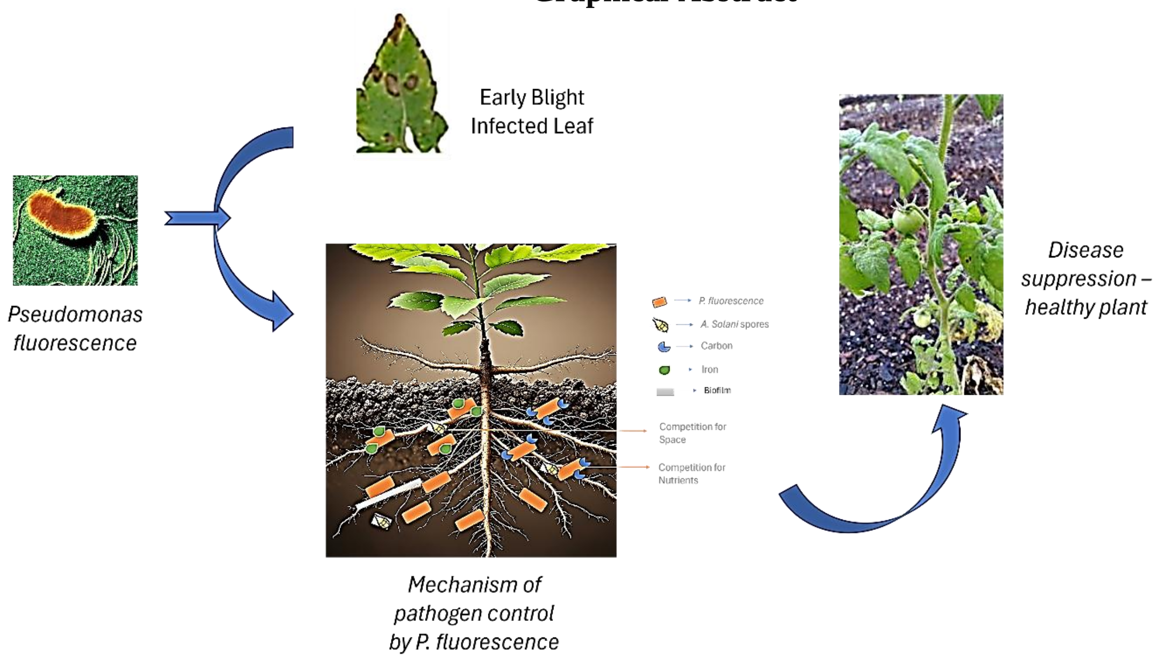
# Harnessing *Pseudomonas fluorescens* for eco-friendly control of tomato early blight: A sustainable agricultural strategy

**Chanthini Kanagaraj Muthu-Pandian**

**Graphical Abstract**





## ABSTRACT

Tomato (*Solanum lycopersicum* L.) is among the most extensively grown vegetables globally, but its yield is significantly under attack by early blight caused by *Alternaria solani*, which could contribute to more than 80% loss of yield under ideal conditions. Routine management is based primarily on chemical fungicides like mancozeb and chlorothalonil, but their excessive use has led to fungicide resistance, environmental issues, and health hazards. This underscores the imperative demand for sustainable and environmentally friendly substitutes. *Pseudomonas fluorescens*, a plant growth-promoting rhizobacterium (PGPR), is also a potential biocontrol agent owing to its multi-faceted systems, such as antibiosis by production of secondary metabolites (2,4-diacetylphloroglucinol, pyoluteorin, phenazines), siderophore-mediated iron sequestration, nutrient and niche competition, and induction of systemic resistance in tomato plants. Field, greenhouse, and laboratory tests have all consistently shown that it can inhibit the growth of hyphae, conidial germination, disease severity, and improve plant vigor and yield. Powder and liquid forms of commercial formulations are already available and have proven to be effective in farmer demonstrations in various parts of India and other nations. In addition, integration of *P. fluorescens* with *Trichoderma* spp., neem extracts, organic amendments, and reduced fungicide regimens further enhanced disease suppression and lowered chemical inputs. Its application in Integrated Pest Management (IPM) systems highlights its ability to decrease fungicide application by 50%, improve ecological resilience, and facilitate residue-free tomato production. This review integrates available evidence regarding the biocontrol potential of *P. fluorescens* against tomato early blight and highlights its potential as part of sustainable agricultural tactics in the future.

**Keywords:** Antifungal metabolites; Siderophore production; Bioformulations; Integrated pest management; 2,4-diacetylphloroglucinol.

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## INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is among the most significant vegetable crops globally, prized for its nutritional value, gastronomical applications, and economic value (Chanthini *et al.*, 2022). As per 2024 estimates, world production of tomatoes was about 186 million metric tonnes, an increase of 3.3% from 2023. China accounts for most world production at around 68.2 million tonnes (almost 37% of global output), followed by India (~20 million tonnes), Turkey (~13 million tonnes), and the United States (~10–12 million tonnes) (Somasekhar and Shaafi, 2025). In addition to its use as a raw vegetable, tomato is extensively processed into sauces, pastes, juices, and other value-added products, with processed tomatoes alone reaching more than 45 million tonnes in 2024. The crop accounts for a major percentage of agricultural GDP and rural livelihoods and is, therefore, the backbone of both local food systems and global trade (Beaulah *et al.*, 2025). But its productivity is often limited by biotic stresses, particularly leaf diseases, that are significant obstacles to sustainable production (Chanthini *et al*., 2022).

Tomato plants are susceptible to a wide range of diseases caused by fungi, bacteria, viruses, and nematodes that seriously threaten crop productivity (Meshram and Adhikari, 2024). Yield losses for fungal diseases like early blight and late blight can vary from 35% up to as high as 80%, depending on environmental conditions and severity. Viral infections and bacterial wilt contribute to average yield reductions between 10% and 50% (Havryliuk *et al.*, 2024). Overall, the prevalence of disease can lead to great economic loss and threaten sustainable tomato production worldwide. Of tomato diseases, early blight of *Alternaria solani* is especially devastating, causing losses of 35% to more than 80% under suitable conditions. The disease infects leaves, stems, and fruit, causing early defoliation, photosynthesis depression, poor fruit set, and low-quality fruit (Chanthini *et al.*, 2023). Its widespread presence in all tomato-producing regions makes it a central limiting factor in sustainable tomato production (Jindo *et al.*, 2021).

Chemical fungicides such as mancozeb, chlorothalonil, and metalaxyl were largely used to manage early blight as long and provided immediate but temporary relief (Lavanya *et al.*, 2024). However, excessive and frequent use has resulted in resistance building up among the pathogen populations, environmental pollution, higher cost of inputs, and health problems for consumers and farm workers. These constraints underscore the need for environmentally sound alternatives that are effective as they are sustainable (Nisha and Vasantha-Srinivasan, 2024). In this context, biological control methods are fast gaining prominence as effective components of integrated disease management measures.

Biopesticides, products of natural origin, are considered one of the major tools to be used in sustainable and environmentally friendly agriculture, especially organic farming. Of microbial, plant extract, and natural mineral origin, biopesticides offer an environmentally friendly alternative to synthetic pesticides (Chellappandian *et al.*, 2019). Application allows effective control of pests, diseases, and weeds with minimum impact on the environment, biodiversity, and human and animal health. Control of phytopathogens involves the induction or stimulation of a plant's defense mechanisms, such as the production of proteins associated with pathogenesis, phytoalexins, histological barriers, and others, with the so-called defense activators or elicitors, among which one can mention salicylic acid and its derivatives, jasmonates (Kumar *et al.*, 2021). Microbial pesticides are derived from microorganisms like bacteria, fungi, and viruses and include molecules/compounds isolated from these organisms to fight plant pathogens and insect pests (Kirupanatha-Rajan *et al.*, 2025). In the last decade, extensive research on microbial biopesticides has resulted in the discovery and development of quite a good number of biopesticides and has given a way for their marketability (Siddiqui *et al.*, 2025). Among the various microbial biopesticides researched for efficient disease management, certain rhizobacteria have been found versatile and effective in controlling fungal pathogens and promoting plant health (Bakr *et al.*, 2025).

*Pseudomonas fluorescens* is a plant growth-promoting rhizobacterium (PGPR) and is one of the most promising microbial biocontrol candidates for fungal disease management like early blight (Jia *et al.*, 2023). The bacterium efficiently colonizes the rhizosphere, produces a broad spectrum of antifungal compounds, competes with pathogens for nutrients, and elicits systemic resistance in the host plants (Panpatte *et al.*, 2016). Apart from suppression of disease, *P. fluorescens* also promotes plant vigour, root growth, and nutrient acquisition and, therefore, is an interesting candidate for sustainable tomato production systems (Gade and Koche, 2022).

This review presents an appraisal of the effectiveness of *P. fluorescens* in managing tomato early blight. It highlights progress in formulation and delivery methodologies to improve rhizosphere colonization and disease suppression, as well as synergies that occur when combined with botanical extracts and integrated into reduced fungicide applications. Finally, it discusses updated knowledge of the molecular processes underlying induced systemic resistance and direct antifungal activity by *P. fluorescens* with a view to identifying future research avenues to optimize the impact of sustainable biocontrol.

## PATHOGEN PROFILE

### *Alternaria solani* SORAUER (Pleosporaceae: Ascomycota)

### Morphology, life cycle, and infection process

*Alternaria solani* is the pathogen of early blight of tomato and a filamentous, necrotrophic fungus of class Dothideomycetes. Morphologically, it forms dark, septate mycelia and beaked conidia borne in chains on simple or branched conidiophores. The conidia are obclavate to ellipsoid, typically 120–300 µm in length and 12–20 µm in width, with both transverse and longitudinal septa, giving them a “muriform” appearance (Bhushan *et al.*, 2025). This morphology is diagnostic for the pathogen and aids in microscopic identification.

The life cycle of *A. solani* begins with survival in plant debris, soil, or volunteer hosts in the form of conidia or dormant mycelium. Conidia germinate and infect the host under favourable conditions through direct penetration or natural openings like stomata (Dhaval *et al.*, 2021). The primary symptom is the appearance of small, dark brown lesions on lower leaves, which spread concentrically to develop the typical "target spot" pattern. The disease gradually spreads from older to younger leaves and also infects stems and fruits. Secondary cycles develop throughout the season through subsequent production and wind, rain splash, or irrigation water dispersal of conidia, resulting in polycyclic epidemics (Guha, 2025).

*Alternaria* spp. have expendable coding chromosomes (ECCs) that harbour phytopathogenic genes responsible for encoding host-specific toxins (HSTs) that are key to their virulence. The genome assembly of *A. solani* (altNL03003) shed light on early blight pathogenicity (Gai *et al.*, 2021) (Table 1). Moreover, polyketide synthase genes (*PksJ*, *PksF*, *PksI*, *PksA*) and regulatory factors like aohR control alternariol (AOH), alternariol monomethyl ether (AME), and tenuazonic acid (TEA) biosynthesis, and gene knockouts eliminate toxin production, drastically impairing virulence in infected host plants (Wenderoth *et al.,* 2019; Liu *et al.,* 2020). These research results emphasize the central importance of secondary metabolite gene clusters in mediating infection as well as host cell death.

**Conditions conducive to disease establishment**

Environmental conditions play an important role in disease development. High temperatures of 24–30 °C, in conjunction with extended leaf wetness or high relative humidity (>85%), highly support infection and disease development. Dense canopy cover, inadequate air movement, and recurring rainfall favor spore germination and dispersal, causing extreme epidemics (Rowlandson *et al.*, 2015). Under conditions of nutrient-deficient or stressed plants, early blight is more destructive. Crop management practices are therefore important in controlling the severity of disease (Singh and Chawla, 2012).

**Significance of focusing on early blight in IPM**

Being polycyclic, persistent in the soil, and capable of contributing to 80% yield loss, early blight poses a significant limitation to tomato production (Jindo *et al.*, 2021). Management must hence be integrated using many approaches such as rotation, resistant cultivars, cultural management, and biological or chemical controls. In Integrated Pest Management (IPM), *A. solani* is an overriding target since it not only lowers yield but also fruit quality and marketability (Ma *et al.*, 2023). Control of early blight by means that are environmentally friendly, such as the use of biological control agents like *P. fluorescens*, is thus important to minimize fungicide reliance and maintain long-term productivity (Jia *et al.*, 2023).

***Pseudomonas fluorescens***

Table 1. Phytopathogenic Genes in *A. solani*

| Gene/Cluster | Function / Role | Key Findings | Reference |
|---|---|---|---|
| *altNL03003* genome (genomic DNA sequencing ID: 4190556) | Whole-genome sequencing | First genome assembly of *A. solani*, revealed genomic architecture, coding genes, and potential pathogenicity determinants | Gai *et al.*, 2022 |
| Secondary metabolite biosynthetic clusters | Mycotoxin biosynthesis | Genome mining revealed clusters encoding toxins and virulence factors specific to early blight development in tomato and potato | Gai *et al.*, 2022 |
| Effector/virulence-associated genes (from transcriptomics) | Pathogenicity & host interaction | Gene expression analyses post-inoculation identified candidate virulence genes linked to host necrosis | Liu *et al.*, 2020 |

**BIOLOGY AND MODE OF ACTION**

**Taxonomy and Rhizosphere Colonization**

*P. fluorescens* is a Gram-negative, rod-shaped, motile bacterium within the family Pseudomonadaceae. It is not pathogenic to plants and humans, unlike other *Pseudomonas* species like *P. syringae*. As a plant growth-promoting rhizobacterium (PGPR), *P. fluorescens* survives in varied soils, where it serves as a core part of the microbial community tasked with ensuring plant health. Its versatility in colonizing soil and root niches makes it eligible to be employed as a biological control agent (Gade and Koche, 2022).

Among the features of *P. fluorescens* that are notable is its potential to colonize efficiently the rhizosphere. Root exudates, having high sugar content, possess amino acids and organic acids and thus are ideal substrata for its growth (Sivasakthi *et al.,* 2014). Once established, *P. fluorescens* forms biofilms and binds to root surfaces, facilitating survival and physical contact with the host plant and competing microbes. This colonization enhances nutrient delivery as well as creating an efficient microbial barrier against pathogens *like A. solani* (Hol *et al.*, 2013).

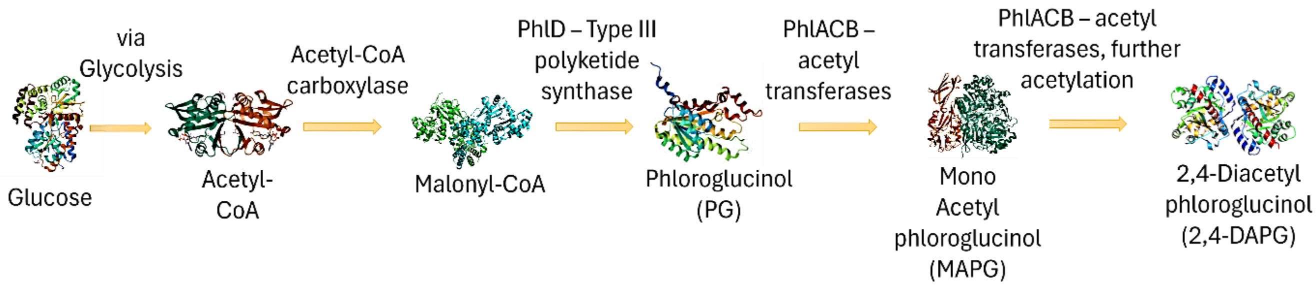
## MECHANISMS OF ANTAGONISM AGAINST *A. solani*

The anti-pathogenic function of *P. fluorescens* against pathogen is multifaceted, involving inhibition of the pathogen directly and indirect stimulation of plant defense. Its major functions are antibiosis, siderophores, induced systemic resistance (ISR), and nutrient as well as space competition (Saranraj *et al.*, 2023).

### Antibiosis: antibiotic production (2,4-DAPG, pyoluteorin, phenazine)

One of the most well-studied functions is the biosynthesis of antifungal antibiotics. *P. fluorescens* synthesizes a variety of secondary metabolites such as 2,4-diacetylphloroglucinol (2,4-DAPG), pyoluteorin, and phenazines, all of which possess strong inhibitory activity against *A. solani* (Alori, 2017) (Figure 1). These metabolites disrupt the cell membrane of fungi, reduce spore germination, and suppress hyphal growth. Maurya *et al.* (2014) reported heavy in vitro inhibition of *A. solani* mycelial growth by *P. fluorescens* isolates of 2,4-DAPG.

Figure 1. Production of 2,4-diacetylphloroglucinol




*P. fluorescens* synthesizes 2,4-DAPG by the phl gene cluster encoding the polyketide biosynthesis enzymes. The malonyl-CoA precursor undergoes condensation reactions to form phloroglucinol, which is acetylated to yield monoacetyl phloroglucinol and then finally transformed into 2,4-DAPG. The biosynthetic process is strictly controlled by quorum sensing, environmental parameters (availability of iron, carbon sources), and global regulatory proteins (Li *et al.*, 2025). Following secretion, 2,4-DAPG is an antifungal substance with a wide range of activity that disrupts membrane integrity, inhibits spore germination, and hyphal inhibition of pathogens (Stepanov *et al.*, 2025).

Pyoluteorin and phenazine derivatives expand this antifungal activity further by generating ROS that induce damage to pathogen cellular structures (Yan *et al.*, 2021). Interestingly, the simultaneous synthesis of more than a single antibiotic facilitates *P. fluorescens* to acquire a broad-range effect, reducing the chances of resistance in *A. solani* (Saranraj *et al.*, 2023). Antibiotic-induced inhibition is a direct biocontrol approach that can be utilized in seed and soil treatments.

### Siderophore production: competition for iron

Iron is a vital micronutrient for plants and for microbe pathogens, though availability in the rhizosphere is usually minimal (Colombo *et al.*, 2014). *P. fluorescens* produces high-affinity iron-sequestering chelators referred to as siderophores (e.g., pyoverdine), which sequester iron and render it unavailable to other microbes (Khan *et al.*, 2018). Iron starvation suppresses fungal germination and growth of conidia, an indirect method of pathogen suppression (Wang *et al.*, 2025). Experiments have shown that tomato plants inoculated with siderophore-producing *P. fluorescens* strains exhibit reduced early blight severity, which indicates the ecological significance of nutrient competition for pathogen suppression (Ali *et al.*, 2022).

**Induced systemic resistance (ISR): activation of host defense enzymes (peroxidase, PAL, chitinase)**

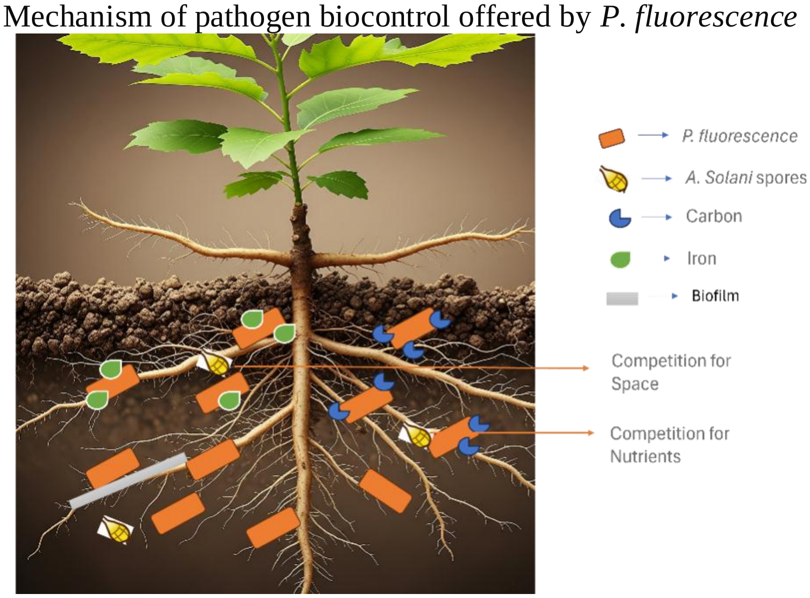
Aside from outright resistance, *P. fluorescens* boosts the innate immunity of the host via ISR, which is analogous to immunization in higher eukaryotes (Yu *et al.*, 2022). ISR is not the direct assault of the bacterium to the pathogens but conditioning the plant to have a stronger response when it is exposed to pathogens. Biochemical analysis has shown that tomato plants treated with *P. fluorescens* exhibit higher activities of defense enzymes such as peroxidase (PO), phenylalanine ammonia-lyase (PAL), and chitinase. These enzymes, which reinforce cell walls, produce phytoalexins, and lyse fungal cell walls, result in a system of multi-dimensional defense (Noureldeen *et al.*, 2021). For instance, *P. fluorescens*-inoculated tomato plants showed higher PAL activity, which was associated with decreased lesion growth of *A. solani* (Kumar *et al.*, 2023).

Field tests also support the ISR effect: *P. fluorescens* suspension seed treatment and root dipping not only suppressed the severity of disease but also increased plant vigor and yield (Ganeshan and Manoj Kumar, 2005; Chin *et al.*, 2022). This systemic resistance improvement makes *P. fluorescens* an attractive candidate for sustainable disease control because it decreases dependence on chemical fungicides while enhancing crop resistance overall.

**Competition for space and nutrients**

The rhizosphere represents a competitive habitat in which microbes compete for scarce resources and niches of colonization (Santoyo *et al.*, 2021) (Figure 2). *P. fluorescens* prevails in this ecological competition by virtue of its high growth rate, metabolic versatility, and capacity to catabolize a wide range of root exudates (Velmourougane *et al.*, 2017). By colonizing root surfaces and forming stable biofilms, *P. fluorescens* inhibits the development of pathogens like *A. solani* (Ansari and Ahmad, 2019).

**Figure 2.** Mechanism of pathogen biocontrol offered by *P. fluorescence*




Competition for carbon substrates is present within the rhizosphere (Solanki *et al.*, 2022). *P. fluorescens* is able to quickly metabolize organic acids and sugars exuded from tomato roots, thereby leaving fewer substrates for *A. solani* (Prakash *et al.*, 2021). This deprivation is linked with spore germination inhibition and decreased rate of pathogen colonization. In addition, studies have shown that higher population densities of *P. fluorescens* in the rhizosphere are inversely correlated with lesion frequency and disease incidence in tomato plants (Abiodun *et al.,* 2017).

Competitive exclusion also significantly governs pathogen population constraint in rhizosphere. Once *P. fluorescens* is founded on root surfaces, it forms a barrier of protecting microbes which prevents pathogen invasion into infection courts. This was supported by earlier studies, which showed intensive colonization of tomato roots by *P. fluorescens* biofilms which physically prevented pathogen invasion (Elsharkawy *et al.*, 2023). Synergistic actions of space and nutrient competition reinforce *P. fluorescens* as a highly competitive rhizosphere colonizer as well as a reliable biocontrol agent of early blight.

## LABORATORY AND GREENHOUSE STUDIES

### In vitro inhibition of radial growth of *A. solani* by *P. fluorescens*

There have been various in vitro experiments that consistently testified that *P. fluorescens* is highly antagonistic against *A. solani,* which is the pathogen of early blight in tomatoes (Attia *et al.*, 2020; Lalhruaitluangi *et al.,* 2022). Dual-culture tests and cell-free filtrate tests indicate drastic inhibition of radial mycelial growth, frequently in the range 40–70%, accompanied by observable morphological changes such as swelling of the hyphae, vacuolization, and deformation (Magesh *et al.,* 2018; Hardiana and Abadi, 2025). This antifungal effect has been assigned largely to the production of diffusible antibiotics, such as 2,4-DAPG and pyoluteorin, that disrupt fungal metabolism and cell wall integrity (Stepanov *et al.*, 2025). Hydrolytic enzymes, such as chitinases and proteases, also break down fungal cell walls, and siderophores chelate iron, generating nutrient-poor conditions that are not conducive to fungal growth (Balhara *et al.*, 2016; Jadhav *et al.*, 2017). Besides, volatile organic compounds from some *P. fluorescens* strains have been found to inhibit fungal growth in non-contact mode as well (Raza *et al.,* 2020). A number of studies have indicated synergistic inhibition where bacterial culture filtrates are used in conjunction with bioactive compounds like chitosan, and this has been thought to enhance biocontrol effects by using integrated methods (Dmitrović *et al.*, 2022; Anuar *et al.,* 2023). Collectively, the findings indicate the various methods in which *P. fluorescens* suppresses *A. solani* on the in vitro level, and with a solid foundation to utilize the organism as a biocontrol agent.

### Germination inhibition of conidia

Besides preventing hyphal growth, *P. fluorescens* was also shown to greatly prevent germination of *A. solani* conidia and thereby reducing the pathogen's opportunities to infect (Alore, 2017). Laboratory tests employing culture filtrates, VOC exposure chambers, and leaf-surface inoculation bioassays repeatedly show decreased germination percentages and aberrant germ tube growth in treated conidia (Hardiana, and Abadi, 2025). Germination suppression is primarily controlled by antibiotic metabolites like DAPG, which interfere with membrane integrity and metabolic processes critical for spore survival (Rhouma, 2025). VOCs are also involved centrally, as experiments on separated plates show that spores treated with bacterial volatiles germinate very poorly even when there is no physical contact (Kukreti *et al.*, 2024). Hydrolytic enzymes released into the environment in some instances or surfactant-like compounds have been suggested to cause the modification of permeability of the spore wall, while siderophone synthesis might indirectly limit iron availability, which is essential for germination of the spores (Jadhav *et al.,* 2017). Findings of several studies are in agreement on the fact that *P. fluorescens* inhibits the structural and metabolic integrity of *Alternaria* conidia, thus lowering the inoculum potential on the host surface (Alore *et al.,* 2017; Rhouma, 2025).

### Pot tests demonstrating reduced severity of disease and enhanced plant growth

Greenhouse and pot experiments have also repeatedly validated the effectiveness of *P. fluorescens* against early blight. Practices like seed coating, root drenching, foliar spraying, and talc- or peat-based formulations effectively minimized

Table 2. Studies on the Bio-efficacy of *P. fluorescens* and Related Biocontrol Agents Against Tomato Early Blight (*Alternaria solani*)

| **Study** | **Strain / material** | **Methods reported** | **Key findings** | **Reference** |
|---|---|---|---|---|
| Kaur *et al*., (Punjab Agricultural Univ. trial; ~2015–2016 report) | Talc formulation of *P. fluorescens* | Greenhouse/pot and field; talc seed/soil application | Talc formulation reduced early blight severity and improved yield components under experimental conditions. | Kaur *et al*., 2016 |
| Synergistic BCA study (*Bacillus* + *Pseudomonas*) (2023) | *B. subtilis* J3 + *P. fluorescens* J8 | *In vitro* inhibition, greenhouse pot experiments, mechanism probing | Consortium showed stronger inhibition and disease suppression than single strains; mechanisms included antibiosis and ISR. | Jia *et al*., 2023 |
| Field/large pot efficacy of commercial *P. fluorescens* product ("SUDO") (~2021) | Commercial *P. fluorescens* formulation | Field sprays, combination with fungicides | Two sprays of product reduced early blight; best results when integrated with fungicide sprays. | Raut *et al*., 2020 |
| Well-characterized biocontrol strains | Strains such as CHA0, Pf-5 | Gene expression, metabolite assays, rhizoplane colonization | DAPG and pyoluteorin are major contributors to antifungal activity; expression depends on rhizosphere conditions. | de Werra *et al*., 2008 |
| Academic Journal trial (AJMR / AJ) — comparative efficacy (2019–2022) | Native *Pseudomonas* spp. isolates | Greenhouse/pot, percent disease index comparisons | Treated plants had significantly lower disease severity vs control; supportive of local isolate use. | Alori *et al*., 2017 |

disease intensity, as supported by reduced percent disease indices, symptom onset delays, and reduced lesion sizes in comparison to the control groups (Kaur *et al*., 2016; Das *et al*., 2021) (Table 2). Besides, treated plants exhibited significant increases in plant height, biomass, and fruit production (Raut *et al*., 2020; Rhouma, 2025). Both disease control and growth promotion were augmented further when *P. fluorescens* was applied together with organic manure or co-applied with beneficial microbes like *Bacillus subtilis* (Bhattacharyya and Jha, 2012; Jia *et al*., 2023). These results strongly confirm the application of *P. fluorescens* as both a biocontrol and plant growth-promotion agent under semi-controlled conditions.

**Field Applications and Formulations**

**Field trials incorporating seed treatment, soil application, and foliar sprays**

Field trials under different agro-ecological conditions have established that *P. fluorescens* controls early blight of tomato through seed treatment, soil incorporation, and foliar application (Das *et al.,* 2021). Talc- or peat-based seed treatment enhances colonization of tomato roots during the initial stages of growth, thus maintaining lower disease incidence during later stages of the crop (Novinscak and Filion, 2020). Soil application, particularly with organic carriers like farmyard manure or vermicompost, ensures intensive rhizosphere colonization and suppresses the initial inoculum of the pathogen *A. solani* (Kaur *et al.,* 2016). Foliar application directly prevents the sporulation of a pathogen on the surface of leaves; repeated application of this bio-control agent delays the dynamics of this disease even under high disease pressure. The integrated application of seed treatment, soil application, and foliar sprays provides consistent and durable control of this disease, thus indicating that multi-site entry is a must to establish durable biocontrol efficacy (Preininger *et al.,* 2018).

Further, the development of effective formulations, namely powder and liquid forms, has improved the practical field deployment of *P. fluorescens*. Powder formulations, comprising carriers such as peat and talc, provide longer shelf life and are preferred for seed coating and soil conditioning, whereas liquid formulations are suitable for foliar sprays and drip irrigation systems, thus encouraging wider use among farmers (Hubballi *et al.,* 2023; Khan *et al.,* 2023). Synergistic integration, including *P. fluorescens* with other biocontrol agents like *Trichoderma* spp., neem extracts, and organic amendments, has resulted in increased disease suppression with a reduction in chemical fungicides by up to 50% without compromising the control efficacy (Jia *et al.,* 2023; Rana *et al.,* 2025). Such an approach, besides reducing environmental impact, sustains soil health, delays pathogen resistance, and improves crop yield and quality, thus reinforcing *P. fluorescens* as one of the foundations of sustainable integrated disease management programs for tomato cultivation (Hajji-Hedfi *et al.,* 2025).

**Efficacy compared to fungicides**

Field experiments have indicated that while *P. fluorescens* may not in all situations offer the immediate curative effect of synthetic fungicides, it has the capability to deliver long-lasting and eco-friendly disease control when used preventively or as part of an integrated control plan (Vessey, 2003; Hardiana and Abadi, 2025). Several trials revealed 40–60% decrease in the intensity of early blight using *P. fluorescens* only, compared to 70–90% control generally achieved with fungicides such as mancozeb or chlorothalonil. However, if *P. fluorescens* is blended with reduced fungicide schedules, the combined approach achieves the level of control comparable to that with full chemical protection, besides cutting chemical inputs (Hardiana and Abadi, 2025). Such interaction indicates that *P. fluorescens* is particularly valuable to use in integrated disease management (IDM) programs, in which it can slow down development of resistance to fungicides and reduce environmental impact.

**Commercial products with *P. fluorescens***

A number of commercial products of *P. fluorescens* are available on the market in powder and liquid forms, which can be easily used as seed coaters, soil conditioners, or foliar sprays (Hubballi *et al.,* 2023). Powder formulations, usually peat- or talc-based, give more shelf life and are found commonly in seed treatment and soil mixing products. Liquid formulations, usually cell suspensions or fermented broth concentrates, are better used in foliar spraying and drip irrigation systems (Khan *et al.,* 2023). In India, Government-sponsored biocontrol programs have formulated commercial products like *P. fluorescens* and liquid bioinoculants for control of tomato early blight and other fungal diseases

(Hegde and Vijaykumar, 2020). Other countries also market similar products with trade names highlighting plant growth promotion and biocontrol, which are frequently certified for organic cultivation. These products provide reliable field delivery of viable bacterial cells and metabolites, and facilitate adoption by farmers on larger acreages (Sharma, 2023).

## INTEGRATION WITH OTHER MANAGEMENT PRACTICES

Integrating it with other agricultural practices makes crop protection more effective and sustainable. If farmers integrate 2,4-DAPG–producing *P. fluorescens* with cultural, biological, and chemical approaches, they can obtain wider disease suppression. Such an integrative approach minimizes the development of resistance, lowers chemical application, and ensures long-term soil and plant well-being.

### Synergy with *Trichoderma* spp., neem extracts, and organic amendments

The cooperative application of *P. fluorescens* in combination with other biocontrol agents and plant products has been extensively researched to optimize disease suppression and crop health. In particular, co-inoculation of *P. fluorescens* with *Trichoderma harzianum* or *T. viride* has exhibited additive action against early blight of tomato in lowering its occurrence because the bacteria offer antibiotic production and colonization in the rhizosphere whereas *Trichoderma* offers mycoparasitism along with lytic enzymes (Lalhruaitluang *et al.,* 2022; Kumar *et al.,* 2023). Equally, neem extract integration (azadirachtin-based products) has shown inhibition of germination of *A. solani* conidia and diminished lesion growth, with evidence presenting improved efficacy when neem is sprayed in alternation with *P. fluorescens* (Almadiy *et al*., 2025). Organic inputs like farmyard manure, neem cake, and vermicompost enhance microbial activity in the soil, providing a favorable habitat for *P. fluorescens* development, and have been linked to larger disease severity reductions than when applied singly (Thakur, 2017). It points to the ability of *P. fluorescens* to complement both microbially and plant-derived products to favor integrated use in sustainable plant disease management.

### Potential for fungicide reduction

One of the most applied benefits of using *P. fluorescens* in tomato cultivation is its capacity to reduce fungicide applications by up to 50% without affecting disease suppression (Gade and Koche, 2022). A number of field trials have proven that tank-mixing or alternating with low mancozeb or chlorothalonil dosages can sustain disease suppression at full fungicide program levels, while cutting chemical application by 30–50% (Ons *et al.*, 2020). This reduction not only decreases the cost of production but also reduces environmental pollution and postpones the onset of fungicide resistance in *A. solani* populations (Islam *et al.*, 2024). Furthermore, consumer pressure for residue-free produce in the domestic market as well as export markets has stimulated adoption of integrated biofungicide–chemical programs where *P. fluorescens* serves as a biological buffer, providing sustainable disease management (Abd-Elsalam and Alghuthaymi, 2023). The use of *P. fluorescens* as part of fungicide reduction plans demonstrates its complementary role in ensuring ecological security and economic sustainability for farmers (Alattas *et al.*, 2024).

### Advances in Deciphering the Biocontrol Potential of *P. fluorescens*

The recent developments emphasize the role of CRISPR interference (CRISPRi) in the dissection of *P. fluorescens* regulatory biofilm networks. The recent advancements highlight the function of CRISPRi in the dissection of *P. fluorescens* regulatory biofilm networks. Strategic integration with known mechanistic understanding of LapA/LapD/LapG surface adhesion control and c-di-GMP signaling creates direct molecular connections among gene regulation, rhizosphere persistence, and pathogen suppression (Newelle *et al.,* 2009). CRISPRi is thus an approach to scaling up the identification of regulatory nodes for optimizing the performance of *P. fluorescens* as a biocontrol agent.

**Commercial Bioformulations of *P. fluorescens* for Sustainable Agriculture**

Several commercial biopesticide products based on *P. fluorescens* are available in India and globally, reflecting its established role in sustainable crop protection. In India, products like "Katyayani Striker *Pseudomonas fluorescens* Bio Fungicide Powder" and "MagicGro *Pseudomonas fluorescens*" are marketed for controlling fungal diseases, promoting plant growth, and improving soil health through eco-friendly modes of action (KO, 2025; OA, 2025). These formulations typically come as powders or liquids for seed treatment, soil application, and foliar sprays. Globally, formulations such as "Blight Ban A506" (used in North America) demonstrate *P. fluorescens* efficacy against various plant diseases, including fire blight and early blight in tomato, showcasing its versatile application in integrated disease management (Mehmood *et al.*, 2023). Commercial product success hinges on the bacterium’s ability to produce secondary metabolites that suppress pathogens, induce systemic resistance, and enhance nutrient uptake, making *P. fluorescens* a key biocontrol component in organic and conventional farming systems.

**Lacunae**

Despite the virtuous progress made in the biological control of tomato early blight using *P. fluorescens*, several critical gaps still prevail. Most of the available literature has focused largely on individual strains, with scant comprehensive evaluation across diverse agro-climatic regions, which limits information regarding strain adaptability and consistency of field efficacy. Moreover, very few attempts have been made to optimize formulations and delivery systems for enhanced rhizosphere colonization and sustained disease suppression under natural farming conditions. The integration of *P. fluorescens* with other biocontrol agents and botanicals, along with reduced fungicide applications, though promising, has been pursued without systematic evaluation to establish scalable and cost-effective protocols. Finally, mechanistic understanding of the pathways of induced systemic resistance in tomato plants remains incomplete for targeted enhancement of biocontrol efficacy.

**Novelty and Future Perspectives**

This review emphasizes the multifaceted role of Pseudomonas fluorescens as a biocontrol agent and underlines recent advances in formulation technologies and integrated applications that significantly enhance its field efficacy against tomato early blight. It presents new information on synergistic interactions with botanical extracts at reduced fungicide inputs, underpinning a shift toward more sustainable disease management approaches. Further research should be directed at large-scale, multi-location trials, exploration of strain-specific genomic traits linked to biocontrol efficiency, and precision delivery systems for optimized rhizosphere colonization. Furthermore, in-depth molecular understanding of plant-microbe-pathogen interactions-including induced systemic resistance pathways-will pave the way for designing next-generation bioformulations capable of resilient and environment-friendly crop protection.

*P. fluorescens* is a highly promising, sustainable, and environmentally friendly option for the biological control of tomato early blight that provides several modes of action such as antibiosis, induced systemic resistance, and nutrient and niche competition. Its compatibility with other biocontrol products, botanicals, and reduced fungicide programs makes it a critical element in integrated disease management programs. Nonetheless, to achieve its complete potential, it is urgently needed that large-scale, multi-site field validations of the product capture its performance in varied agro-climatic conditions. Farmer-level adoption bolstered by inexpensive formulations, policy support, and demonstration-based approaches will be critical in assisting *P. fluorescens* transition from experimental success to a real solution in routine tomato production.

**AUTHOR CONTRIBUTION**

Chanthini Kanagaraj Muthu-Pandian- wrote original manuscript, revised and edited.

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