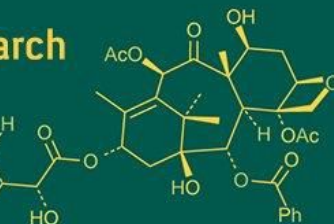


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Pooja Sangwan
Department of Plant
Pathology, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Rakesh Sangwan
Department of Plant
Pathology, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Vinod Kumar Malik
Department of Plant
Pathology, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Manjeet Singh
Department of Plant
Pathology, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Deepak Swami
Department of Plant
Pathology, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Corresponding Author:
Deepak Swami
Department of Plant
Pathology, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Evaluation of botanicals and bioagents for the management of early blight of tomato

Pooja Sangwan, Rakesh Sangwan, Vinod Kumar Malik, Manjeet Singh and Deepak Swami

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Abstract

Early blight caused by *Alternaria solani* is a major constraint to tomato production, leading to severe yield losses under favorable conditions. The present study evaluated the effectiveness of selected botanicals, bioagents and a chemical fungicide for the management of early blight of tomato under field conditions over three consecutive cropping seasons (2018-2019 to 2020-2021). Treatments included leaf extracts of Clerodendron and Bougainvillea, ginger rhizome extract, *Trichoderma harzianum*, *Trichoderma viride*, *Pseudomonas* spp., and mancozeb, along with an untreated control. The experiment was conducted in a randomized block design with three replications, and treatments were applied at disease initiation followed by three sprays at 15-day intervals. Disease intensity and yield per hectare were recorded and pooled analysis was performed. All treatments significantly reduced disease intensity and improved yield compared with the control. Among them, *Trichoderma harzianum* has been reported as the most effective, exhibiting the lowest pooled disease intensity along with the highest yield enhancement and is followed by *T. viride* and *Pseudomonas* spp. Mancozeb has also reported in disease suppression but it was less effective than *T. harzianum* in pooled analysis. Within the botanical treatments, Clerodendron leaf extract showed superior performance as compared with bougainvillea and ginger extracts, though botanicals were generally less effective than bioagents. The results of the study conclude that *Trichoderma harzianum* offers a sustainable and eco-friendly alternative to chemical fungicides and it provides effective control of early blight and enhancement of tomato productivity under field conditions.

Keywords: Early blight, *Alternaria solani*, *Trichoderma harzianum*, biological control, tomato yield

1. Introduction

Tomato (*Solanum lycopersicum* L.) belongs to the family *Solanaceae* and it ranks as the second most important vegetable crops worldwide after potato. It is consumed as fresh and as processed forms globally and is also referred to as the “poor man’s apple”. Fresh tomatoes global annual production is estimated at approximately 124.4 million tonnes and it also reflects its immense economic and dietary significance (Wang *et al.*, 2009) [58]. Due to its wide culinary application and high nutritional value, the consumer demand for tomatoes continuously rising, thereby necessitating its sustained increases in production to meet the current and future market requirements (Adhikari *et al.*, 2019) [5]. Tomatoes consist predominantly of water of around 95.3% and they are rich source of antioxidants, essential nutrients such as calcium and niacin that supports the metabolism of humans. A balanced supply of vitamins A, C and E are present in tomatoes which play a crucial role in maintaining overall human health. In recent years, the cultivation of tomatoes is expanded globally due to its adaptability to diverse agro-climatic conditions and also due to its nutritional attributes (Chourasiya *et al.*, 2013) [18].

In India, tomato is cultivated in approximately 737.19 thousand hectares with a total production of about 19,468.36 thousand tonnes and an average productivity of 26.41 t ha⁻¹. In Haryana, the crop occupies nearly 20.74 thousand hectares, producing around 350 thousand tonnes with a productivity of 16.88 t ha⁻¹ (Anonymous, 2025) [1]. Tomato is grown throughout the year in tropical and subtropical regions and is believed to have originated in tropical America, particularly the regions encompassing present-day Peru and Mexico. Major tomato-producing states in India include Gujarat, Bihar, Karnataka, Uttar Pradesh, Odisha, Andhra Pradesh, Maharashtra, Madhya Pradesh and West Bengal. Despite its economic

importance, tomato productivity is severely constrained by diseases, with early blight alone accounting for yield losses ranging from 48 to 80 per cent in countries such as India, Canada, the USA and Nigeria (Mathur & Shekhawat, 1986; Pandey *et al.*, 2003) ^[38, 40].

Tomato plants are susceptible to a wide array of biotic stresses including fungi, bacteria, viruses and nematodes (Imran *et al.*, 2022) ^[4]. Among these, fungal pathogens pose the greatest threat, causing substantial pre- and post-harvest losses at different stages of crop growth (Gondal *et al.*, 2012; Kolomiets *et al.*, 2017; Tomazoni *et al.*, 2017; González-Fernández *et al.*, 2021; Abo-Elyousr *et al.*, 2022) ^[25, 33, 54, 26, 4]. Major soil-borne diseases include wilt caused by *Rhizoctonia solani* and *Fusarium oxysporum* f. sp. *lycopersici*, and damping-off caused by *Pythium aphanidermatum*. Foliar diseases such as early blight caused by *Alternaria solani* or *A. alternata*, Septoria leaf spot (*Septoria lycopersici*) and late blight (*Phytophthora infestans*) are particularly destructive (Khaire *et al.*, 2021) ^[32]. Early blight, caused by *Alternaria solani* (Ellis & Martin) Jones & Grout, is considered one of the most serious fungal diseases affecting tomato, leading to marked deterioration in both fruit yield and quality (Abdel-Sayed, 2006; Abada *et al.*, 2008; Anand *et al.*, 2010) ^[3, 2, 7]. The pathogen is soil-borne but can also spread from alternative hosts through airborne conidia and rain splash. Infection of the host occurs either through direct penetration of tissues or via the wounds and it is followed by rapid sporulation of the pathogen and that facilitates secondary spread by the wind and water (Agrios, 2005) ^[6]. The disease can develop within a wide range of climatic conditions and the disease is most severe in areas where frequent rainfall, high relative humidity, dense plant canopies and prolonged leaf wetness occurs during the fruiting stage (Deepti & Nidhi, 2015) ^[21]. For the rapid disease development, the optimal temperatures conditions between 24 and 29 °C and coupled with high humidity is favorable (Peralta *et al.*, 2005) ^[42]. These environmental conditions, favors multiple infection cycles during a single cropping season and leads to epidemic outbreaks in these regions (Chaerani & Voorrips, 2006) ^[16]. The pathogen infects leaves, stems and fruits, causing leaf blight, collar rot and fruit rot, and causes severe damage at all growth stages of plant (Foolad *et al.*, 2000) ^[23]. As a result, early blight of tomato has become as a major limiting factor in its production and the yield losses has ranging from 15 to 100% is reported (Babu *et al.*, 2000; Pandey *et al.*, 2003) ^[10, 40].

Initial symptoms of the early blight disease appear as small, dark brown lesions on the lower and older leaves and these lesions gradually enlarge over time and often developing as characteristic concentric rings that produce a “bull’s-eye” appearance on the infected leaves. Under favorable environmental conditions, the disease progresses and the lesions coalesce and it leads to extensive leaf necrosis, defoliation and subsequent exposure of fruits to sunscald and secondary infections occurs (Kouyoumjian, 2007) ^[35]. The mode of reproduction in *Alternaria solani* is mainly asexual by producing dark-colored conidia and they lack a sexual stage. The primary hosts of *Alternaria solani* are tomato and potato, but it also infects plants such as cabbage, cucumber and zinnia (Schultz & French, 2009) ^[49]. The fungus produces darkly pigmented mycelium and a number of multicellular conidia having both transverse and longitudinal septa. Many *Alternaria* species are found

ubiquitous saprophytes and they produce phytotoxins, which exhibit specificity of host and it ultimately contributes to disease severity (Agrios, 2005) ^[6].

Chemical fungicides remain as one of the most widely used approaches for controlling the early blight disease, however, the excessive and repeated use has led to a serious concerns regarding environmental pollution, human health risks and the emergence of fungicide-resistant pathogen populations. These issues had gained a widespread global attention after the publication of *Silent Spring* (Carson, 1962) ^[15]. There are frequent reports regarding the development of resistance in *A. solani* against commonly used fungicides (Chaerani *et al.*, 2007; Ramkissoon *et al.*, 2016) ^[17, 46]. Although protectant fungicides such as mancozeb and captan have been recommended for disease management, their short residual activity on plant surfaces requires their repeated applications and it often resulted in inadequate disease control. Reduced sensitivity of *A. solani* to fungicides has been partly linked to the production of melanin by the fungus, which enhances pathogens survival and competitive ability under unfavorable environmental conditions (Bell & Wheeler, 1986) ^[12].

In response to these limitations, nowadays the attention has been shifted towards the development of sustainable and eco-friendly disease management methods. As a result, biological control has emerged as a viable alternative to chemical pesticides and it also supports organic farming systems and ultimately reducing ecological risks (Atia, 2005; Atia & Ahmed, 2011; Sarhan *et al.*, 2018; Imran *et al.*, 2022) ^[8, 9, 48, 4]. There are many plant extracts reported, that exhibits antimicrobial activity against early blight pathogens under both laboratory and field conditions, indicating their potential to be as a component in integrated disease management strategies (Nashwa & Sallam, 2011) ^[39]. Among microbial antagonists, *Trichoderma harzianum* has been well recognized for its ability to suppress *A. solani* through multiple mode of actions (Atia & Ahmed, 2011; Camlica & Tozlu, 2019) ^[14, 9]. Similarly, *Bacillus subtilis* and *Trichoderma* spp. isolates, applied either individually or in combination, have shown substantial reduction in early blight disease severity along with the improvement in plant health (Chowdappa *et al.*, 2013; Imran *et al.*, 2022) ^[19, 4]. These bioagents are regarded as environmentally safe and have been commercialized in the form of biopesticides, biofertilizers and soil conditioners (El-Fiki, 2017) ^[22]. Under these circumstances, the development and evaluation of biodegradable, eco-friendly plant-based and microbe-based pesticides have become essential. Consequently, the present investigation was undertaken to assess the efficacy of selected biocontrol agents and botanical extracts in managing early blight of tomato.

2. Materials and methods

2.1 Isolation and Maintenance of the Pathogen

Alternaria solani (Ellis and Martin) Jones and Grout, the causal agent of Early blight of tomato, was isolated from naturally infected leaf samples collected from Plant Pathology fields of CCSHAU, Hisar. The infected tissues were surface-sterilized with 1% sodium hypochlorite for 1 min, rinsed thrice in sterile distilled water, and aseptically placed on potato dextrose agar (PDA). Pure cultures were obtained through hyphal tip isolation and maintained on PDA at 25 ± 1 °C for subsequent experimentation.

2.2 Management of Early blight of tomato under Field Conditions (2018-2019 to 2020-2021)

Management studies on Early blight of tomato caused by *Alternaria solani* were conducted during three consecutive years, 2018-2019 to 2020-2021, under Research farm of Department of Plant Pathology. Tomato (*Solanum lycopersicum* L.) variety (Hisar Arun) was used for all consecutive three years to maintain uniformity in varietal response. Nursery beds were prepared and standard agronomic practices were followed. Seedlings were transplanted into field at 30-35 days after sowing.

The following treatments were imposed:

- **T1:** Clerodendron leaf extract @ 20%
- **T2:** Bougainvillea leaf extract @ 20%
- **T3:** Ginger rhizome extract @ 20%
- **T4:** *Trichoderma harzianum* @ 1×10^8 spores/ml
- **T5:** *Trichoderma viride* @ 1×10^8 spores/ml
- **T6:** *Pseudomonas* spp. @ 1×10^8 spores/ml
- **T7:** Control (Spray with plain water)

The experiment was conducted at the research farm of the Department of Plant Pathology using a randomized block design (RBD) with three replications, in which each treatment plot measured 3×2.7 m. The first spray of the respective treatments was applied at the initial appearance of disease symptoms, followed by three subsequent sprays at 15-day intervals. The same treatment schedule and experimental layout were maintained uniformly across three consecutive cropping seasons (2018-2019 to 2020-2021) to facilitate both year-wise comparison and pooled analysis. Observations were systematically recorded on per cent disease intensity and yield per hectare to evaluate treatment efficacy.

3. Results

Over the three consecutive seasons (2018-2019 to 2020-2021), all treatments significantly reduced disease intensity compared with the untreated control, which showed the highest pooled disease intensity (50.55%), and it indicates severe disease development in the absence of any management practices (Table 1, Fig. 2). Among all treatments, bioagents consistently performed better than other approaches with *Trichoderma harzianum* (T4) was the most effective and records the lowest pooled disease intensity (35.33%) and the highest pooled disease control (30.11%), followed by *Trichoderma viride* (T5) which showed 38.11% disease intensity and 24.61% control. This trend is strongly supported by recent studies, reporting that *Trichoderma* spp. effectively suppress soil-borne and foliar-borne pathogens through mechanisms such as

mycoparasitism, antibiosis, competition, and induction of systemic resistance in host plants (Harman *et al.*, 2021; Poveda *et al.*, 2023) [28, 43]. Considerable disease suppression has been found in the case of Mancozeb (T7) which shows 37.27% pooled disease intensity and 26.27% control which is consistent with recent reports describing mancozeb as an effective broad-spectrum protectant fungicide that continues to provide reliable disease reduction under field conditions. However, current concerns related to resistance development and environmental safety continue to limit its long-term reliance as an effective method of disease control. *Pseudomonas* spp. (T6) showed moderate efficacy and resulted in 42.11% pooled disease intensity and 16.70% control that is consistent with recent findings that fluorescent *Pseudomonas* strains can reduce disease intensity via production of siderophores, antibiotics, and induction of plant defense responses, but it often shows variable field performances as depending on strain used and the environmental conditions (Santoyo *et al.*, 2021; Backer *et al.*, 2022) [47, 11]. Clerodendron leaf extract (T1) was the most effective among botanical extracts and it showed 40.89% pooled disease intensity and 19.11% control, followed by Bougainvillea (T2) and ginger (T3), which corresponds with recent studies reporting that *Clerodendrum* species contain phenolics and flavonoids and they are having antifungal properties (Ghosh *et al.*, 2020) [24]. The least effective botanical was Ginger rhizome extract (T3) exhibiting 44.61% pooled disease intensity and 11.75% control, suggesting that despite reports of antifungal activity of gingerols and shogaols, many factors such as formulation, concentration, and field conditions strongly influence its efficacy (Singh & Rao, 2021; Sharma *et al.*, 2023) [53, 50]. Overall, these results reinforce current disease-management literature and indicates that bioagents, particularly *Trichoderma* spp., provide a more sustainable and effective disease control compared with botanicals and untreated conditions.



Fig. 1: Characteristic disease symptoms of Early blight on tomato

Table 1: Effect of different botanicals and bioagents on % disease intensity of tomato:

Treatments	2018-2019	2019-2020	2020-2021	% Disease Intensity Mean (Pooled)	% Disease control Mean (Pooled)
T ₁ = Clerodendron leaf extract @ 20%	41.05	38.20	43.42	40.89	19.11
T ₂ = Bougainvillea leaf extract @ 20%	46.20	39.50	42.30	42.67	15.59
T ₃ = Ginger rhizome extract @ 20%	45.25	41.10	47.48	44.61	11.75
T ₄ = <i>Trichoderma harzianum</i> @ 1×10^8 spores/ml	35.40	38.50	32.10	35.33	30.11
T ₅ = <i>Trichoderma viride</i> @ 1×10^8 spores/ml	38.75	35.20	40.39	38.11	24.61
T ₆ = <i>Pseudomonas</i> spp. @ 1×10^8 cfu/ml	42.90	38.60	44.83	42.11	16.70
T ₇ = Mancozeb 75% WG @ 0.1%	37.95	39.36	34.50	37.27	26.27
T ₈ = Control (Spray with plain water)	50.80	46.20	54.66	50.55	-
CD (5%)	6.78	6.32	4.59	5.89	-

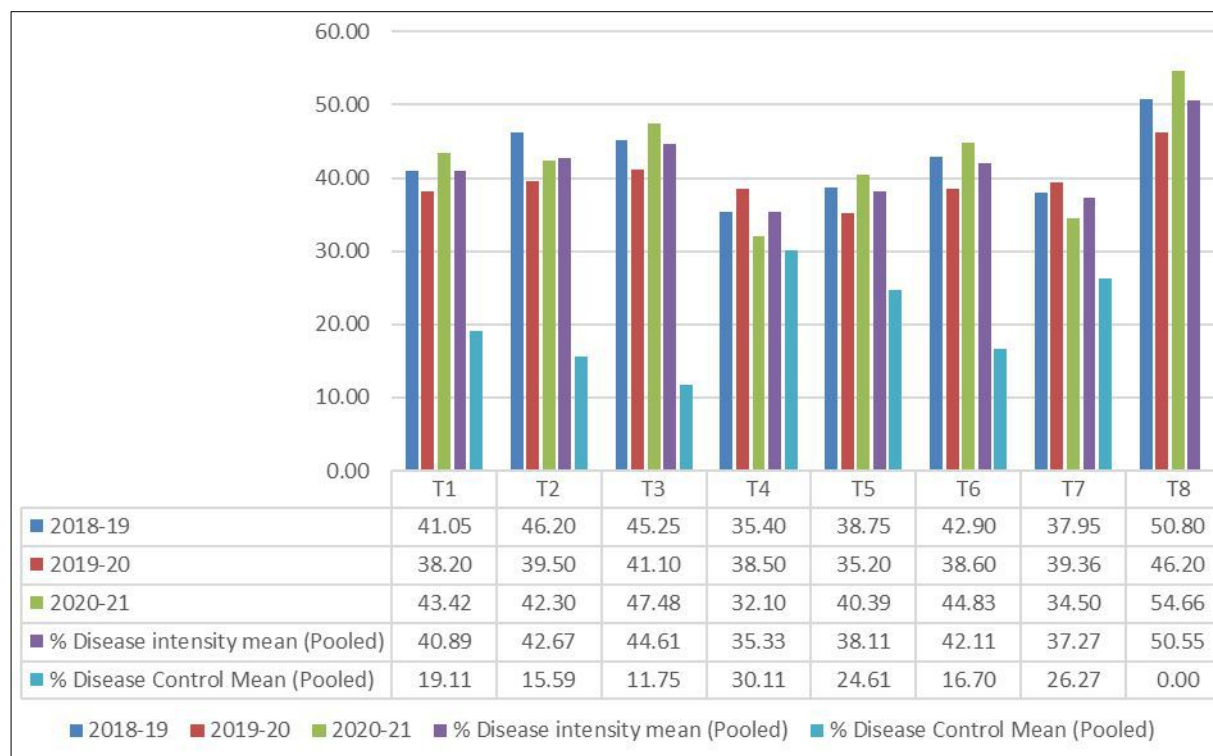


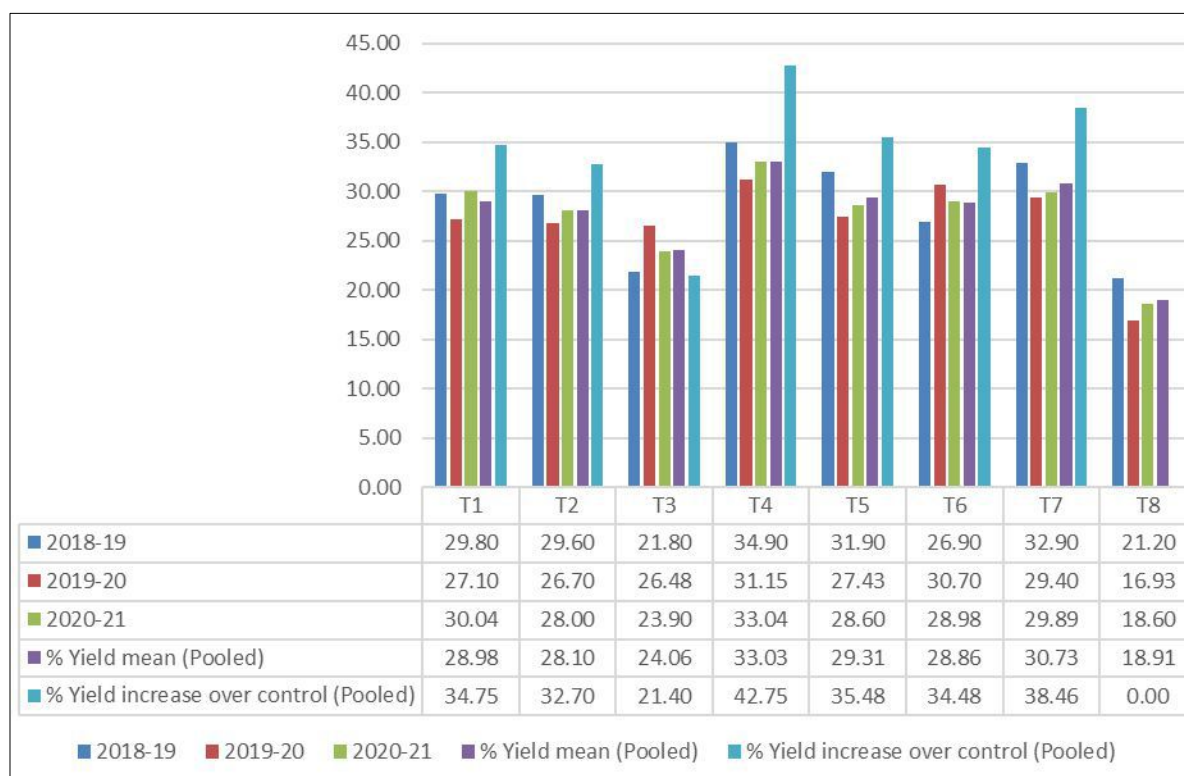
Fig 2: Effect of Various Botanicals and Bioagents on Percent Disease Intensity of Tomato Over Three Growing Seasons (2018-2021)''

Across the three consecutive seasons, yield response varied markedly among treatments, clearly reflecting the influence of disease management strategies on crop productivity (Table 2, Fig. 3). The untreated control consistently recorded with the lowest pooled mean yield (18.91%), indicating that under unmanaged conditions, yield formation is severely restricted due to the persistent disease pressure. In contrast, bio-based treatment has resulted in substantial yield enhancement. *Trichoderma harzianum* (T4) has produced the highest pooled mean yield (33.03%) with the greatest yield improvement (42.75%) and it suggests its dual role as a biocontrol agent and a plant growth promoting micro-organism. Recent ecological and agronomic studies also suggest that *Trichoderma* spp. enhance crop yield through improving root system development, facilitating nutrient solubilization, modulating phytohormone balance, and mitigation of biotic stress, that resulted in stable productivity under field conditions (Berg *et al.*, 2022; Vinale & Sivasithamparam, 2023) [12, 57]. *Trichoderma viride* (T5) also resulted in significant yield improvements (29.31% pooled mean; 35.48% increase), which is consistent with other findings that suggests *T. viride* improves plant vigor and biomass accumulation through rhizosphere colonisation with the stimulation of plant metabolic and growth-related pathways (Woo *et al.*, 2022) [59]. A relatively high pooled mean yield (30.73%) and yield increase (38.46%) has been observed in the case of chemical fungicide Mancozeb (T7), indicating the effective chemical disease control can improve crop productivity. However, recent ecological assessments suggest that such gains may

be for short-term when compared with biologically mediated yield stability (van Bruggen *et al.*, 2021; Zubrod *et al.*, 2022) [56, 60]. *Pseudomonas* spp. (T6) resulted in moderate yield enhancement (28.86% pooled mean; 34.48% increase), supporting recent findings that plant growth-promoting *Pseudomonas* strains enhance yield by improving nutrient availability, regulating ethylene levels, and improving plant stress tolerance, although their field performance is often influenced by environmental conditions (Compant *et al.*, 2021; Trivedi *et al.*, 2022) [20, 55]. Among botanical treatments, Clerodendron leaf extract (T1) resulted in the highest pooled mean yield (28.98%) and yield improvement (34.75%) and it suggests that plant performance is positively influenced by reduction in disease stress combined with bioactive secondary metabolites. Recent studies suggest that plant-derived extracts that are rich in phenolics and terpenoids can indirectly improve yield by suppressing pathogens and improving plant physiological efficiency (Isman, 2020; Pandey *et al.*, 2023) [30, 41]. Bougainvillea extract (T2) showed moderate yield improvement, whereas ginger rhizome extract (T3) was the least effective (24.06% pooled mean; 21.40% increase), despite growing evidence that ginger-based compounds can support plant health under controlled conditions, with variable outcomes are observed as per the varied field conditions. Overall, the yield results clearly demonstrate that biologically based disease management, particularly using *Trichoderma harzianum*, offers more consistent and ecologically sustainable yield enhancement than botanicals or untreated control.

Table 2: Effect of different botanicals and bioagents on yield of tomato

Treatments	2018-2019	2019-2020	2020-2021	% Yield Mean (Pooled)	% Yield increase over control (Pooled)
T ₁ = Clerodendron leaf extract @ 20%	29.80	27.10	30.04	28.98	34.75
T ₂ = Bougainvillea leaf extract @ 20%	29.60	26.70	28.00	28.10	32.70
T ₃ = Ginger rhizome extract @ 20%	21.80	26.48	23.90	24.06	21.40
T ₄ = <i>Trichoderma harzianum</i> @ 1×10 ⁸ spores/ml	34.90	31.15	33.04	33.03	42.75
T ₅ = <i>Trichoderma viride</i> @ 1×10 ⁸ spores/ml	31.90	27.43	28.60	29.31	35.48
T ₆ = <i>Pseudomonas</i> spp. @ 1×10 ⁸ cfu/ml	26.90	30.70	28.98	28.86	34.48
T ₇ = Mancozeb 75% WG @ 0.1%	32.90	29.40	29.89	30.73	38.46
T ₈ = Control (Spray with plain water)	21.20	16.93	18.60	18.91	-
CD (5%)	6.179	6.38	1.601	4.72	-

**Fig 3:** Effect of Various Botanicals and Bioagents on Tomato Yield Over Three Growing Seasons (2018-2021)

4. Discussion

The present investigation clearly suggests that the application of bioagents and botanicals has significantly influenced the development of early blight disease and the yield of tomato across three consecutive cropping seasons. The consistent reduction in disease intensity with the improvement in yield observed over three consecutive cropping seasons highlights the reliability and reproducibility of the treatments under field conditions. In contrast, the untreated control consistently recorded the highest disease intensity and the lowest yield, suggesting the severe yield losses caused by *Alternaria solani* in the absence of management, an outcome widely reported in earlier studies on early blight epidemics. Among all the treatments, *Trichoderma harzianum* has been reported to be the most effective in suppressing disease intensity and enhancing the crop yield. Its superior performance may be attributed to its multiple mode of actions such as mycoparasitism, competition for nutrients and space, secretion of antifungal metabolites, and induction of systemic resistance in host plants. These actions not only reduce pathogen growth and development but also improve plant vigor that ultimately leads to enhancement in overall

yield. Similar observations have also been reported by several other researchers who found that significant reduction of early blight and improvement in tomato productivity after the applications of *Trichoderma* under field conditions. The effectiveness of *T. viride*, that is slightly lower as compared with the *T. harzianum*, also supports the role of *Trichoderma* spp. as a reliable biocontrol agents capable of providing sustainable management for early blight disease. *Pseudomonas* spp. showed moderate but consistent disease suppression and improvements in yield in the present study, and it also aligns with earlier reports that fluorescent *Pseudomonas* strains suppress foliar pathogens through siderophore production, antibiotic secretion, and stimulation of plant defense responses. The relatively lower efficacy compared with *Trichoderma* may be due to environmental conditions, strain-specific variability, and differences in rhizosphere colonization by *Pseudomonas* spp. Nevertheless, the observed yield improvements indicate that *Pseudomonas* spp. can play a supportive role in integrated disease management strategies.

Chemical control using mancozeb resulted in substantial disease reduction and yield improvement, that confirms its

effectiveness as a broad-spectrum protectant fungicide. However, its performance was inferior when compared to *T. harzianum* in terms of pooled disease control, and its repeated applications raise concerns regarding environmental safety and resistance development in pathogen. The comparatively lower persistence of mancozeb on foliage and the melanin-mediated tolerance of *A. solani* may explain well the incomplete disease suppression observed, as reported in earlier studies. Among botanicals, Clerodendron leaf extract exhibited the highest efficacy in reducing disease intensity and improving crop yield and is followed by Bougainvillea and ginger extracts. The antifungal activity of Clerodendron is linked to the presence of phenolic compounds, flavonoids, and other bioactive metabolites that inhibits pathogen growth and reduce disease progression. Although ginger rhizome extract is well known for its antifungal properties but its relatively lower effectiveness under field conditions suggests the influence of environmental factors, rapid degradation of active compounds, and formulation limitations may reduce its practical utility. The positive correlation between reduced disease intensity and increased yield observed in the present study confirms that effective disease management directly contributes to improved crop productivity. Overall, the results strongly support the integration of bioagents, particularly *Trichoderma harzianum*, and selected botanicals as eco-friendly alternatives to reliance on chemical fungicides. Such strategies reduce disease pressure, enhance yield stability, and contribute to sustainable tomato production with lower environmental risk.

5. Conclusion

The present study has showed that early blight of tomato caused by *Alternaria solani* can be effectively managed through using bioagents and botanicals under field conditions. Across three consecutive seasons, all treatments significantly reduced disease intensity and increased yield as compared with the untreated control, confirming the severe yield losses associated with unmanaged early blight. Among the treatments, *Trichoderma harzianum* was consistently the most effective and it records the lowest disease intensity and the highest yield improvement, followed by *T. viride* and *Pseudomonas* spp. Chemical control with mancozeb also reduced disease and enhanced yield but was comparatively less effective than *T. harzianum* and raises concerns related to sustainability. Among botanicals, Clerodendron leaf extract performed better than Bougainvillea and ginger extracts, though botanicals were generally less effective than bioagents. Overall, the results highlight the that, *Trichoderma harzianum* can be used as an eco-friendly, sustainable alternative to chemical fungicides for the management of early blight and for improving tomato productivity.

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