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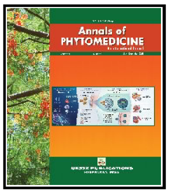

Review Article : Open Access

Garlic derived compounds in plant health management: A review of current insights and future direction

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Abstract

In the agricultural sector, most farmers rely on chemical-based inputs to manage biotic and abiotic stresses. However, growing concerns about the environmental and health impacts of synthetic agrochemicals have stimulated interest in plant-derived compounds as sustainable biostimulants. Among these, garlic (*Allium sativum* L.) has emerged as a potent natural agent due to its rich profile of bioactive constituents, including phenolics and organosulfur metabolites. These compounds enhance plant tolerance to biotic (*e.g.*, pests and diseases) and abiotic (*e.g.*, drought and salinity) stresses by regulating gene expression, activating immune responses, and modulating metabolic processes at the cellular level through their antioxidant, antifungal, and other bioactive properties, thereby improving crop growth and resilience. The use of garlic extract supports environmentally friendly agricultural practices, reduces dependence on synthetic inputs, paves the way for future research on biostimulants, and aligns with global efforts to minimize environmental impact. This review highlights the promising contributions of garlic bioactive compounds, their extraction methods, and their applications in sustainable agriculture.

1. Introduction

Biotic and abiotic stresses markedly impair crop yield and quality by disrupting physiological processes essential for plant growth, thereby compromising overall agricultural productivity. These stresses increase crop susceptibility to pests and diseases by altering key metabolic and defence mechanisms. The simultaneous occurrence of multiple biotic and abiotic stressors presents complex challenges for farmers, complicating the development and execution of effective crop management strategies (Pandey *et al.*, 2017). In current agricultural production, synthetic chemicals have been extensively used to mitigate the detrimental effects of biotic and abiotic stresses, thereby protecting plant health and sustaining productivity. However, the widespread and prolonged use of these chemicals has led to unintended negative consequences, including adverse environmental impacts and risks to human health (Khan *et al.*, 2025). As an alternative, the use of phytochemical biostimulants has gained momentum in sustainable farming practices (Kumar *et al.*, 2025). Biostimulants have emerged as promising natural tools to boost agricultural productivity by 8-30 % with minimal application per unit area (Katsenios *et al.*, 2023). Biostimulants have emerged as promising natural tools to enhance agricultural productivity by 8-30% with minimal application rates per unit area (Katsenios *et al.*, 2023). Consequently, biological amendments that help overcome soil constraints and improve nutrient use efficiency are critical for addressing current agricultural challenges. However, their widespread adoption depends on these solutions being socially acceptable, commercially viable, and environmentally sustainable (Abbott *et al.*, 2018). Over the past century, advances in the understanding of plant-derived compounds have revealed a range of biologically active substances with significant agricultural potential (Hayat *et al.*, 2022). Stress tolerance in plants facing climatic changes can be enhanced through the application of allelopathic hormesis, specifically by utilizing potentially allelopathic plant extracts as biostimulants (Di Sario *et al.*, 2025). These extracts improve photosynthetic efficiency, activate stress-responsive gene expression, and support plant adaptation to both biotic and abiotic stressors, thereby increasing productivity and protection levels (Table 1) (Kumar *et al.*, 2025).

Recent research is focusing on plant extracts and their potential biochemical compounds, which act as defensive secondary metabolites and offer an effective method for enhancing the resilience of recipient plants (Tiwari and Rana, 2015). Garlic (*Allium sativum* L.) is a prominent medicinal herb known for its potent antimicrobial and antioxidant activities in crop management (Kutasy *et al.*, 2022). It enhances plant stress tolerance by priming defence mechanisms and improving physiological functions. These combined effects enable plants to better withstand both biotic and abiotic stresses, thereby promoting improved crop growth and development (Shang *et al.*, 2019; Hayat *et al.*, 2018). The role of garlic extract in plant defence has been demonstrated through its influence on protective

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mechanisms, disruption of molecular pathways, and regulation of reactive oxygen species (ROS) (Hayat *et al*., 2018; Perelló *et al*., 2013). Garlic extract has also shown promise as a natural insecticide for managing pests in stored products, contributing to both environmental and human safety (Figure 1). Recent research consistently highlights that garlic and its bioactive compounds possess antibacterial, antifungal, anti-inflammatory, and antioxidant properties when used in agriculture through seed treatment, foliar application, and field application (Khan *et al*., 2025; Hayat *et al*., 2016). Garlic and its extracts have beneficial potential across various research areas; this review specifically focuses on their applications and impact in agriculture.

2. Importance of natural based extract

Plant extracts have emerged as prominent biostimulants in sustainable agriculture due to their rich content of bioactive phytochemicals, which help enhance resistance to biotic and abiotic stresses by activating plant defence mechanisms. These mechanisms regulate crucial physiological processes such as nutrient uptake, photosynthesis, hormone synthesis, and stress tolerance (Zhang *et al*., 2024). The phytochemical properties of these extracts also contribute to improved soil health and increased agricultural productivity (Godlewska *et al*., 2021) (Han *et al*., 2024). The effectiveness of these bioactive compounds depends on plant species and extraction methods (Table 1 and Table 4).

Table 1: Plant derived bioactive compounds and its effects

Plant source	Key compounds	Effect of their compounds	References
Garlic	Organosulfur compounds such as allicin, alliin, sulphides, S-allyl cysteine	Its act as an antioxidant, antimetropias, and growth promoter as well as biopesticide. Stimulates root development, induces anti-oxidant enzymes (SOD, peroxidase, CAT), and activates defence related genes in plants under stress condition.	Hayat *et al*., 2018
Neem	Azadirachtin, limonoids, other terpenoids	It is used as a bioprotectant by disrupting pest developmental processes and also contains compounds that promote plant growth.	Farhan *et al*., 2024
Medicinal/ aromatic plants	Phenolic compounds (flavonoids, phenolic acids), essential oils	Enhances growth attributes, yield, and stress resistance, serving as a bioprotectant.	Kisiriko *et al*., 2021
Moringa	Zeatin (cytokinin), vitamins, phenolics	Boosts seedling emergence, growth, biomass, and regulates hormonal activity.	Soares *et al*., 2021
Aloe vera	α-D glucose, lactose, myristic acid, capric acid and phenols	Promotes plant growth, nutrient uptake, and stress tolerance.	Alkuwayti *et al*., 2022
Licorice extract	Triterpene saponins, glycyrrhizin	Antioxidant defence, nutrient uptake, and photosynthetic performance, ultimately leading to higher crop productivity.	Pourghasemian *et al*., 2020

3. Biological properties of garlic extract

More than 200 natural active substances are found in garlic. Some of the most important are sulfur-based compounds, which are especially useful in agriculture, particularly when garlic is in extract form. In addition to these, garlic extract contains valuable nutrients such as vitamin C, vitamin B6, manganese, and selenium, all of which help enhance its nutritional quality (El-Saadony *et al*., 2024).

Table 2: Quantity of identified organosulfur compounds in garlic extract

Compounds	Quantity (mg/g)	References
Alliin	0.5 - 1.5	Zhu *et al.* (2016)
S-allyl cysteine	0.2 - 0.8	Sahidur *et al.* (2023)
Diallyl disulfide	0.1 - 0.3	Hirata *et al.* (2025)
Diallyl trisulfide	0.05 - 0.15	Zhu *et al.* (2016)
2-Propenyl 1-(2-propenylsulfinyl) propyl disulfide	0.3 - 0.6	Talib *et al.* (2024)
Bis-2-propenyl trisulfide	0.02 - 0.05	Dai *et al.* (2025)
S-methyl cysteine	0.1 - 0.4	Zhu *et al.* (2016)
β-glutamyl-S-allyl cysteine	0.1 - 0.2	Dai *et al.* (2025)

The strong bioactivity of garlic is largely attributed to its rich content of sulfur compounds, which play a significant role in boosting plant health, supporting crop development, and offering protective effects (Shang *et al*., 2019). Organosulfur compounds contribute to antioxidant defence by reducing lipid peroxidation and alleviating oxidative stress (Omar and Al-Wabel, 2010). Key organosulfur compounds such as allicin, alliin, S-allylcysteine (SAC), diallyl disulfide (DADS), diallyl trisulfide (DATS), diallyl sulfide (DAS), and ajoene are primarily responsible for garlic's biological activity. In addition, γ-glutamyl-cysteine (γ-GCS) derivatives form another significant group of bioactive molecules (Shang *et al*., 2019). Among these, allicin, DADS, and DATS are especially noted for their potent antimicrobial properties against antibiotic-resistant pathogens, as well as their strong antioxidant potential (Table 3). These sulfur-based compounds interact with thiol-containing metabolites such as glutathione, leading to the formation of reactive sulfur species, thiol depletion, and S-allylation-induced protein modifications. These biochemical interactions disrupt the cellular redox balance and impair normal physiological functions. As a result, garlic extract is increasingly recognized as a natural and effective alternative for antimicrobial strategies (Bhatwalkar *et al*., 2021; Nakamoto *et al*., 2020).

Garlic also contains essential amino acids such as arginine and cysteine, which play critical roles in protein synthesis, metabolic regulation, and the maintenance of vital physiological processes in plants (Cheng *et al*., 2016; Yan *et al*., 2021). Garlic extracts are rich in a wide range of secondary metabolites, including alkaloids, flavonoids, saponins, tannins, and glycosides, all of which contribute to their significant biological activity. The mineral composition of garlic per 100 g includes 83.83 mg of calcium, 4.30 mg of vitamin C, 3.14 mg of magnesium, 0.028 mg of iron, 0.007 mg of manganese, and 0.0005 mg of copper. Additional key constituents are detailed in Table 2. This comprehensive profile of minerals and phytochemicals enhances the nutritional value of garlic and underpins its multifunctional role in promoting plant health and its potential applications in sustainable agricultural practices (Dalhat *et al*., 2018).

Table 3: Mechanistic role of organosulfur compounds

Organosulfur compounds	Mode of interaction with plant mechanism	References
Allicin	Allicin reacted with fungal proteins free cysteine groups which is reducing their physiological activity finally causing cell damage and also act as antibacterial and natural insecticide.	Hayat *et al.* (2022); Nwachukwu and Asawalam (2014)
Diallyl disulfide	Influences cell division, phytohormone levels (indole-3-acetic acid, zeatin riboside, gibberellic acid), and expansion gene expression in receiver plant.	Cheng *et al.* (2016)
S-allyl-cysteine (SAC)	SAC can enhance nutrient absorption and involve growth promotion under abiotic stress condition.	Shang *et al.* (2019)
Ajoene	Ajoene exhibits potent antimicrobial effects against a range of pathogens, including bacteria and fungi. It inhibits quorum sensing, enhancing antibiotic efficacy and reducing bacterial load and tissue damage.	Shang *et al.* (2019); Bhatwalkar *et al.* (2021)
Thiosulfinate	Helping in the inhibition of oxidative damage. Decreases the formation of reactive oxygen species (ROS. It has anti-inflammatory and antioxidant properties.	Avendaño-Ortiz *et al.* (2023)

3.1 Effect of organosulfur compounds

Lipid soluable organosulfur compounds such as ajoenes, allyl sulfides, and allicin exhibit antibiofilm, antitoxin, bactericidal, and anti-quorum sensing properties against resistant and multidrug-resistant bacteria (Cheng *et al*., 2016). According to Iciek *et al*. (2009) organosulfur compounds particularly those found in garlic modify redox-sensitive proteins and influence cellular signaling pathways, both of which are vital biological processes (Pârvu *et al*., 2019). Essential oil of garlic extracte specially diallyl disulfide and diallyl trisulfide, disrupt the nervous systems of insects. This disruption may result in acute contact toxicity, fumigant effects, repellent behavior, and, in some cases, death. In addition, garlic phytochemicals exhibit antifeedant properties and inhibit insect growth and development, thereby reducing pest survival and reproduction rates (Mobki *et al*., 2014) (Figure1). Garlic extract induces symptoms of intoxication in both adult insects and larvae, including regurgitation, reduced feeding activity, and progressive paralysis. It can also cause localized tissue damage in critical areas such as the mouthparts, pronotum, legs, abdomen, and anus. Furthermore, these compounds significantly reduce respiration rates across all life stages, with diallyl disulfide showing particularly strong repellent effects (Plata-Rueda *et al*., 2017).

Allicin reduces bacterial virulence by inhibiting exotoxin A, elastase activity, biofilm formation, and by disrupting sulfhydryl-dependent enzymes (Bhatwalkar *et al*., 2021). Notably, allicin is not present in raw garlic but is rapidly formed when garlic cloves are crushed or cut, triggering the enzymatic action of C-S lyase (allinase) on alliin. After mechanical disruption, allicin constitutes approximately 70% of the total thiosulfinates in garlic cloves (Chhouk *et al*., 2017). Allicin also interferes with lipid biosynthesis and RNA synthesis, and reacts with thiol groups, which may alter intracellular functions and provide antioxidant protection (Rahman, 2007). Garlic contains essential amino acids, with proline (0.43 to 3.91 mg/g) and arginine (0.24 to 3.45 mg/g) being the most prominent (Jiménez-Amezcua *et al*., 2023. In addition to its sulfur compounds, garlic also possesses a variety of phenolic acids, including gentisic acid (60 ± 5 μg/ml), chlorogenic acid (65 ± 5 μg/ml), 4-hydroxybenzoic acid (25 ± 3 μg/ml), and *p*-coumaric acid (44 ± 4 μg/ml. The presence of these phenolic compounds further enhances garlic antioxidant capacity and overall biological effectiveness (Igu *et al*., 2021).

4. Techniques for extracting active compounds from garlic

The method used to extract bioactivecompounds from garlicis crucial in determining its stability and yield. While traditional methods are still in use because of their simplicity, modern methods have much to offer in terms of efficiency and sustainability. Mainly the type of solvent greatly influencing that extract recovery like methanol, ethanol, chloroform, petroleum ether *etc*. (Bar *et al.,* 2022). The several methods of extraction that can be employed to isolating the bioactive substances from garlic were listed in (Table 4).

Table 4: Extraction techniques for isolating bioactive compounds

Methods	Principles	Outcome	Solvents and using source	References
Soxhlet extraction	It involves continuous cycling of the solvent through the solid sample to enhance extraction efficiency.	Effectively isolates desired compounds, ensuring purer extracts.	Methanol, ethanol, acetone	Bar *et al.* (2022); Chhouk *et al.* (2017); Kumari *et al.* (2024)
Solvent-free microwave extraction (SFME)	SFME utilizes microwave radiation to directly interact with polar molecules in plant materials, causing dipole rotation and ionic displacement.	It is highly efficient, achieving a 91.7% yield of bioactive compounds, preventing compound degradation.	Microwave	Yingngam *et al.* (2022); Boukhatem *et al.* (2022)
Solid-liquid extraction (SLE)	Solid sample is mixed with a solvent that dissolves the target compounds, allowing them to be extracted from the solid matrix.	Simultaneous extraction of various bioactive compounds and improves extraction efficiency, reducing extraction time.	Isopropanol and ethyl acetate	Jiménez-Amezcua *et al.* (2023); Maia *et al.* (2017)
Ultrasound-assisted extraction	High-frequency ultrasound produces pressure cycles to generate and collapse bubbles, which produce extreme conditions that rupture plant cell walls, release bioactive compounds, and facilitate mass transfer, increasing the efficiency of extraction.	Cavitation improves the mixing of the solvent with the plant material enhances the diffusion of the solvent into the plant matrix heat-sensitive compounds are preserved.	Ultrasound	Loghmanifar *et al.* (2022); Shekhar *et al.* (2023)
Steam distillation	The distillation device is filled with steam, which evaporates the essential oils as it moves through the plant material. The oil is subsequently separated from the non-volatile components by condensing the vapor back into liquid form.	Optimized enzymatic conditions break down cell walls, increasing essential oil yield while preserving terpenoids, enhancing potency.	Steam	Zhang *et al.* (2025)
Hot water method	Boiling or steeping plant materials in water, heating enhances their solubility and diffusion, polysaccharides dissolve in hot water.	Minimizes protein denaturation while effectively extracting polysaccharides. Heating increases the kinetic energy of molecules.	Water	Cheng and Huang (2018)
Pulsed electric field extraction	PEFE employs electric pulses to generate transmembrane voltage, forming pores in cell membranes, which increases the permeability and enables the extraction of bioactive compounds.	PEF minimizes thermal degradation and preserves the functional properties of extracted compounds, resulting in higher quality end products.	Electric pulses	Tang *et al.* (2024)
Carbon dioxide expanded ethanol	CO, is added to ethanol, it reduces the viscosity of the solvent. the mixture can allow it to penetrate the plant material better. temperature and CO_2 flow rate mainly influencing factor.	Presence of CO, in ethanol changes the polarity of the solvent mixture. Lower polarity can increase the solubility of certain bioactive compounds.	CO_2 expanded ethanol	Chhouk *et al.* (2017)
Supercritical water Extraction	SWE employs water at temperatures above its boiling point but below its critical point, allowing it to act as a solvent with modified properties.	Extract both polar and non-polar compounds effectively	Water	Shinde and Mahadik (2019)

5. Biochemical compounds as antimicrobial and antioxidant agents

Garlic exhibits broad-spectrum antimicrobial activity due to its potent fungicidal, bactericidal, and antiviral properties, as reported by various researchers (Hayat *et al.*, 2022). Notably, compounds such as allicin and ajoene possess significant antibacterial, antifungal, and antiviral effects, making them promising alternative therapeutic agents in the fight against infectious diseases (Bhatwalkar *et al.*, 2021) (Table 3). Given the growing global issue of antibiotic resistance, the antibacterial properties of garlic present significant opportunities for the development of novel antibiotics (Tang *et al.*, 2024).

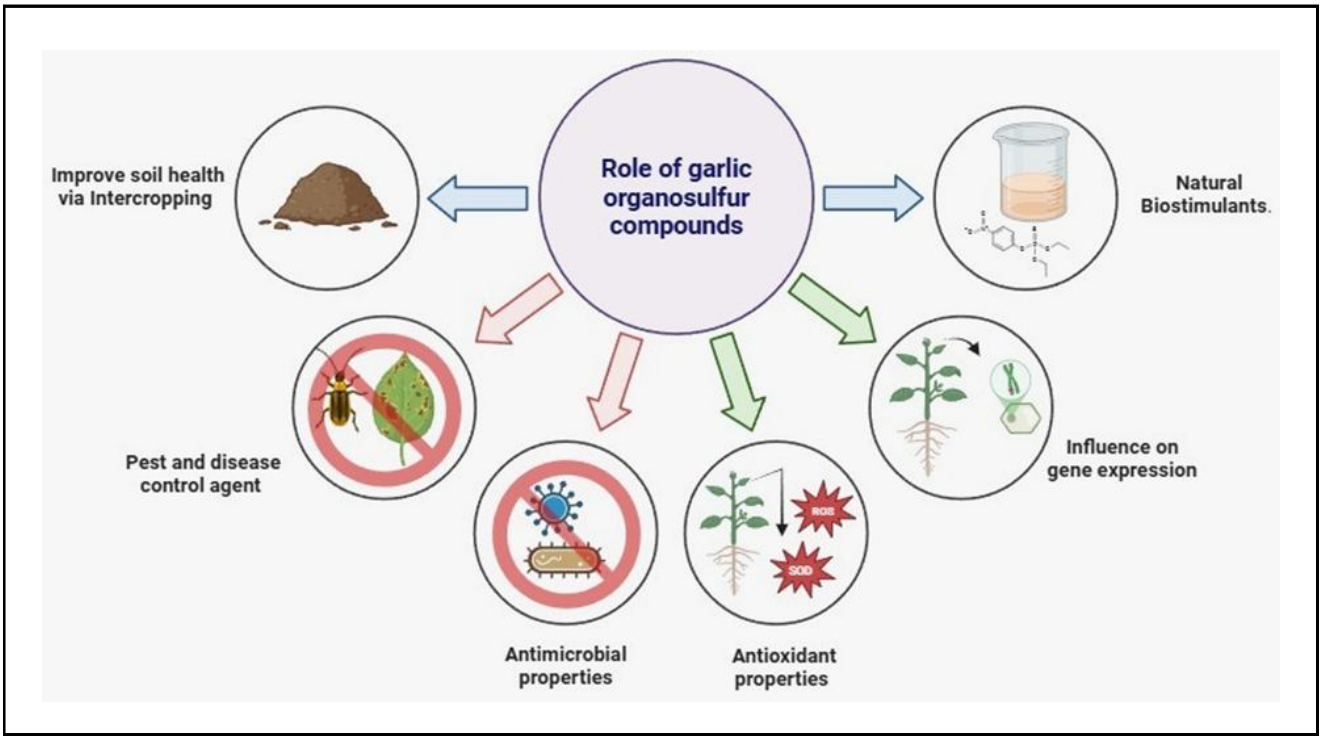

Figure 1: Potential of garlic biochemical properties.

5.1 Antibacterial properties

Garlic antibacterial compounds inhibit biofilm formation and enhance bacterial sensitivity to tobramycin, and reduce pathogenicity by downregulating virulence genes and disrupting quorum sensing. Garlic extracts are capable of eradicating pre-formed biofilms as well as preventing their development, with ajoene significantly enhancing the activity of antibiotics (Bhatwalkar *et al*., 2021). Given the rise in antibiotic resistance, the use of garlic represents a promising avenue for the development of novel antibiotics. The disruption of bacterial cell membranes by garlic occurs through the formation of disulfide linkages with the sulfhydryl groups of enzymes (Cheng *et al*., 2016). The antibacterial activity of garlic extracts has been demonstrated against *Staphylococcus aureus, Escherichia coli,* and *Candida albicans* using the agar well diffusion technique, showing effective inhibition of these microorganisms (Akullo *et al*., 2022).

5.2 Antifungal properties

Allicin and DADS act as potent antifungal agents by lysing fungal cell membranes due to increased permeability and by participating in thiol-disulfide exchange reactions, which cause cell damage and death. Their ability to penetrate phospholipid membranes enhances their efficacy, while their binding to free cysteine residues in fungal cells impairs essential cellular functions. Various studies have demonstrated that garlic extract and its volatile oils efficiently inhibit fungal pathogens, establishing them as promising natural antifungal agents (Borlinghaus *et al*., 2014; Cheng *et al*., 2016). Allicin exhibits antifungal activity even at low concentrations, resulting in notable morphological alterations in hyphae, such as roughened surfaces, cytoplasmic disintegration, and disruption of the microbial membrane (Aala *et al*., 2014). This compound directly interacts with free cysteine residues in fungal cells, disrupting their physiological processes and inhibiting fungal growth. Its fungicidal action is also attributed to the breakdown of fungal cytoplasmic constituents (Hayat *et al*., 2016).

5.2.1 Allicin as predominant antifungal agent in agriculture

Garlic extract, when used as a seed treatment, has shown beneficial effects on wheat seeds affected by two fungal pathogens, *Bipolaris -sorokiniana* (spot blotch) and *Drechslera tritici-repentis* (tan spot). It improves germination and seedling vigor by promoting the development of radicles and plumules while effectively combating seed-borne fungi (Perelló *et al*., 2013). Furthermore, garlic extract effectively inhibits *Fulvia fulva*, the fungus responsible for leaf mold in tomatoes, in both *in vitro* and pot experiments. The extract completely inhibits mycelial growth at 80 mg/ml and achieves 96.08% inhibition of spore germination at 40 mg/ml. Importantly, it provides both therapeutic and preventive effects on tomato leaves and seedlings without causing any harmful impact on plant growth. In pot trials, garlic extract demonstrated preventative effects when applied through spraying or topical application, with reported inhibition rates of 82.19%, 79.37%, 85.32%, and 83.49% at concentrations of 160 mg/ml and 80 mg/ml, respectively (Ting-Ting *et al*., 2011). Moreover, a concentration of 20 g/100 ml water garlic extract completely inhibited the growth of *Rhizoctonia solani*, *Sclerotium rolfsii*, and *Botrytis cinerea*. These results highlight garlic extract as an effective option for biological control, given its broad-spectrum activity against a range of harmful fungi (Tedeschi *et al*., 2011).

5.3 Antioxidant properties

Plants have enzymatic (*e.g.*, superoxide dismutase, catalase, ascorbate peroxidase) and non-enzymatic antioxidants to protect against ROS effects. Environmental stresses predominantly enhance the production of ROS, resulting in gene expression adjustments and stress tolerance mechanisms (Ahmad *et al.,* 2008). Plant derived biostimulants are promote the formation of antioxidant properties such as carotenoids, ascorbic acid, and phenolics, which enhance antioxidant activity. The garlic compounds scavenge ROS thereby minimizing oxidative stress and protecting plant cells from stress condition (Kumar *et al.,* 2025). Onions and garlic consist phenols and sulfur compounds are enhancing their ability to scavenge harmful reactive species and maintain cellular integrity, stabilization of free radical *via* electron donation (Bar *et al.,* 2022; Younas *et al.,* 2025).

Strong antioxidant activity was demonstrated by inhibitory concentration (IC_{50}) values ranging from 12.35 to 25.92 µg/ml, with lower values indicating greater potency. In a hydroponic co-culture system, garlic extracts significantly reduced malondialdehyde (MDA) levels at low concentrations by promoting pepper plant growth, enhancing chlorophyll content, and increasing antioxidant enzyme activities. The allelochemicals present in garlic stimulated physiological responses in pepper plants, resulting in improved root development, nutrient uptake, and total biomass accumulation. (Ding *et al.,* 2016). More over Organosulfur compound cops the cucumber seedlings under stress SOD and CAT to detoxify ROS, preventing oxidative stress. Garlic extract at moderate concentrations 150 µg ml^{-1} water stimulates these enzymes, supporting growth and decreasing stress markers such as MDA. Here balanced ROS regulation is necessary to develop stress signalling and cell growth (Hayat *et al.,* 2018).

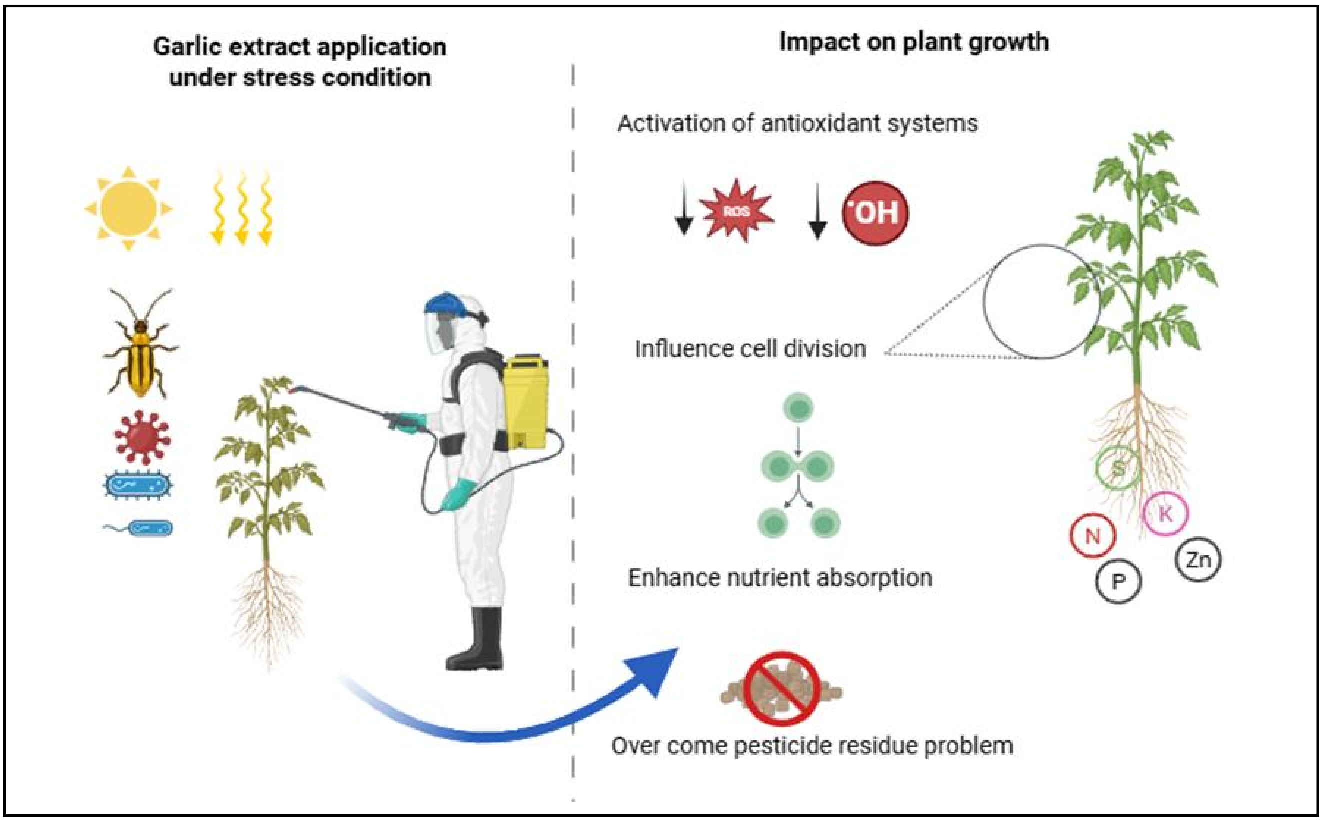

Figure 2: Field application and its benefits.

6. Natural biostimulant on plant physiological development

Eggplant and pepper seedlings treated with garlic extracts and acetyl salicylic acid *via* foliar and fertigation method exhibited growth, increased plant heights, and changes in plant metabolites. The extract of garlic stimulated antioxidant enzymes and root activity, enabling plants to fight off infections via activated antioxidant mechanisms and protective metabolites (Hayat *et al.,* 2018). Garlic biochemical compounds primarily regulate plant hormones, such as auxins, gibberellins, and cytokinins, thereby promoting cell division, growth, and photosynthesis when applied as a 5% foliar spray under sandy soil conditions. This treatment stimulates root development, facilitates improved water and nutrient uptake, and enhances nitrogen metabolism, resulting in increased protein synthesis. Specifically, the flavonoids and phenolic acids present in garlic extracts can alleviate oxidative stress (Mohamed *et al.,* 2020) (Figure 2). Main biochemical compounds are increased the levels of auxin (IAA), gibberellic acid (GA3), cytokinin (ZR), and abscisic acid (ABA), which had a substantial influence on phytohormonal control during tomato seed germination (Hayat *et al.,* 2020). Foliar application of garlic extract at concentrations of 400 and 600 ppm on soybean plants resulted in increased levels of non-enzymatic antioxidants, such as ascorbic acid, α-tocopherol, and glutathione, under drought stress conditions. This treatment also enhanced the activities of enzymatic antioxidants, including SOD, glutathione reductase, and ascorbate peroxidase, thereby enabling the plants to better cope with oxidative stress. Overall, garlic extract application effectively strengthens the antioxidant defense system and mitigates the detrimental effects of drought stress in soybean plants (Mohamed and Akladious, 2014). DADS treatment has a dose dependent effect had on cucumber roots by stimulating growth at low concentrations. The hormone levels, *viz.,* IAA, ZR, ABA, GA3 were trigger and influence growth related genetic pathways in root development dimensions (Ren *et al.,* 2018).

Treating *Vicia faba* seeds with garlic extracts reduces the negative impacts of drought stress, enhancing plant growth and tolerance. The extracts lengthen the roots, heighten the shoots, and retain more water in the plants while reducing indicators of stress damage and maintaining normal functions. They also maintain osmotic strength in balance, which results in healthier and stronger plants during periods of dryness (Kasim *et al.,* 2017). Seed priming with aqueous garlic extract alters antioxidant enzyme activities and modulates reactive oxygen species (ROS), which are crucial for early plant development.

It is a potent biostimulant for enhancing eggplant seed germination and seedling growth. Garlic extract enhances physiological and antioxidant activities leading to the growth of healthy seedlings (Ali *et al.,* 2019). The foliar application of garlic extract at $150\ \mu g\ ml^{-1}$ on cucumber plants regulates prooxidative and antioxidative reactions in cucumber seedlings, which is beneficial for enhanced growth. In contrast, an overdose of AGE ($300\ \mu g\ mml^{-1}$) causes lipid peroxidation and imposes stress on the cucumber seedlings. However, more appropriate and targeted approaches are needed to understand the actual biostimulatory effects of AGE as an induced defense chemical, and to identify its molecular pattern within plant biology (Hayat *et al*., 2016).

7. Molecular insights: Garlic extract influence on gene expression

Organosulfur compounds affect antioxidant enzymes and stress-response genes that regulate hormone signals. While high doses ($300\ \mu g/\mu l^{-1}$) cause oxidative stress and inhibit growth-related genes, low dosage ($100\text{-}200\ \mu g/\mu 1^{-1}$) promote positive gene expression (Ali *et al.,* 2019). Particularly DADS, an allelochemical increases root growth by upregulating the genes for FZY and PIN, raising IAA and ZR levels, and modifying phytohormones. Its potential for sustainable agriculture is highlighted by its effects on expansin gene expression, hormone signalling, and cell division (Cheng *et al.,* 2016). The expression of expansin genes like EXPB2, EXP1, and EXPB3 at higher levels during DADS treatment suggests that DADS promotes root growth and cell wall loosening in tomato plants by elevating the expression of these genes at different developmental stages. Expansin genes are a class of genes whose proteins facilitate plant cell wall relaxation, a requirement for cell expansion and growth. Through the changes in the bond between cellulose microfibrils and polysaccharides, the proteins facilitate cell walls to elongate, allowing cells to expand during growth procedures (Hayat *et al.,* 2016).

Garlic extract encapsulated in liposomes has been shown to enhance the expression of ABA pathway and pathogenesis related genes in wheat. This includes the upregulation of transcription factor families such as AP2, C2H2, HD-ZIP, and MYB, which are crucial for plant defence responses (Kutasy *et al*., 2022). DADS controls mitosis genes in cucumber roots at low concentration (200 µl/l), the genes were overexpressed after 24 h, promoting elongation of roots, and CYCA and CDKB were still active at 48 h. At high concentration (1200 µl/l), the genes were repressed greatly within 24 h, suppressing growth of roots, with slight recovery at 48 h but with overall suppression (Ren *et al.,* 2018). DADS compounds also change the regulation of cell cycle, namely arresting cell cycle at the G2/M phase, and initiating detoxification mechanisms (Cheng *et al.,* 2016). Genes related to plant development, metabolism, and stress response are regulated by garlic extract-chitosan nanoparticles. In order to promote development, the therapy elevated differentially expressed genes, particularly those involved in the phenylpropanoid and alpha-linolenic acid pathways and also ABA signaling and glutathione metabolism, which increased stress tolerance and germination (Mondéjar-López *et al.,* 2024).

8. Garlic extract as a biopesticide

The primary mechanism by which garlic extract acts against pests is through its ability to alter the behavior of both adult and larval insects, resulting in high mortality rates. In addition to its direct contact and fumigant toxicity, garlic extract also functions as a repellent and antifeedant (Mobki *et al*., 2014). Allicin and diallyl polysulfides, the two main compounds in garlic, generate reactive oxygen species (ROS) and disrupt the redox balance in insects. These compounds are less harmful to non-target organisms while effectively targeting key agricultural pests (Anwar *et al*., 2016). Foliar application of garlic extract to the radish variety *Raphanus sativus* var. lobo led to notable biochemical alterations, including an increase in polyphenol content and a marked elevation in disaccharide levels. These increases enhanced the plant's energy storage and contributed to better control of targeted pests (Golubkina *et al*., 2022).

In red palm weevil larvae, a mixture of onion and garlic significantly reduces the expression of detoxification genes, including cytochrome $P4_{50}$, glutathione S-transferase (GST), and esterase. Finally, its leads to lower fertility and higher mortality rates. The mixture demonstrated strong insecticidal efficacy at doses ranging from 10 to 50 mg/ml. Notably, sterility reached 91.89% at 50 mg/mland fecundity dropped sharply to 51.26% at 30 mg/ml, indicating a substantial negative impact on female reproductive capacity (Al-Shuraym *et al*., 2020). Specifically, methyl allyl disulfide and diallyl trisulfide have been shown to control *Sitophilus zeamais* and *Tribolium castaneum* by inhibiting egg hatching, suppressing pest growth, and exhibiting high contact and fumigant toxicity (Huang *et al*., 2022). *Tenebrio molitor* is also highly susceptible to diallyl sulfide and diallyl disulfide, with rapid mortality observed in larvae, pupae, and adults, often accompanied by necrosis and paralysis at all life stages (Plata-Rueda *et al*., 2017). Significant insecticidal and repellent effectiveness has also been demonstrated against stored grain pests, including *Sitophilus zeamais* and *Tribolium castaneum* (Nwachukwu and Asawalam, 2014). High doses of garlic extract caused rapid worm deaths, and soil treatments effectively reduce nematode populations fatherly encouraging grapevine root development. Particularly,nematicides based on garlic can be a useful and sustainable method of managing grapevine nematodes (*Xiphinema index*) in vineyards, especially in integrated and organic farming systems (D'Addabbo *et al.,* 2023).

9. Impact on agricultural practices

Decomposed garlic stalks can promote the soil health by activate the soil chemical properties and key enzymes activity (Hayat *et al.,* 2022). Intercropping garlic with cucumber crucially enriches cucumber nutritional quality through the promotion of biomass, nutrient harvest, and soil nutrient content (Xiao *et al.,* 2013) (Figure 1). Garlic extracts effectively reduces the hop stunt viroid in micro propagated grape vine plantlets at the 74.45% concentration (Kang and Jeong 2025). In cabbage plants intercropped with onions and garlic, infection by *Bemisi atabaci* and *Brevicoryne brassicae* was greatly reduced due to the repellent effect of the allicin compound, resulting in a lower occurrence of these pests (Debra and Misheck, 2014). Garlic has been intercropped with eggplant, resulting in improved growth and yields of the companion eggplant crop. These benefits are attributed to garlic intercropping, which lowers oxidative stress, enhances soil health, and increases nutrient availability. This is evidenced by decreased stress (as indicated by lower MDA levels and higher enzyme activity) and improved growth parameters such as plant height, stem diameter, and leaf area, ultimately indicating enhanced productivity and plant health (Wang *et al.* 2015). Garlic clove extract was applied via foliar spray at three concentrations (1:40, 1:20, and 1:10) two times at 30 and 45 days after sowing (DAS) in a field trial on snap bean (*Phaseolus vulgaris* L.). The treatment significantly enhanced growth characteristics, biochemical attributes, and yield, likely due to the action of phytohormones. Among the tested concentrations, the 1:10 dilution showed the greatest improvement in plant biomass, number of pods, and overall yield (Elzaawely *et al*., 2018). Garlic extracts considerably promotes the growth of quinoa plants through enhanced plant height, branch number, and fresh and dry weight. It also enhanced the contents of chlorophyll a, chlorophyll b, and carotenoids. The greatest improvements in growth were achieved with a concentration of 15% garlic clove extract (El-Rokiek *et al.,* 2019).

The Faba bean - Nubaria 1 cultivar productivity under sandy soil conditions has greatly influenced by garlic extracts application via plant growth, biomass, pod number, and seed yield. Mainly which is helps to reduce biochemical stress, increased stress tolerance (Mohamed *et al.,* 2020). Lettuce cultivars were tested for crop growth and seed yield with regard to the impacts of individual as well as combined foliar sprays of sodium selenate and garlic bulb extract. Mainly antioxidant activity was enhanced and lipid peroxidation was lowered by garlic extract, as it has enhanced seed germination and plant emergence. With high polyphenol and quercetin, its presence also influenced plant health as well as growth (Golubkina *et al.,* 2024). 100 $\mu g.ml^{-1}$ water garlic extract seed priming for 6 hours was highly significant in increasing catalase and SOD activity over control treatments, but extended priming (12 h) at 200 $\mu g.ml^{-1}$ lowered CAT activity. High levels of auxin (IAA) were detected in seedlings exposed to garlic biochemicals, indicating a close association with auxin biosynthesis (Hayat *et al.,* 2020).

Foliar applications of garlic extract at 10 g/l have been shown to improve the growth of pea plants by increasing yield components such as pod weight and the number of seeds, as well as enhancing vegetative growth (El-Rokiek *et al*., 2019). Similarly, in faba beans, garlic extract improves yield characteristics, including the number of pods, seed yield, and seed weight. Furthermore, garlic compounds increase biochemical parameters such as carbohydrates, amino acids, and chlorophyll, thereby enhancing plant resistance to stress (Mohamed *et al*., 2020).

10. Conclusion

Garlic extract is emerging as a powerful natural biostimulant that promotes sustainable agriculture by offering an effective alternative to synthetic agrochemicals. Rich in organosulfur compounds, secondary metabolites, and phenolic compounds, garlic extract addresses multiple agricultural challenges, including enhancing plant growth, improving stress tolerance, and protecting crops from harmful pathogens. By combining pest management and plant stimulation within a single natural product, it provides a comprehensive and eco-friendly solution for modern farming. Its insecticidal properties, growth-promoting effects, and ability to modulate gene expression strengthen plants' natural defence mechanisms, enabling crops to better withstand adverse environmental conditions. The bioactive compounds in garlic extract not only enhance crop resilience but also contribute to improved soil health and long-term agricultural sustainability. Moreover, integrating garlic extract into farming practices helps mitigate the negative impacts of synthetic chemicals, supporting ecological balance and fostering resilient, productive agroecosystems.

11. Future aspect

Garlic extracts possess considerable potential to drive innovation in agricultural practices, offering effective solutions to overcome critical challenges. Garlic extracts are expected to play a significant role in driving innovation in agricultural practices, providing effective solutions to address critical challenges. Moving forward, this potential will be realized through the development of advanced formulations for seed treatment, soil applications, and plant growth enhancement. In the agricultural sector, particularly in stress mitigation, the potential of garlic will become a key focus. Future studies will investigate how garlic's bioactive compounds interact with plant metabolism, physiological processes and gene expression, with the aim of enhancing and demonstrating their beneficial effects. These advancements will be developed into commercially viable and efficient solutions to empower farmers with improved knowledge and practical applications *via* natural based formulation. These scientific advancements will be developed into commercially viable and efficient natural-based formulations, empowering farmers with enhanced knowledge and practical tools to foster sustainable and productive farming systems.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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