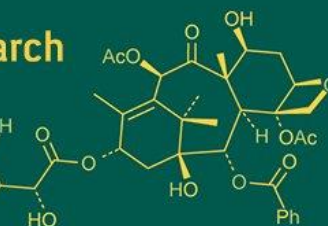
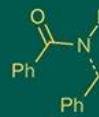


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(6): 185-191
www.biochemjournal.com
Received: 02-03-2026
Accepted: 06-04-2026

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Role of micronutrients and growth regulators in managing *Alternaria* blight of tomato: A review

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i6Sc.8581>

Abstract

Tomato (*Solanum lycopersicum* L.) is one of the most economically important crops worldwide, and *Alternaria* blight is one of the most devastating diseases of tomato, being primarily caused by *Alternaria solani* and *Alternaria alternata*. Under optimum environmental conditions the losses of the disease can reach 50-80%. Chemical fungicides are the major tools used in the management of this disease; however, fungicide resistance, environmental pollution, and health effects are becoming an increasing problem. Researchers have been looking for alternatives to pesticides in recent years that are environmentally friendly and have been identified as disease management materials such as micronutrients and plant growth regulators (PGRs). Zinc (Zn), Boron (B) and Copper (Cu) are some micronutrients which are important to boost plant immunity, plant cell wall structure and activate defense enzymes. Growth regulators like salicylic acid (SA), indole-3-acetic acid (IAA) and naphthalene acetic acid (NAA) have been demonstrated to trigger systemic resistance and boost plant resistance to infection. The present review summarizes the available information regarding the fungal role of these micronutrients and growth regulators in lowering the severity of *Alternaria* blight in tomato and their mechanisms of action, the effective concentrations and integration of these micronutrients and growth regulators in the disease management strategy.

Keywords: *Alternaria solani*, early blight, zinc, boron, copper, salicylic acid, IAA, and NAA

1. Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated vegetable crops that are grown in the world and economically valuable. It is cultivated in over 170 countries and is a source of vitamins, minerals and antioxidants for human health (FAO, 2023) [12]. But tomato production is hindered greatly by a variety of fungal, bacterial and viral diseases. *Alternaria* blight is one of the most common and damaging diseases of the foliar parts of the crop and occurs in all growth stages of the crop (Chaerani & Voorrips, 2006) [8].

The primary causes of *Alternaria* blight of tomato are *Alternaria solani* (Ellis & Martin) Jones & Grout, which causes early blight, and *Alternaria alternata*. Fruit rot and leaf spot are caused by Kissel in some areas. The initial symptom is small, dark, brown, circular-to-oval spots with concentric rings (target boards) on older leaves. In some instances the spots coalesce, leaves change color to yellow, and the plant experiences premature leaf drop. Infection spreads rapidly to stems and fruits under warm and humid conditions, resulting in collar rot, stem canker, and fruit decays, respectively (Foolad *et al.*, 2008; Kumar *et al.*, 2020) [15, 20].

It has been reported that *Alternaria* blight may cause a loss of 50-80% yield in susceptible varieties in epidemic years (Chaerani & Voorrips, 2006) [8]. Chemical fungicides are the most important management tools in the toolbox of the farmer for controlling this disease; including mancozeb, chlorothalonil, iprodione and azoxystrobin. The extensive use of chemicals fungicides has contributed to the development of resistant pathogens populations, environmental pollution, and concerns regarding food safety (Matheron & Porchas, 2010; Singh *et al.*, 2021) [24, 35].

In response to these challenges, researchers have begun to search for alternative methods of disease management that are safer and more environmentally friendly. The use of micronutrients (mainly zinc (Zn), boron (B) and copper (Cu)) and plant growth regulators

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(PGRs) like salicylic acid (SA), indole-3-acetic acid (IAA) and naphthalene acetic acid (NAA) are promising. These compounds stimulate the growth of the plants and induce the defense mechanism of the plants to make them resistant against the fungal pathogen (Marschner, 2012; Raza *et al.*, 2021) [23, 31].

The purpose of this review paper is to give an outline of the role of these micronutrients and growth regulators in the control of *Alternaria* blight of tomato in a comprehensive and updated manner. The ways in which they operate, experimental dosages, and how they fit into management are explained.

2. *Alternaria* Blight of Tomato: An Overview

2.1 The Pathogen

Alternaria solani is a deuteromycete fungus, class Hyphomycetes. The fungus forms dark brown, muriform, multicellular conidia that are divided both across and down. Conidia are usually club-shaped with a long beak, and are spread by wind and rain. The fungus remains viable in infected plant debris and soil for long periods of time and may infect the host by penetrating the epidermal cells, or via the stomata (Thomma, 2003) [37]. Apart from *A. solani*, leaf spot and fruit rot symptoms have been linked to *A. alternata* in recent years, especially under stressful conditions of the plants (Woudenberg *et al.*, 2015) [41].

2.2 Disease Symptoms

Symptoms of *Alternaria* blight are small, dark brown, water-soaked spots on lower, older leaves. These spots grow and form concentric rings, like a target board, as the disease advances. A yellow border is seen around the lesion. Infected leaves will later become yellow (chlorosis) and die and drop causing defoliation. The fungus is responsible for a dark, sunken, elongated disease called collar rot which occurs on stems, particularly in the soil near the shoot apex in young seedlings. Sunken, leathery, dark brown lesions with black mold growth are seen around the stem end on fruits (Foolad *et al.*, 2008; Kumar *et al.*, 2020) [15, 20].

2.3 Disease cycle and epidemiology

Primary inoculum is from infected plant debris or soil and forms the starting point to the disease cycle of *A. solani*. Conidia are produced when wet and warm and deposited on susceptible leaf surfaces. The optimum temperature range for infection is 25-30°C and relative humidity greater than 90% while leaf wetness is maintained for more than 2 hours (Chaerani & Voorrips, 2006) [8]. Secondary spread is through rain splash, wind, farm tools, and infected transplants and is rapid. Garg *et al.* (2022) [16] reported that the disease spreads from older leaves to the younger leaves in a few weeks' time and can cause heavy defoliation in favorable weather Garg *et al.*, (2022) [16].

2.4. Biological control of *Alternaria* blight using microorganisms for managing *Alternaria* blight

The micronutrients are mineral elements that are present in minute amounts in plants and are necessary for their growth and metabolism. Although they are required in very small amounts, their deficiency can have significant adverse effects on plant growth and health and also increase the susceptibility of plants to disease (Marschner, 2012) [23]. The enhanced resistance to pathogens via strengthening cell walls, activation of defense enzymes, and improvement of

antioxidant system after foliar application of micronutrients has been demonstrated (Fageria *et al.*, 2009; Singh & Singh, 2022) [11, 34]. Roles of zinc, boron and copper in controlling *Alternaria* blight of tomato are discussed in subsequent sections.

3.1 Zinc (Zn)

3.1.1 Role of Zinc in Plant Defense

One of the most crucial micronutrients for plant defence is zinc. It serves as a co-factor in the activity of over 300 enzymes that are required for DNA repair, protein synthesis and antioxidant activity (Broadley *et al.*, 2007) [5]. Zinc is involved in the synthesis of phytoncides, compounds which naturally fight against fungi. It is also involved in maintaining the structural integrity of cell walls and membranes, and it makes it more difficult for fungi that attack plants to get through the walls and membranes (Fones & Preston, 2013) [14].

Plants have been reported to be more prone to foliar disease such as *Alternaria* blight when zinc is deficient. Under adequate supply of zinc, defense related enzymes like superoxide dismutase (SOD), peroxidase (POD) and polyphenol oxidase (PPO) are activated which play a vital role in the oxidative defence system of the plant (Cakmak, 2000; Yadav *et al.*, 2020) [6, 42].

3.1.2 Experimental Evidence in Tomato

The effectiveness of zinc on decreasing *Alternaria* blight severity in tomato have been reported by several studies. Kumar and Singh (2020) [21] found that foliar application of zinc sulphate (ZnSO₄) at 0.5% concentration was found to be most effective to control the disease and reduced the disease severity by 42-55%. The activities of defense enzymes (SOD, POD and PPO) in leaf tissues was increased in the treated plants. The authors further reported that the zinc treatment resulted in a delayed onset of the first disease symptoms of 7-10 days.

In the study conducted by Raza *et al.* (2021) [31] different foliar treatment were evaluated for the management of *Alternaria* blight in tomato. The application of ZnSO₄ at (0.3%) significantly reduced *Alternaria* blight percent disease index (PDI) from 68.5% in the control to 31.2%. The chlorophyll content, leaf area index and yield of plants treated with zinc was found to be quite high. Similarly Ahmed *et al.*, (2022) [1] reported that the combined application of zinc and boron applied together yielded more synergistic effect resulting in a significant reduction in disease incidence than when applied individually.

Garg *et al.* (2022) [16] demonstrated the effectiveness of nano-zinc oxide (ZnO NPs) at 100 ppm was shown to be highly effective in reducing *Alternaria* blight in a field with disease reduction up to 63% compared with control. Nano-zinc particles disrupt the cell membrane integrity by damaging the fungi and inducing reactive oxygen species (ROS) which is toxic to the fungi and is believed to inhibit the germination of fungal spores and the growth of hyphae.

3.2 Boron (B)

3.2.1 Role of Boron in Plant Defense

Boron is a micronutrient which is important in cell wall biosynthesis, membrane functions and sugar transport. It also produces borate esters with cell wall polysaccharides (mostly pectin) which contribute to the rigidity of cell wall and acts as a physical barrier to the entry of pathogens

(O'Neill *et al.*, 2004) [28]. Boron is also involved in regulating phenolic metabolism which is an important pathway involved in plant defence.

Properly supplied B causes plants to synthesize high amounts of phenolic compounds like hydroxycinnamic acids, flavonoids and lignin which are antimicrobial and help to reinforce cell walls against penetration by fungi (Camacho-Cristóbal *et al.*, 2008) [7]. Boron is also involved in the synthesis of IAA, and regulates the activity of various defense enzymes, which closely correlates to the hormone defense network in plants.

3.2.2 Experimental Evidence in Tomato

Boron deficiency has been shown to lead to *Alternaria* blight in tomato and foliar application can help prevent and alleviate the disease symptoms. Singh *et al.* (2021) [35] found that the disease incidence and disease severity in tomato with the application of 0.2% boric acid have reduced by 38.7% and 41.5%, respectively under field condition. The boron-treated plants exhibited greater lignification of cell walls and this physically inhibited pathogen entry into the plant. It has been observed in greenhouse experiment by Patel and Patel (2020) [30] that the area of leaf spot was significantly reduced (46.2%) when plants were treated with 200 ppm boron as compared to the untreated plants. Boron treatment further enhanced plant height, stem girth, leaf number and fruit weight, implying that it not only increased plant growth, but also increased resistance to disease. Sharma *et al.* (2023) [33] performed that the effect of boron deficiency on the interaction with other nutrients and found that plants grown under boron deficiency had thinner epidermis cell walls and were found to be more susceptible to infection by *Alternaria*. The results indicate not only the importance of maintaining a proper boron nutrition for plant growth but also the role of it as a passive defense strategy to foliar diseases.

3.3 Copper (Cu)

3.3.1 The Role of Copper in Plant Defense

Copper has been available in France since the 1880s when the Bordeaux mixture (copper sulfate and lime) was first developed and has been in use for over 150 years. Copper is a co-factor of crucial defense enzymes at cellular level like laccase, ascorbate oxidase and SOD. It is directly toxic to fungal pathogens, by disrupting the cell membrane lipids, inhibition of enzyme activity and interference with DNA replication in the fungus (Flemming & Trevors, 1989; Yruela, 2005) [13, 43].

Copper in plants plays a role in the metabolism of cell walls, respiration, photosynthesis and hormone signaling. Copper supply induces plant's oxidative burst response, which is a burst of ROS generation at the infection site, leading to killing or limiting the pathogen (Marschner, 2012; Nogueira *et al.*, 2022) [23, 27]. Copper also induces the synthesis of antifungal secondary metabolites, called phytoalexins.

3.3.2 Experimental Evidence in Tomato

Control of *Alternaria* blight of tomato has been well researched using copper compounds. There are 2 commercial fungicides that have been proven to control *Alternaria* blight in the field, copper oxychloride (0.25%) and copper hydroxide (0.15%), and treatments with these fungicides have been successful in reducing blight by 50-70%. (Matheron & Porchas, 2010). Their repeated use,

however, has been the cause for concern in regards to copper accumulating in the soil.

More recent studies have investigated the use of lower concentrations of copper sulfate (CuSO₄) as foliar sprays, and the use of nano-copper particles. Nogueira *et al.* (2022) [27] showed that the *Alternaria* lesion diameter in tomato seedlings by 52% with CuSO₄ at 0.1% concentration is decrease and significantly increased defense enzymes activity. The treatment also decreased the germination of conidia *in vitro* by 78%.

4. Role of Plant Growth Regulators in Managing *Alternaria* Blight

Plant Growth Regulators (PGRs) are naturally occurring and synthetic organic substances that at very low concentrations, control plant growth and development. In the last 20 years, PGRs have been recognized to have a significant role besides growth promotion in stimulating plant immune systems to resist pathogens (Bari & Jones, 2009) [3]. PGRs can trigger a priming of the plant defense system, a process known as 'priming' or 'induced resistance,' and make the plant more alert and able to react quickly to a pathogen attack (Conrath *et al.*, 2015) [9].

4.1 Salicylic Acid (SA)

4.1.1 Mechanism of Action

Salicylic acid (SA) is a phenolic phytohormone and signaling molecule, which is pivotal in plant defense. It is one of the main factors of systemic acquired resistance (SAR) that is a generalist and long lasting immunity induced in plants against a broad spectrum of pathogens (Vlot *et al.*, 2009) [39]. Pathogenesis-related (PR) genes encoding proteins with antimicrobial properties, such as glucanases, chitinases and PR-1 proteins, are expressed in plant cells when attacked by pathogens, as a result of the accumulation of SA in the cell (Dong, 2004) [10].

Another one of the mechanisms promoted by SA is hypersensitive response (HR), which is a localized rapid cell death reaction at the site of infection that isolates the infection and stops spreading. Moreover, the direct antifungal activity and the ability to decrease the spore germination and the elongation of hyphal fragments observed by SA also plays a crucial role in its direct growth inhibition of *Alternaria* (Mandal *et al.*, 2009; Raza *et al.*, 2021) [22, 31].

4.1.2 Experimental Evidence in Tomato

Many trials have proved SA to be effective against *Alternaria* blight of tomato. The foliar application of SA at 1 mM was one of the earliest studies by Mandal *et al.* (2009) [22] to demonstrate that SA spraying enhance the activity of defense enzymes in tomato and up-regulated expression of SA-responsive genes which resulted in significantly decreased severity of *Alternaria* leaf spot. The authors were able to report that treatment of the plants with SA resulted in a reduction in disease incidence of 54% compared to plants in the control treatment.

Razee *et al.* (2021) [31] assessed SA at 0.5 mM, 1.0 mM and 1.5 mM concentrations and observed that SA was the most effective, resulting in 49.3% reduction in PDI in comparison to untreated control. It also enhanced the yield of fruits by 35.6%, height of the plants by 18.2% and chlorophyll content by 22.4%. The activities of POD, SOD and CAT

were significantly greater in SA treated plants, which is an indication of activation of the oxidative defense system. Islam *et al.* (2022) ^[18] tested the efficacy of SA in the priming of tomato plants against the pathogen *A. solani*, and they found that SA priming (pre-treatment 3 days before inoculation) is more effective than post-inoculation treatment. The defense response in the pre-treated plants was induced more rapidly, lesions were smaller and phenolics were more abundant. These findings indicate that the use of SA is more beneficial as a preventative treatment than a treatment to cure.

The results of Ali *et al.* (2023) ^[2] showed that the SA with half dose fungicide application was similar to the full dose fungicide application indicating that the SA could reduce the amount of fungicide required for disease control without any reduction in the disease control. This has important implications for sustainable disease management.

4.2 Indole-3-Acetic Acid (IAA)

4.2.1 Mechanism of Action

Indole-3-acetic acid (IAA) is the most prevalent naturally occurring auxin and is synthesized in the plant meristems, young leaves and seeds. IAA controls cell elongation, root initiation, apical dominance and fruit development (Woodward & Bartel, 2005) ^[40]. The relationship between IAA and immunity is complex and depending on the dose in the context of disease resistance. If applied at low concentrations, IAA may encourage plant growth and increase physical barriers which would decrease disease. Increased levels of IAA do however have a negative impact on SA mediated defense signaling in what is called hormonal crosstalk or antagonism (Kazan & Manners, 2009) ^[19]. IAA stimulates the activity of enzymes which strengthen the cell wall (e.g. peroxidase which deposits lignin in the cell wall). The enzymatic degradation of lignified cell walls is more difficult than that of non-lignified cell walls and hence fungal pathogens like *Alternaria* are less able to degrade them. IAA also induces lateral root growth and thus enhances the surface area for uptake of nutrients/ water and leads to healthy and vigorous plants which in turn help in overcoming the disease pressure (Bhatt & Bhatt, 2019) ^[4].

4.2.2 Experimental Evidence in Tomato.

The efficacy of foliar application of IAA at 25, 50 and 75 ppm was evaluated in tomato plants infected with *A. solani* and it was observed that IAA @ 50 ppm showed significant reduction of disease severity by 34.8% over control as reported by Bhatt and Bhatt (2019) ^[4]. The greatest concentration (50 ppm) also improved the plant height by 21.3%, number of branches by 17.5% and total fruit production by 28.6%. IAA treatment did lead to higher POD and PPO enzyme activity assays of 1.8-fold and 2.1-fold respectively.

Yadav *et al.* (2020) ^[42] conducted the other study where they used IAA as 40 ppm in the tomato integrated disease management study and recorded a 28.5% reduction in *Alternaria* blight incidence. When used in combination with SA, IAA in combination with SA gave additional protection over IAA, however, there was no additional protection when used in combination with SA. The authors postulated that the IAA + SA treatment was effective due to the combined promotion of both physical and biochemical defence mechanisms: strengthening of cell walls and induction of PR proteins.

Mishra and Tiwari (2023) ^[26] found that 100 ppm IAA treatment for seed before transplanting was effective in reducing collar rot of seedlings due to *A. solani*. The IAA treated seeds produced seedlings with strong root system, thick stems and higher endogenous IAA content, which resulted in increased resistance against the pathogen in the early growth phase.

4.3 Naphthalene Acetic Acid (NAA)

4.3.1 Mechanism of Action

Naphthalene acetic acid (NAA) is a synthetic auxin widely used in horticulture for promoting rooting, preventing pre-harvest fruit drop, and improving fruit size and quality. Like IAA, NAA exerts its biological effects by activating auxin receptors in plant cells and regulating gene expression involved in cell division and elongation (Thimann & Koepfli, 1935; Woodward & Bartel, 2005) ^[36, 40]. In terms of disease resistance, NAA has been shown to activate peroxidase and other cell wall-modifying enzymes, thereby strengthening the plant's physical defenses against fungal invasion.

NAA at low doses can improve photosynthetic efficiency, increase chlorophyll content, and enhance overall plant vigor, all of which contribute to better tolerance of disease stress (Gupta & Thind, 2020) ^[17]. Unlike SA, which mainly activates biochemical defense, NAA primarily acts through improving plant growth and physical barriers, providing a different but complementary mode of disease suppression.

4.3.2 Experimental Evidence in Tomato

Sharma *et al.* (2019) ^[32] evaluated NAA at 20, 40, and 60 ppm on tomato against *Alternaria* blight under field conditions. NAA at 40 ppm was found to be the most effective concentration, reducing PDI by 36.1% and increasing fruit yield by 32.4%. The authors attributed the disease reduction to enhanced lignification of epidermal cells and increased POD activity in treated plants. Higher doses (60 ppm) were less effective and sometimes phytotoxic, emphasizing the importance of using NAA at the right concentration.

In a two-year study by Meena *et al.* (2021) ^[25], NAA at 30 ppm was applied as a foliar spray at the 4-leaf stage, flowering stage, and fruit set stage on tomato. They found that three-time application of NAA gave the best results, reducing *Alternaria* blight disease incidence by 40.2% and severity by 38.7% compared to untreated control. The number of marketable fruits per plant was also significantly higher in NAA-treated plants.

Gupta and Thind (2020) ^[17] compared the effectiveness of NAA, IAA, and SA and concluded that while SA was the most effective growth regulator for disease management, NAA was superior to IAA in terms of improving fruit yield and quality. They recommended a three-spray program using SA (1 mM) followed by NAA (30 ppm) for integrated management of *Alternaria* blight while maintaining good fruit quality.

5. Conventional and Integrated Disease Management (Control)

5.1 Chemical Control

Chemical fungicides remain the most widely used method for managing *Alternaria* blight of tomato. Commonly used fungicides include mancozeb (0.25%), chlorothalonil (0.2%), iprodione (0.1%), azoxystrobin (0.1%), and copper

oxychloride (0.25%). These compounds are applied as foliar sprays at 10-15 day intervals, starting from the early appearance of disease symptoms. Studies have consistently shown that 3-5 fungicide sprays during the crop season can reduce disease incidence by 60-80% and protect yield (Matheron & Porchas, 2010; Verma & Sharma, 2021) [24, 38]. However, the major drawbacks of chemical control include: (i) development of fungicide-resistant strains of the pathogen, (ii) disruption of non-target soil microorganisms, (iii) toxicity to pollinators such as bees, (iv) residue problems in fruits, and (v) high cost of repeated applications. These concerns have prompted researchers to integrate micronutrients and growth regulators into disease management programs as partial or complete substitutes for synthetic fungicides (Singh *et al.*, 2021) [35].

5.2 Cultural and Biological Control

Cultural practices form the foundation of any disease management program. Recommended practices for *Alternaria* blight management include: use of disease-free transplants, crop rotation with non-solanaceous crops, removal and destruction of infected plant debris, proper spacing to improve air circulation, drip irrigation to keep foliage dry, and use of resistant varieties. Resistant varieties such as Pusa Ruby, Roma, Arka Ahuti, and hybrid varieties with partial resistance can significantly reduce disease severity compared to susceptible ones (Foolad *et al.*, 2008) [15].

Biological control agents, including *Trichoderma harzianum*, *Bacillus subtilis*, and *Pseudomonas fluorescens*, have shown promising results in suppressing *A. solani* in tomato. These biocontrol agents produce antifungal compounds (such as iturin, surfactin, and volatile metabolites), compete with the pathogen for nutrients and

space, and induce systemic resistance in the host plant (Pal & McSpadden Gardener, 2006; Kumar *et al.*, 2020) [29, 20]. Integration of biological control with micronutrient and PGR applications can provide environmentally safe and economically viable disease management.

5.3 Integrated Disease Management (IDM)

Integrated disease management (IDM) involves combining multiple approaches cultural, biological, chemical, and nutritional to achieve effective disease control while minimizing environmental impact. Several studies have shown that IDM strategies that include micronutrients and PGRs alongside reduced doses of fungicides can provide better disease control than any single approach alone. For example, Ali *et al.* (2023) [2] demonstrated that combining SA (1 mM) with half the recommended dose of mancozeb (0.125%) was as effective as the full recommended dose of mancozeb alone. Similarly, Ahmed *et al.* (2022) [1] reported that a combination of ZnSO₄ (0.3%) + boric acid (0.2%) + mancozeb (0.15%) gave the best results in terms of disease control (PDI reduced by 72.3%) and fruit yield, outperforming each treatment applied alone. Sharma *et al.* (2023) [33] evaluated a comprehensive IDM schedule that included: (i) soil application of *Trichoderma harzianum* at transplanting, (ii) foliar spray of SA (1 mM) at first sign of disease, (iii) ZnSO₄ (0.3%) spray at 15-day intervals, and (iv) one application of copper oxychloride (0.25%) at high disease pressure. This IDM program reduced PDI by 74.8% and increased fruit yield by 45.6% compared to untreated control, while requiring fewer fungicide applications.

6. Summary of Key Studies

Table 1: Summary of selected studies on micronutrients and growth regulators for *Alternaria* blight management in tomato

Treatment	Dose/Conc.	% Disease Reduction	% Yield Increase	Reference
Zinc sulfate (ZnSO ₄)	0.50%	42-55%	30.20%	Kumar & Singh (2020) [20]
ZnSO ₄	0.30%	54.50%	28.70%	Raza <i>et al.</i> (2021) [31]
Nano-ZnO NPs	100 ppm	63.00%	38.50%	Garg <i>et al.</i> (2022) [16]
Boric acid	0.20%	41.50%	25.30%	Singh <i>et al.</i> (2021) [35]
Boron	200 ppm	46.20%	22.60%	Patel & Patel (2020)
Copper sulfate (CuSO ₄)	0.10%	52.00%	21.80%	Nogueira <i>et al.</i> (2022) [27]
Copper oxychloride	0.25%	68.40%	40.20%	Verma & Sharma (2021) [38]
Salicylic acid (SA)	1.0 mM	54.00%	35.60%	Raza <i>et al.</i> (2021) [31]
SA	1 mM	49.30%	28.40%	Islam <i>et al.</i> (2022) [18]
IAA	50 ppm	34.80%	28.60%	Bhatt & Bhatt (2019) [4]
IAA + SA	40 ppm + 1 mM	62.30%	42.10%	Yadav <i>et al.</i> (2020) [42]
NAA	40 ppm	36.10%	32.40%	Sharma <i>et al.</i> (2019) [32]
NAA	30 ppm	40.20%	29.80%	Meena <i>et al.</i> (2021) [25]
ZnSO ₄ + Boric acid + Mancozeb	0.3% + 0.2% + 0.15%	72.30%	45.60%	Ahmed <i>et al.</i> (2022) [1]
SA + half Mancozeb	1 mM + 0.125%	65.20%	38.90%	Ali <i>et al.</i> (2023) [2]
IDM (Trichoderma + SA + Zn + Cu)	Combined	74.80%	45.60%	Sharma <i>et al.</i> (2023) [33]

7. Methods to Minimize the Damage from Disease Suppression

While micronutrients and growth regulators are chemically distinct and have different main functions, they have similar modes of action to suppress *Alternaria* blight in tomato. It is significant to understand these mechanisms to develop and improve the use of these in disease management programs. Micronutrients (Zn, B, Cu) suppress *Alternaria* blight in the following ways: (i) physical barrier strengthening by promoting cell wall lignification and silicification, which block *Alternaria* entry; (ii) enzyme activation as co-factors

or activators of defense-related enzymes such as SOD, POD, PPO, and CAT; (iii) direct antifungal activity; copper ions and zinc are directly toxic to fungal cells at high levels; (iv) reactive oxygen species (ROS) modulation: maintaining ROS in a balanced state, which activates oxidative burst to fight pathogens, without causing damage to the plants (Marschner, 2012; Nogueira *et al.*, 2022) [23, 27].

The mechanisms that are important for growth regulators (SA, IAA, and NAA) include the following: (i) induction of systemic acquired resistance (SAR) by SA; activation of PR genes and NPR1 signaling pathway; (ii) promotion of

hypersensitive response (HR) by SA to confine the pathogen at the entry site; (iii) activation of biosynthesis of phenolics and phytoalexins; (iv) cell wall reinforcement through auxin-mediated peroxidase activity; and (v) improvement of overall plant health and vigor, increasing tolerance to disease stress (Vlot *et al.*, 2009; Bari & Jones, 2009; Conrath *et al.*, 2015) [39, 3, 9].

8. Conclusion and Future Perspectives

Alternaria blight caused by *Alternaria solani* continues to be a severe disease of tomato crops throughout the world. There is a heavy dependence on synthetic fungicides, which has generated resistance and environmental issues and there is a need for effective strategies to manage them that are safer and more sustainable.

From this review, it is evident that all micronutrients (zinc, boron, and copper) and all plant growth regulators (salicylic acid, IAA and NAA) exhibit great promise towards the management of *Alternaria* blight of tomato. Their compounds act in several complementary ways such as reinforcing cell walls, triggering defense enzymes, triggering systemic resistance and directly inhibiting growth of fungi. They can be used alone or in combination and when used on a regular basis can decrease the severity of disease by 30-75% and increase the fruit yield by 20-45%.

Salicylic acid (SA) at 1mM exhibited the most consistent and high disease suppressing activities while copper oxychloride (0.25%), nano-ZnO NPs (100 ppm) and zinc sulphite and boric acid combination was the next. NAA and IAA were moderately effective, and are more effective when applied in conjunction with other compounds rather than alone.

The following research areas should be given attention in future research: (i) optimization of doses and timing of application for different agro-climatic zones; (ii) molecular studies to understand the genes and pathways that are activated by such compounds; (iii) combination studies to see if there are synergistic effects between the compounds; (iv) long-term field trials to assess the sustainability and economics of such methods; (v) the investigation of nano-formulations of micronutrients to improve efficiency and reduce the number of applications; (vi) investigating the residue effects and ecological safety of the nano-copper and nano-zinc particles.

The use of micronutrients and growth regulators in the IDM frameworks, as well as resistant varieties, biological control, and judicious use of fungicides, are the most promising and sustainable options for managing *Alternaria* blight of tomato in the future.

References

- Ahmed S, Khan MA, Rahman MH. Synergistic effects of zinc and boron micronutrients on the management of *Alternaria* blight in tomato. *Asian Journal of Plant Pathology*. 2022;16(2):78-89.
- Ali S, Iqbal Z, Hussain M. Integration of salicylic acid with reduced doses of mancozeb for eco-friendly management of *Alternaria* blight of tomato. *Pakistan Journal of Phytopathology*. 2023;35(1):45-56.
- Bari R, Jones JDG. Role of plant hormones in plant defence responses. *Plant Molecular Biology*. 2009;69(4):473-488.
- Bhatt P, Bhatt K. Efficacy of plant growth regulators against *Alternaria solani* causing early blight of tomato. *International Journal of Current Microbiology and Applied Sciences*. 2019;8(3):2671-2679.
- Broadley MR, White PJ, Hammond JP, Zelko I, Lux A. Zinc in plants. *New Phytologist*. 2007;173(4):677-702.
- Cakmak I. Possible roles of zinc in protecting plant cells from damage by reactive oxygen species. *New Phytologist*. 2000;146(2):185-205.
- Camacho-Cristóbal JJ, Rexach J, González-Fontes A. Boron in plant physiology. *Journal of Integrative Plant Biology*. 2008;50(10):1247-1255.
- Chaerani R, Voorrips RE. Tomato early blight (*Alternaria solani*): the pathogen, genetics, and breeding for resistance. *Journal of General Plant Pathology*. 2006;72(6):335-347.
- Conrath U, Beckers GJM, Langenbach CJG, Jaskiewicz MR. Priming for enhanced defense. *Annual Review of Phytopathology*. 2015;53:97-119.
- Dong X. NPR1, all things considered. *Current Opinion in Plant Biology*. 2004;7(5):547-552.
- Fageria NK, Filho MPB, Moreira A, Guimarães CM. Foliar fertilization of crop plants. *Journal of Plant Nutrition*. 2009;32(6):1044-1064.
- FAO. World food and agriculture — Statistical yearbook 2023. Food and Agriculture Organization of the United Nations; 2023.
- Flemming CA, Trevors JT. Copper toxicity and chemistry in the environment: a review. *Water, Air, and Soil Pollution*. 1989;44(1-2):143-158.
- Fones H, Preston GM. The impact of transition metals on bacterial plant disease. *FEMS Microbiology Reviews*. 2013;37(4):495-519.
- Foolad MR, Merk HL, Ashrafi H. Genetics, genomics and breeding of late blight and early blight resistance in tomato. *Critical Reviews in Plant Sciences*. 2008;27(2):75-107.
- Garg H, Singh DK, Tiwari R. Nano zinc oxide nanoparticles as an effective tool for the management of *Alternaria* blight of tomato. *Nanomaterials*. 2022;12(8):1350.
- Gupta N, Thind SK. Management of *Alternaria* blight of tomato by plant growth regulators: comparative efficacy of SA, IAA and NAA. *Indian Phytopathology*. 2020;73(2):289-298.
- Islam MT, Hossain MM, Islam MS. Priming-induced resistance by salicylic acid against *Alternaria solani* in tomato. *Phytopathology Research*. 2022;4(1):15.
- Kazan K, Manners JM. Linking development to defense: auxin in plant-pathogen interactions. *Trends in Plant Science*. 2009;14(7):373-382.
- Kumar A, Tripathi MK, Pandey VK. Management of early blight of tomato caused by *Alternaria solani* using botanicals and biocontrol agents. *Journal of Pharmacognosy and Phytochemistry*. 2020;9(1):897-902.
- Kumar P, Singh R. Efficacy of micronutrients in the management of *Alternaria* blight of tomato and their effect on enzymatic activity. *International Journal of Chemical Studies*. 2020;8(4):1254-1260.
- Mandal S, Mallick N, Mitra A. Salicylic acid-induced resistance to *Fusarium oxysporum* f. sp. *lycopersici* in tomato. *Plant Physiology and Biochemistry*. 2009;47(7):642-649.
- Marschner P, editor. Marschner's mineral nutrition of higher plants. 3rd ed. Academic Press; 2012.

24. Matheron ME, Porchas M. Activity of boscalid, fenhexamid, fluazinam, penthiopyrad, and thifluzamide on growth of *Sclerotinia minor* and *S. sclerotiorum* and development of lettuce drop. *Plant Disease*. 2010;94(7):839-845.
25. Meena PD, Singh K, Rathore RS. Influence of plant growth regulators on *Alternaria* blight of tomato under field conditions. *Legume Research*. 2021;44(9):1094-1100.
26. Mishra A, Tiwari S. Seed priming with IAA for early protection against *Alternaria solani* in tomato seedlings. *Horticultural Science and Technology*. 2023;41(2):175-183.
27. Nogueira MA, Shiomi HF, Zampieri MCT, Favarin JL. Copper application for tomato disease management: antifungal activity and enzyme induction. *Tropical Plant Pathology*. 2022;47(3):344-354.
28. O'Neill MA, Ishii T, Albersheim P, Darvill AG. Rhamnogalacturonan II: structure and function of a borate cross-linked cell wall pectic polysaccharide. *Annual Review of Plant Biology*. 2004;55:109-139.
29. Pal KK, McSpadden Gardener B. Biological control of plant pathogens. *The Plant Health Instructor*. 2006.
30. Patel NB, Patel HR. Effect of micronutrients on disease severity and plant growth in tomato infected with *Alternaria* blight. *Journal of Entomology and Zoology Studies*. 2020;8(2):1028-1033.
31. Raza W, Ghazanfar MU, Wakil W, Ali B. Evaluation of micronutrients and plant growth regulators for the management of *Alternaria* blight of tomato. *Journal of Plant Protection Research*. 2021;61(4):389-400.
32. Sharma A, Sharma P, Dhaliwal LK. Role of naphthalene acetic acid in the management of *Alternaria* blight of tomato. *Journal of Hill Agriculture*. 2019;10(1):82-87.
33. Sharma P, Verma KS, Bhardwaj R. Integrated disease management of *Alternaria* blight of tomato using bio-agents, micronutrients and growth regulators. *Phytoparasitica*. 2023;51(2):353-368.
34. Singh A, Singh R. Micronutrient-mediated defense activation in vegetables: a review. *Frontiers in Sustainable Food Systems*. 2022;6:908477.
35. Singh D, Kumar A, Maurya S. Efficacy of boron and copper micronutrients against *Alternaria* blight of tomato and their effect on yield and quality. *Indian Journal of Horticulture*. 2021;78(1):63-70.
36. Thimann KV, Koepfli JB. Identity of the growth-promoting and root-forming substances of plants. *Nature*. 1935;135:101-102.
37. Thomma BPHJ. *Alternaria* spp.: from general saprophyte to specific parasite. *Molecular Plant Pathology*. 2003;4(4):225-236.
38. Verma M, Sharma S. Field evaluation of copper formulations against early blight of tomato. *Annals of Plant Protection Sciences*. 2021;29(2):144-149.
39. Vlot AC, Dempsey DA, Klessig DF. Salicylic acid, a multifaceted hormone to combat disease. *Annual Review of Phytopathology*. 2009;47:177-206.
40. Woodward AW, Bartel B. Auxin: regulation, action, and interaction. *Annals of Botany*. 2005;95(5):707-735.
41. Woudenberg JHC, Groenewald JZ, Binder M, Crous PW. *Alternaria* redefined. *Studies in Mycology*. 2015;75:171-212.
42. Yadav R, Singh K, Sharma N. Combined effect of IAA and salicylic acid in inducing resistance against *Alternaria* blight of tomato. *Vegetos*. 2020;33(1):152-160.
43. Yruela I. Copper in plants. *Brazilian Journal of Plant Physiology*. 2005;17(1):145-156.