method is highly effective due to the unique properties of supercritical CO_2, which exhibits both liquid-like solvating power and gas-like diffusivity, enabling selective and efficient extraction of target compounds. Similarly, subcritical water extraction (SWE) utilizes water at subcritical temperatures (100-374°C) and pressures, a characteristic that enhances the polarity of the solvent and, consequently, improves specificity and yield (Marino et al., 2006). Both techniques offer significant advantages, including the selective and efficient extraction of specific compounds while being eco-friendly, as they require minimal use of organic solvents, reducing environmental impact.

Magnetic solid-phase extraction (MSPE) and hydrolytic enzyme extraction

MSPE refers to a solid-borne extraction process that uses M.NPs to adsorb target analytes, simplifying the extraction process and enhancing extraction productivity. Similarly, hydrolytic enzyme extraction involves using enzymes to decompose plant tissue, leading to the efficient release of bioactive compounds. The most significant advantage of both methods lies in their ability to facilitate the extraction of distinct bioactive molecules, such as organosulfur and phenolic derivatives, making them highly valuable techniques in bioactive compound isolation.

Optimization of extraction conditions

Several factors influence gas efficiency in extracting bioactive compounds from garlic.

Temperature

Temperature plays a crucial role, as higher temperatures can enhance extraction rates but may also degrade heat-sensitive compounds. Allicin, a key bioactive component, loses its antimicrobial properties at 80°C (Okada et al., 2005). The optimal temperature varies depending on the extraction method; for instance, UAE is more effective at ambient temperatures.

Time

Extraction time also affects yield and compound stability. Although prolonged extraction can increase the amount of bioactive compounds obtained, it may also lead to the degradation of certain elements. Allicin, for example, is highly unstable and decomposes within minutes at room temperature (Borlinghaus et al., 2014). Thus, extraction protocols must balance time efficiency with compound preservation.

Concentration

Another critical factor is the concentration of garlic material in the solvent, which directly influences both yield and bioactivity. Studies have shown that the inhibitory effects of garlic extract on pathogenic bacteria such as *Fusarium solani* and *Ralstonia solanacearum* increase with higher concentrations (25%, 50%, and 100%) (Al-Janabi et al., 2007; Ali, 2017).

By optimizing these parameters, temperature, time, and concentration, scientists can enhance both the quantity and potency of bioactive compounds of garlic. This optimization makes the extracts more effective for agricultural and medicinal applications, improving their potential as natural antimicrobial agents.

Antifungal activity of garlic

Mechanism of action

Garlic contains active components responsible for its antifungal activity, notably allicin and other organosulfur derivatives. These compounds exert their antifungal effects through multiple mechanisms.

Inhibition of lipid, protein, and nucleic acid synthesis

One primary mechanism involves the inhibition of lipid, protein, and nucleic acid synthesis. This disruption affects vital metabolic pathways necessary for fungal growth and multiplication, ultimately preventing the fungi from proliferating (Amagase, 2006; Hasib et al., 2016).

Membrane damage

Another crucial antifungal action of garlic is its ability to damage fungal cell membranes. Allicin, the main active compound, interacts with free thiol groups in membrane proteins, leading to structural damage and loss of membrane integrity. This interference weakens the fungal cell membrane, making it permeable and unstable, which results in cell death (Borlinghaus et al., 2014).

Role of allicin in blocking fungal growth via thiol group interactions

Allicin also plays a significant role in blocking fungal growth through its interactions with thiol (sulfhydryl) groups in fungal enzymes and proteins. By penetrating the fungal cell membrane, allicin reacts with these thiol groups, disrupting critical enzymatic pathways required for fungal survival and pathogenicity. This enzymatic inhibition suppresses fungal development, ultimately contributing to the effective control of fungal infections (Ghannoum, 1990; Harris et al., 2001).

Effectiveness against human pathogenic fungi

Garlic has demonstrated significant fungicidal activity against a broad spectrum of human pathogenic fungi. Among these, *Aspergillus* species are well-documented for causing aspergillosis, a serious infection that primarily affects immunocompromised individuals. *Trichophyton* species are another major concern, as they are responsible for dermatophytosis, commonly manifesting as athlete's foot and ringworm. Moreover, *Candida* species contribute to various infections, including oral candidiasis, vaginal yeast infections, and systemic candidiasis, which can pose severe health risks, particularly in individuals with weakened immune systems.

Another critical fungal pathogen affected by garlic is *Cryptococcus*, which is responsible for cryptococcal meningitis, a life-threatening condition frequently observed in HIV/AIDS patients. Moreover, *Torulopsis* and *Rhodotorula* species are opportunistic pathogens capable of causing infections in immunocompromised hosts. Given its broad antifungal properties, garlic continues to be explored as a natural alternative for managing fungal infections, particularly in cases where conventional antifungal treatments may be limited or less effective (Bhandari, 2012; Kareem et al., 2020).

Applications in treating oral candidiasis and preventing recurrence of aphthous ulcers

It has been proven that garlic extracts are effective in treating oral candidiasis, a fungal infection caused by *Candida albicans*. Furthermore, garlic helps prevent the recurrence of aphthous ulcers due to its antifungal properties, with no reported adverse effects. The antifungal activity of garlic in these applications is primarily attributed to allicin, which inhibits fungal adherence to host cells and disrupts biofilm formation (Ghannoum, 1990; Minnu et al., 2021).

Effectiveness against plant pathogenic fungi

Garlic not only has potential therapeutic applications for treating PAP but also exhibits strong antifungal properties, making it an effective agent in combating plant pathogens in antifungal therapy. Its antifungal effects have been demonstrated against several plant pathogenic fungi. For instance, *Fusarium oxysporum*, a notorious pathogen, causes vascular wilts in various crops, including tomatoes and bananas, leading to severe yield losses. Similarly, *Alternaria solani*, responsible for early blight in potatoes and tomatoes, significantly impacts crop health by inducing foliar necrosis and reducing productivity. Another major fungal threat, *Rhizoctonia solani*, is a saprophytic soil-borne pathogen that causes damping-off disease and root rot, affecting a wide range of crops and hampering early plant establishment.

Furthermore, *Botrytis cinerea*, known for causing gray mold, is a postharvest pathogen that severely affects fruits and vegetables, leading to significant economic losses. *Phytophthora infestans*, the causal agent of late blight in potatoes and tomatoes, is another devastating pathogen that has historically contributed to severe crop failures, including the infamous Irish potato famine. The antifungal potential of garlic against these pathogens highlights its importance in integrated disease management strategies (Chanel et al., 2014; Elshaer et al., 2019; Al-Enezi and Jamil, 2023).

Beyond its efficacy against plant pathogens, garlic extracts have also been successfully utilized for the control of postharvest pests. Particularly, they have been employed to mitigate postharvest injuries caused by fungal species such as *Penicillium expansum*, which is responsible for blue mold in apples, and *Neophabia alba*, which leads to Bull's Eye rot in apples. Studies have shown that both aquatic and ethanol-based garlic extracts effectively inhibited mycelial development, with some cases indicating greater efficacy of aquatic extracts (Chanel et al., 2014).

In vivo and _in vitro_ studies

Reduction in disease severity and improvement in plant growth parameters

Field studies have demonstrated that garlic extracts significantly reduced the severity of diseases caused by *Macrophomina phaseolina* and *Rhizoctonia solani*. In addition to their antifungal properties, these extracts enhanced key plant growth parameters, such as shoot length, root length, and biomass, confirming their potential as biofungicides (Elshaer et al., 2019; Al-Mosawi et al., 2021; Taha et al., 2023).

Volatile compounds from garlic as effective antifungal agents

Volatile compounds derived from garlic, such as diallyl disulfide and allyl methyl sulfide, exhibited strong antifungal activity. These compounds have been found effective against postharvest pathogens like *B. cinerea* and *P. expansum*, providing a non-contact method for fungal control (Chanel et al., 2014).

Antibacterial activity of garlic

Mechanism of action

The main mechanisms involved include the disruption of bacterial membranes and the inhibition of essential enzymes. Allicin, the primary bioactive compound in garlic, is believed to interact with free thiol groups in bacterial proteins through exchange reactions with disulfides, leading to endoplasmic damage and enzyme dysfunction (Borlinghaus et al., 2014). Furthermore, certain garlic extracts exhibit a synergistic effect when combined with antibiotics such as vancomycin, enhancing their bacteriostatic activity (Harris et al., 2001).

Effectiveness against gram-positive and gram-negative bacteria

Garlic exhibited a broad spectrum of antibacterial activity against both gram-positive and gram-negative bacteria. Among the notable gram-positive pathogens affected by garlic are *Staphylococcus aureus*, *Bacillus subtilis*, and *Clostridium*, while gram-negative bacteria such as *Escherichia coli*, *Pseudomonas*, *Klebsiella*, *Salmonella*, and *Shigella* also demonstrated susceptibility to its antibacterial properties. The variation in bacterial susceptibility to garlic is primarily attributed to differences in membrane composition. The inhibitory effect of garlic extract on *E. coli* was reported to be up to ten times higher than that observed in *Lactobacillus casei* at the same concentration, which is linked to structural differences in bacterial membranes and varying levels of susceptibility to allicin (Hussein et al., 2021).

Application in agriculture

Garlic extracts have important applications in agriculture for controlling seed-related bacteria and plant diseases.

In terms of controlling seed-related bacteria, garlic extracts effectively prevent the development of pathogens and serve as an alternative seed protection product (SPP), as demonstrated in carrot seeds (Cellini et al., 1996).

Regarding the prevention of bacterial infections, aqueous garlic extracts at concentrations of 1%, 2%, 4%, and 8% completely inhibited the growth of *Ralstonia solanacearum*, the bacterial pathogen responsible for bacterial wilt in tomatoes (Al-Janabi et al., 2007).

Antiviral activity of garlic

Mechanism of action

The antiviral activity of garlic is mediated through its interaction with viral phospholipids and amino acids involved in infection. Allyl methyl sulfide, a primary active compound derived from allicin, prevents viruses from attaching to host cells by denaturing them (El-Saber et al., 2020). This mechanism disrupts the early stages of viral infection, making garlic a potential candidate for antiviral therapy.

Effectiveness against DNA and RNA viruses

Garlic-derived compounds show potential in treating both mild and severe viral infections caused by DNA and RNA viruses. However, current antiviral drugs often face limitations such as toxic side effects, drug resistance, and poor bioavailability. Natural alternatives like garlic offer a promising solution due to their broad-spectrum antiviral properties and minimal side effects (Rouf et al., 2020).

Application in human health

Garlic compounds are rapidly recognized for their role in reducing oral diseases and systemic infections:

Oral diseases

Garlic extracts have been effective in treating oral candidiasis and preventing the recurrence of aphthous ulcers without side effects (Minanu et al., 2021).

Systemic infections

The antiviral properties of garlic make it a valuable aid in managing systemic viral infections and offer a natural alternative to synthetic medicines (Sahli et al., 2021).

CONCLUSIONS

Garlic is a versatile plant with significant antimicrobial, antioxidant, and therapeutic properties. Its bioactive compounds, including allicin, organosulfur derivatives, phenolic compounds, vitamins, and minerals, contribute to various biological activities such as antioxidant, cardioprotective, anticancer, anti-inflammatory, and immune-modulating effects. Allicin, the primary active compound, disrupts bacterial and fungal membranes by interacting with thiol groups in proteins, thereby inhibiting essential enzymes and cellular processes.

Garlic has demonstrated strong antifungal activity against human pathogens such as *Aspergillus*, *Candida*, and *Cryptococcus*, as well as plant pathogens like *Fusarium oxysporum* and *Botrytis cinerea*. It also exhibits broad-spectrum antibacterial activity against both gram-positive (*Staphylococcus aureus*) and gram-negative (*Escherichia coli*, *Pseudomonas*) bacteria, although its efficacy depends on the composition of the bacterial membrane. Moreover, garlic extract effectively controls seed-borne bacteria, prevents diseases such as bacterial wilt, and manages postharvest pests like *Penicillium expansum*.

Garlic plays a role in infection control due to its antiviral potential, which is linked to its interaction with viral phospholipids. Advanced extraction methods, such as ultrasound-assisted extraction, enhance the yield and stability of its bioactive compounds, making garlic a promising candidate for environmentally sustainable applications in medicine and agriculture.

With its natural antimicrobial properties, garlic serves as a viable alternative to synthetic drugs and pesticides. Further research on its bioactive compounds can enhance its therapeutic significance and agricultural applications, contributing to global health and addressing environmental challenges.

FUTURE RESEARCH DIRECTIONS

Future research should focus on developing stable allicin analogs to overcome its instability, thereby enhancing its applicability in medicine, agriculture, and food preservation. Investigating the synergistic effects of garlic compounds with conventional treatments could improve efficacy against drug-resistant pathogens. Comprehensive studies on the mechanisms of garlic-derived compounds against emerging multidrug-resistant pathogens, along with the optimization of advanced extraction methods, are crucial for industrial applications. Expanding research on antiviral properties of garlic, conducting clinical trials for human health applications, and exploring its impact on gut microbiota could provide valuable insights. Additionally, developing garlic-based formulations for organic farming and utilizing genetic tools to enhance the production of bioactive compounds would not only improve its therapeutic and agricultural value but also contribute to environmental and economic sustainability.

AUTHORS' CONTRIBUTIONS

DSJ conceptualized the idea, collected and arranged data; STAM and AKH collaboratively analyzed information, forming the foundation for this review; DSJ, STAM and AAA provided essential guidance throughout the writing, formatting, and publication process.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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