Research Article

Exploration of Epidemiological Factors for the Management of Early Blight of Tomato

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Abstract | Early blight, caused by *Alternaria solani*, is a destructive disease of tomatoes with significant yield and quality losses. Twelve lines/cultivars (Bonita, Lima, Zarnitza, Legend, Rockey, Nagina, Saad-49, Pakit, Nadir, Naqeeb, Rio Grande, and Roma) were screened for resistance potential. None of the cultivars were found to be resistant while Legend, Saad-49, Rocky, and Bonita were found moderately resistant. To evaluate the efficacy of fungicides against early blight, fungicides were applied with the help of an atomizer, three times at seven days intervals at their recommended doses. The fungicide "Santri" was found to be the most effective, followed by "Amistar Top". "Cabrio Top" was not particularly effective in combating the infection. The fungicide "Santri", along with the variety "Rio grande" exhibited the minimum disease severity of 7.51% followed by the combination of fungicide "Santri" along with variety "Naqeeb" which showed a disease severity of 15.10%. The maximum disease severity was observed in variety "Naqeeb" was used as "Control", which showed a disease severity of 82.77%. Epidemiological studies showed that the disease severity negatively correlated with the maximum and minimum temperatures (°C) but positively correlated with relative humidity (%). The study would provide a base to decide on the proper combination of germplasm, fungicides keeping in view the weather parameters to fight against early blight disease.

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Introduction

Tomato (*Lycopersicon esculentum* Mill.) belongs to the *Solanaceae* family and is one of the most important and popular vegetables in Pakistan (Yitayih *et al*., 2020). Its worldwide production is estimated at 161.7 million metric tons and has an estimated value of USD 59 billion (Batool *et al*., 2025). Tomatoes are rich in vitamins (A, B, C, K), minerals (Fe, P, K Ca, Zn, Mg), essential amino acids, sugars, low-calorie dietary fibers, and many anti-oxidants (Bauchet *et al*., 2017). In another study, lycopene in tomatoes was shown to inhibit the growth and spread of cancer cells in lung cancer by reducing oxidative stress and inducing apoptosis (Szabo *et al*., 2018). Unfortunately, the average yield per hectare in Pakistan is very low (9.6-10.5 tons) ranking Pakistan 142nd globally in yield (Anjum *et al*., 2020). The low yield may be due to any of the various tomato diseases caused by fungi, bacteria, viruses, and nematodes known all over the world (Gupta *et al*., 2020).

Among the fungal diseases, early blight disease, caused by *Alternaria solani*, is a particularly destructive disease on tomatoes and other solanaceous crops (Riaz *et al*., 2021). The airborne, soil-inhabiting pathogen can attack at all stages of plant growth and thereby affect all above-ground parts of tomatoes, including the leaf, stem, and fruit (Mphahlele *et al*., 2020). This disease is the most destructive with a 35% to 78% reduction in yield incurring losses at both pre and post-harvest stages (Jindo *et al*., 2021). In some studies, annual economic losses in tomatoes due to early blight have been estimated as 79% (Adhikari *et al*., 2017).

Early blight produces brown leathery areas at infection sites with dark concentric circles (Adhikari *et al*., 2017). Considerable variation in physiology, morphology, and virulence variation has been reported within and among *Alternaria* species (Al-lami *et al*., 2020). Vagelas (2024) stated that a study on tomato early blight disease reveals that Fibonacci numbers frequently appear in the lesion patterns of the fungus that shows Fibonacci numbers optimizes resource allocation for fungal mycelial growth within plant tissue and enhances reproductive success of the fungus. At present, EB is primarily managed by the application of various fungicides applied at 7-10 days intervals (Adhikari *et al*., 2017). Even with this large number of sprays damage reduction is not always achieved, due to the high susceptibility of currently cultivated genotypes and longer prevalence of favorable conditions to the disease (Holm *et al*., 2003). In addition, resistance to fungicides has also been reported in *A. solani* due to high genetic variability among isolates (Pasche *et al*., 2004) which could also compromise host genetic resistance (van der Waals *et al*., 2004). Increased concern regarding the use of fungicides and other pesticides requires the implementation of alternative disease control practices. To combat EB and reduce losses in tomatoes, the development of resistant cultivars can be a most effective and sustainable control measure (Adhikari *et al*., 2017). However, to date, no EB-resistant tomato genotypes are grown in Pakistan (Akhtar *et al*., 2019).

Resistant varieties increase the effect of fungicides, enhance fungicide efficacy and extend spray intervals and manage disease (Shamurailatpam and Kumar, 2020). Early blight of tomato can be controlled through the selective use of chemical fungicides. Primary methods of controlling *Alternaria* leaf blight include preventing long periods of wetness on the host surface, field scouting, cultural practices, and developing host resistance (Kirk *et al*., 2005). Cultivation of resistant varieties is the ultimate control of this disease. Different fungicides for combating early blight disease are available on the market. Azoxystrobin, ziram, pyraclostrobin, mancozeb, copper products, and potassium bicarbonate are among the fungicides used against early blight (Shamurailatpam and Kumar, 2020). The early blight of tomato is considered the most devastating disease affecting both pre and postharvest stages leading to a drop in yields of 35 to 78% (Bais *et al*., 2019). The use of fungicides is considered the most effective approach for controlling early blight, as stated by several workers (Sarfraz *et al*., 2018). The fungicide mancozeb has been widely used for the last two decades to control early blight, reducing the severity of the disease and enhancing tomato yield (Bais *et al*., 2019). Farooq *et al*. (2019) stated that hexaconazole and pyraclostrobin are the best fungicides to reduce the occurrence of the disease by inhibiting maximum growth of mycelium. According to Bais *et al*. (2019), sanchar followed by mancozeb and carbendazim were superior for controlling the disease. Rani *et al*. (2017) reported that tebuconazole and difenoconazole were the most effective fungicides in controlling early blight of tomato.

Ecological and environmental conditions significantly influence the outcome of the interaction between Alternaria and its tomato host (Kumar, 2017). Environmental conditions favor early blight development. This disease progresses quickly when environmental conditions alternate between wet and dry weather (Parmar *et al*., 2020). *Alternaria* spores, humidity, and temperature are the main factors that contribute to the occurrence of this disease (Gupta *et* al., 2020). This disease can spread rapidly in conducive environments due to its polycyclic infection and short disease cycle which may lead to 80% yield losses (Kaur *et al*., 2020). Many scientists correlated meteorological variables with the abundance of airborne spores in the atmosphere of climatically different areas (Escuredo *et al*., 2011). Pathogen infection and conidia germination can be intensified when relative humidity is high (Gullino *et al*., 2020).

Concerning the importance of tomatoes in the domestic, medical and commercial sectors, new research is needed to be made for the well-being of the tomato crop. The current study was planned to find out new management strategies by testing the newly available fungicides in the market.

- The objectives of the current studies were:
- To screen tomato germplasm for the source of resistance against the early blight of tomato
- To evaluate the efficacy of fungicides for managing the early blight disease of tomato under field conditions
- To assess the impact of environmental conditions on the development of the pathogen and disease

Materials and Methods

Collection of available tomato germplasm

The tomato germplasm was collected from Vegetable Research Institute (VRI), Ayub Agricultural Research Institute (AARI), Faisalabad, and Institute of Horticulture Sciences (IHS), University of Agriculture, Faisalabad (Pakistan).

Table 1: *Tomato germplasm used for screening of resistance source against the early blight of tomato*

Sr. #	Varieties	Name
1	V_1	Bonita
2	V_2	Lima
3	V_3	Zarnitza
4	V_4	Legend
5	V_5	Rockey
6	V_6	Nagina
7	V_7	Saad-49
8	V_8	Pakit
9	V_9	Nadir
10	V_{10}	Naqeeb
11	V_{11}	Rio grande
12	V_{12}	Roma

Experimental site and establishment of tomato crop under field condition

For the establishment of the tomato crop under field conditions, the nursery was harvested so that the plant could withstand the field environment with as little shock as possible. The field land was prepared before transplanting by adding well-rotted farmyard manure for maintaining good physicochemical conditions and fertility status of the soil seedbeds were prepared for transplanting the seedlings after plowing and rotavating. After that, the land was leveled thoroughly for uniform water distribution. Seedlings of 15-25 cm tall that had 3-6 true leaves were transplanted. Recommended fertilizers and irrigation were applied for better growth of the tomato plant and also to overcome the shock. Proper hoeing and weeding were done in order to minimize the competition between tomato plants and weeds for nutrients and water. The whole experimentation was conducted in the research area of the Department of Plant Pathology, University of Agriculture, Faisalabad (Pakistan).

Screening of tomato germplasm for resistance source

All of the twelve varieties (described in Table 1) were sown for evaluating the response of tomato lines/cultivars against the early blight of tomato. The varieties were sown using the recommended augmented design for screening purposes. About forty plants of each tomato line/cultivar were transplanted for this purpose.

Evaluation of the efficacy of fungicides

Efficacy of fungicides against Alternaria solani under field conditions.

The fungicides were applied, with the help of an atomizer, three times at 7 days intervals at their recommended doses (Table 2).

Table 2: *Trade names of applied fungicides along with their active ingredients and percentage*

Sr. #	Trade name	Active ingredient	Percentage	Dose
1	Manco-zeb	Mancozeb	80.0%	1g/L
2	Santri	Mancozeb metalaxyl	64.0%8.00%	1g/L
3	Amistar top	Azoxystrobin dif-enoconazole	18.2%11.4%	5ml/L
4	Cabrio top	Pyraclostrobin metiram	5.00%55.0%	1g/L
5	Untreated	Fresh Water	-	

Efficacy of fungicides on plant growth attributes under field conditions

The effect of three applications on plant parameters was also observed in this study to assess the positive or negative effects of fungicides on plants and on their yield. For this purpose, the following parameters were taken into account.

- Plant height (cm)
- Number of fruits per plant
- Yield per plant (g)
- Fresh weight of plant (g)
- Average weight of nine tomato fruits

Characterization of environmental effect on the development of disease

The study of epidemiology is crucial both for understanding how diseases originate and for treating them. The current study was designed to determine how environmental variables affect disease development. The Department of Crop Physiology UAF's website provided meteorological information, such as the highest and lowest temperatures for the day, relative humidity, and sunlight. To determine how environmental variables affect disease severity, Pearson correlation and regression studies were performed.

Experimental designs and data collection

The selection of experimental designs is of crucial importance in conducting an experiment. In the current study, three experiments were conducted. The first experiment was regarding the evaluation of disease resistance in tomato germplasm. This recommended experimental design for this study was "Augmented design" with three replications. The second and third experiments were related to the evaluation of applied fungicides' efficacy against the disease as well as efficacy on the plant growth parameters. The adopted experimental design for these two experiments was "Randomized Complete Block Design" (RCBD) with three blocks/replications.

$$\text{Disease incidence (\%)} = \frac{\text{Number of diseased Plants}}{\text{Total number of observed Plants}} \times 100$$

$$\text{Disease severity(\%)} = \frac{\text{Number of infected leaves per plant}}{\text{Total number of leaves per plant}} \times 100$$

The cultivars were categorized according to disease rating scale devised by Pandey *et al.* (2003).

Disease rating scale for early blight disease

Rating	Reaction	Disease severity (%)
0	Free from infection	0
1	< 10% surface area covering leaf, stem and fruit infected by early blight	1-9
2	Foliage of plant covered with a few isolated spot	11-25%
3	Many spot coalesced on the fruit, covering surface area of plant	26-50%
4	Area of the plants infected fruits also infected at peduncle end defoliation and blightening started. Sunken lesions with prominent concentric ring on stem, petioles and fruits	51-75%
5	Area of plant part blighted, severe lesion on stem and fruit rotting on peduncle end	> 75%

Statistical data analysis

All the collected data were statistically analyzed with the help of statistical software named "Statistix 8.1". Fischer's analysis of variance technique was adopted to find out the significance of collected data at a 5% level of significance (Steel *et al.*, 1997). For pairwise comparison of treatment's means, an all-pairwise comparison test was used. Regression and correlation analyses were also carried out between environmental data and disease severity (%) data followed by the calculation of the coefficient of determination (R^2).

Results

Screening of tomato varieties against early blight of tomato for resistance source

Under field conditions, none among the screened cultivars was found as immune, highly resistant and resistant, according to disease rating scale (Table 3). The cultivars (Legend, Saad-49, Rocky, and Bonita) were regarded as moderately resistant, with 26.17%, 29.96%, 33.83%, and 37.32%, disease severity respectively. The varieties "Lima" and "Zarnitza" were found to be moderately susceptible and susceptible, which exhibited 50.71% and 66.81% disease severity, respectively. All other cultivars (Pakit, Riogrande, Nagina, Roma, Naqeeb, and Nadir), were highly susceptible, with 74.23%, 77.37%, 80.26%, 82.38%, 84.84%, and 87.20%, disease severity, respectively (Table 3).

Table 3: *Response of tomato varieties against early blight disease of tomatoes*

Sr. No.	Scales	Varieties	Disease Severity (%)	Varietal response
1	0	-	-	Immune
2	00.1-10.0	-	-	Highly resistant
3	10.1-25.0	-	-	Resistant
4	25.1-40.0	Legend saad-49 rocky bonita	26.17 29.96 33.83 37.32	Moderately resistant
5	40.1-55.0	Lima	50.71	Moderately susceptible
6	55.1-70.0	Zarnitza	66.81	Susceptible
7	>70.0	Pakit ri-ogrande nagina roma naqeeb nadir	74.23 77.37 80.26 82.3884.84 87.20	Highly susceptible

Where; I = Immune; HR = Highly Resistant; R = Resistant; MR = Moderately Resistant; MS = Moderately Susceptible; S = Susceptible; HS = Highly Susceptible

Table 4: *Analysis of variance for disease severity (%) after application of treatments*

Source	DF	SS	MS	F	P
Replications	2	4.1	2.05		
Treatments	4	27672.9	6918.23	1176.33	0.0000**
Varieties	3	2452.9	817.62	139.02	0.0000**
Treatments x Varieties	12	677.0	56.42	9.59	0.0000**
Error	38	223.5	5.88		
Total	59	31030.4			

*** Highly Significant p-value < 0.01*
** Significant p-Value < 0.05*
NS Non Significant p-Value > 0.05

Effect of fungicides on disease intensity (%)

Applied fungicides were highly effective role in decreasing the disease intensity (%) (incidence and severity) to a different extent. The interactive effect of treatments and varieties along with their individual effect were highly significant. This exhibited that the means of at least one treatment and variety were different from others according to Tukey HSD all pairwise comparison test (Table 4).

F-value of varieties indicates the highly significant effect on disease severity level when compared with P value. Cultivars having moderate level of resistance show lowest level of disease indices at ($p < 0.05$) compared to susceptible cultivars. These explanations describe that genetic variation among screened cultivars have a vital role in resistance, not just random variability. F-values for treatments ascertain their efficacy for disease management when compared to P-values.

The pairwise comparison test after ANOVA revealed that all the treatment means were statistically different from each other. Fungicide "Santri" performed best among the applied fungicides with an average disease severity 13.88% that was minimum. The 2nd most effective fungicide was "Amistar Top" that exhibited 29.47% disease severity followed by "Mancozeb" and "Cabrio Top" which presented a disease severity of 51.72% and 58.57%, respectively. On the other hand, the maximum disease severity (74.48%) was depicted by control treatment after the 3rd application of treatments (Table 5).

Table 5: *Tukey HSD All-Pairwise comparisons test of disease intensity (%) after application of treatments*

Treatments	Mean disease severity (%)	Mean disease incidence (%)
Control	74.48 a	91.58 a
Cabrio top	58.57 b	74.04 b
Mancozeb	51.72 c	61.34 c
Amistar top	29.47 d	34.93 d
Santri	13.88 e	18.37 e
Alpha = 0.05		
Tukey HSD-Value = 2.8352		

Table 6: *Tukey HSD All-Pairwise comparisons test of plant parameters for treatments*

Treatments	Plant Height (cm)	No. of fruits/ plant	Yield/ plant	Fresh weight (g)	Average weight
Santri	95.353 a	36.833 a	1185.2 a	843.68 a	44.87 a
Amistar Top	86.498 b	31.333 b	960.2 b	770.38 b	38.09 b
Mancozeb	70.062 c	27.333 c	723.1 c	558.89 c	30.16 c
Cabrio Top	62.386 d	20.167 d	582.2 d	427.44 d	24.52 d
Control	50.223 e	17.000 e	427.3 e	361.11 e	20.39 e
Alpha = 0.05					
Tukey HSD-Value = 2.7456					

Effects of fungicides on plant parameters

The effect of fungicides were checked on plant height (cm), number of fruits per plant, yield per plant (g), fresh weight of plant (g), averaged weight of nine tomato fruits (g).

The pairwise comparison test after ANOVA revealed that fungicide "Santri" performed best and exhibited maximum plant height of 95.35cm. The second most effect fungicide was "Amistar Top" that exhibited the plant height of 86.49cm followed by "Mancozeb" and "Cabrio Top" which presented a plant height of 70.06cm and 62.39cm (Table 6).

Effect of environmental factors on disease development

The onset of early tomato blight is significantly influenced by epidemiological variables. Disease development is influenced either directly or indirectly in all areas where the tomatoes are grown. The pathogen *Alternaria solani* severely harms the tomato crop when the weather is ideal. The current experiment was also carried out with these facts in mind, and the findings for disease development in connection to environment are shown in Table 7.

Table 7: *Correlations (Pearson) between environmental factors and Disease severity (%) of tomato varieties*

	Nadir	Naqeeb	Roma	Ri-ogrande
Naqeeb P-Value	0.9740 0.0000**			
Roma P-Value	0.9746 0.0000**	0.9645 0.0000**		
Riogrande P-Value	0.9617 0.0000**	0.9739 0.0000**	0.9635 0.0000**	
Max. Tempera-ture P-Value	-0.9729 0.0000**	-0.9740 0.0000**	-0.9627 0.0000**	-0.9867 0.0000**
Min. Tempera-ture P-Value	-0.9802 0.0000**	-0.9685 0.0000**	-0.9857 0.0000**	-0.9769 0.0000**
Relative Hu-midity P-Value	0.6103 0.0351*	0.6795 0.0151*	0.4888 0.0406*	0.6522 0.0215*
Sunshine P-Value	-0.5138 0.0875[NS]	-0.5714 0.0523[NS]	-0.3650 0.2433[NS]	-0.4620 0.1305[NS]

Effect of environmental conditions on disease development

The effect of maximum temperature, minimum temperature (°C), relative humidity (%), sunshine on disease development under field conditions was described in Table 7. The correlation analyses for each variety revealed that a negative correlation was found between maximum and minimum temperature and disease severity (%) in case of each variety. The correlation coefficients for Nadir, Naqeeb, Roma, and Riogrande were -0.97 (-0.98), -0.97 (-0.96), -0.96 (-0.98), and -0.98 (-0.97) respectively at 5 % level of significance and $p < 0.01$. The regression analysis revealed that the disease development was highly and significantly affected by the maximum and minimum temperatures. There was significantly positive relationship between disease severity and relative humidity while a non-significant and negative relationship was found for sunshine.

Discussion

Resistance as a disease management tool

Identifying resistance source in plant germplasm is the most effective way for controlling plant diseases. Cultivating tolerant varieties can significantly reduce yield losses and suppress pathogen infection. These results were in line with Akhtar *et al.* (2019) who conducted experiments to identify the resistant tomato cultivars against the early blight of tomato caused by *Alternaria solani* and found only one genotype '21396' as resistant among 401 cultivars. Roy *et al.* (2019) screened the five tomato varieties against *A. solani* and PDI value indicates the highest percentage of disease incidence (57.77%) was recorded in BARI Tomato-9, followed by BARI Tomato-2 (55.55%), BARI Tomato-3 (40.55%), BARI Tomato-15 (35.55%) and BARI Tomato-7 (31.11%).

There was a varied response of tomato genotypes against early blight disease under field conditions where screening was done by natural inoculum of *Alternaria solani*. The varieties rated as resistant according to disease rating scale possess genetic tolerance potential against early blight (Yerasu *et al.*, 2020). Cultivars with resistant response may be a good source of obtaining genes of resistance that could be utilized in breeding for new genotypes. Genotypes depicting highest disease intensity was regarded as susceptible that could not be recommended for general cultivation at the farmer's level. Tomato entries with potential resistance source and significant growth and development feature should be conserved for future breeding programs to maintain sustainable cultivation (Fatima *et al.*, 2024).

The current study aligns with various previous experiments on tomato early blight disease; varieties with resistance potential which share closely related wild ancestors which could be explored for potential sources of additional resistance genes (Panthee *et al*., 2024). Some researchers backed the conventional screening experiments with extensive molecular studies; among resistant lines ethylene response factors and genes activated through jasmonic acid (JA) were identified after transcriptome analyses, these factors boost the defense signals against pathogenic attack (Tominello-Ramirez *et al*., 2024). In some of the previous studies higher level of resistance were observed in cultivars that may be the varied level of virulence in *A. solani* isolates, favorable environmental conditions and their coincidence for disease development or seed quality and cultural practices opted. The outcomes of the current experiment showed the resistance potential in available germplasm which could be utilized for screening on multiple field conditions to identify durable resistance.

Future breeding programs would be based upon field screening followed by molecular studies leading to sustainable crop improvement (Goutam *et al*., 2024). A pool of genes for resistance and locus of resistance could be marked through marker-assisted selection (MAS) and gene regulatory network analysis (Kumari *et al*., 2024). Eventually, the incorporation of resistant genotypes into breeding programs improves the efficiency of the tomato cultivation against early blight but also reduces the usage of fungicides. (Ahmed *et al*., 2024).

Effect of fungicides on disease management

The efficacy of different fungicides was also evaluated against the early blight of tomatoes that reduced disease intensity to a considerable level. Fungicides i.e. Metalaxyl, Mancozeb, Azoxystrobin, Difenoconazole, Pyraclostrobin were used against early blight which not only reduced disease but also improved plant health.

Fungicides are a quick and efficient method of early blight disease management in tomato that is evident from prior studies, more than 60% disease control was recorded by using different formulations of fungicides (Sharma *et al*., 2018). Effectiveness of fungicides was assessed from the limitation of lesions on foliage and reduced defoliation; fungicides have significantly inhibited the spore germination and mycelial development thus protected the photosynthetic area of leaves and increased the plant vitality (Egel *et al*., 2019).

Fungicides have certain mode of action that not only inhibits the growth of pathogen but also positively impacts plant growth and development. Growth parameters i.e. plant height, number of leaves, stem diameter etc. enhanced in fungicide treated fields which contributed towards increase in qualitative and quantitative yields of the plants (Farooq *et al*., 2019). There was significant increase in tomato yields after the application of Azoxystrobin and Tebuconazole apart from decrease in early blight disease intensity; that suggested the dual role of fungicides for plant health and physiology i.e. nutrient uptake and tolerance against stresses (Ali, 2025). Azoxystrobin has a systemic mode of action against *Alternaria solani*; it is absorbed through foliage and translocate within the plant system for its protective and curative roles. Azoxystrobin blocks electron transfer at Qo site of cytochrome b after being exposed to the fungal mitochondria and disrupts respiration. Inhibition of respiration leads to limited energy generation at cell site causing death (Erdurmus *et al*., 2025).

A reduction of 37% was recorded in growth of *A. solani* while applied at 0.1% concentration only under laboratory conditions indicating its efficiency among other tested fungicides against the pathogen (Deshmukh *et al*., 2020). In our study, azoxystrobin proved to be an effective fungicide; however a previous research in Kenya inferred that repeated use of azoxystrobin developed resistance in *A. solani* because of mutations and disease control was reduced up to 60% (Nuwamanya *et al*., 2022). As fungicides have varied modes of action, in case of combinations of azoxystrobin and tebuconazole there was significant reduction in early blight severity and quantitative yield was improved (Hossain and Mohanta, 2025). Mancozeb was ranked among the most effective fungicides in current study, it inactivates sulfhydryl (SH) groups in fungal proteins; inhibits spore germination by disrupting lipid metabolism, respiration and ATP production (Sidgel *et al*., 2022). Pyraclostrobin is a quinone outside inhibitor (QoI) that exhibits translaminar movement which protects both sides of the tissues and acts as antifungal agent against *Alternaria* by halting ATP production through inhibition of mitochondrial respiration and ATP production (Dhaval *et al*., 2023). Difenoconazole gave significant disease reduction of early blight disease as it targets C14-demethylase, leading to loss of cell membrane integrity (Li *et al*., 2025). Abdulbaqi (2023) stated the role of metalayxl in the management of early blight disease which inhibits the synthesis of

RNA in fungal cells by blocking RNA polymerase and thus suppresses spore germination, mycelial growth and subsequent infection of the fungi in host plant.

Role of environmental factors in disease management

Although fungicides have significant contribution to early blight disease suppression but the mechanism of disease development and efficacy of fungicides is greatly influenced by the prevailing weather conditions that coincide with interaction of pathogen and host. The efficacy of fungicides was more in current experiment which may be attributed the method and concentration of fungicides applications, prevailing weather conditions during and after applications, soil and plant health. It is pivotal to understand the role of environment in disease development for effective and sustainable disease development. *Alternaria solani* requires almost 25°C for its optimum growth of mycelium, spore production and infection development; however in current study it showed a negative relationship between disease development and temperatures both maximum and minimum i.e. increase in temperature caused decrease in fungal growth and disease intensity. An optimum radial growth of *A. solani* was recorded at 25°C which continued to be reduced till 35°C and almost halted at 40°C (Parvin *et al*., 2021). An excellent spore production was recorded under in-vitro conditions for *A. solani* at about 22°C that was nearly negligible at above 35°C (Patel, 2019). The findings of de Morais *et al*. (2025) were also in line with previous studies for the effect of temperature on A. solani growth, however he suggested that relative humidity has positive effect on fungal growth which gave increasing trend. Atri *et al*., (2024) reported that under in vitro conditions, *A. solani* showed highest formation of conidia (93%) and elongation of germ tube (238.95 µm) at 100% RH. A similar trend was observed in case of field conditions where above 85% disease severity was recorded at 100% relative humidity that significantly lowered with decrease in Rh (Xiao *et al*., 2024). Heat reflections from soil and plant microclimate may influence the temperature effect on disease development. Temperature alone don't play a vital role in disease development, it is also affected by moisture and relative humidity.

Conclusions and Recommendatoins

Sustainable disease management could only be achieved by the integration of effective fungicides, regular monitoring of weather and cultivation of resistant genotypes. Environmental variables not only influence the different stages of disease development but also have close relationship on the efficacy of fungicides. Identification of resistant sources and their incorporation into future breeding programs would be a most promising approaches for disease management under changing climate scenario.

Data driven future directions

There is need to identify resistance loci in moderately resistant cultivars by using transcriptomics and QTL mapping. Disease predictive models should be developed by integration of fungicide application time. There should be a thorough study on the mechanism of fungicides against fungal growth and impact on plant growth.

Practical Implications

Integrating moderately resistant cultivars, effective fungicides, and weather-based prediction can significantly reduce early blight severity and economic losses in tomato production.

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Novelty Statement

The study was focused on the use of environmentally less hazardous fungicides in connection with modeling of environmental factors for precise use of the chemicals and at an accurate time.

Generative AI or AI assisted technology statement

The authors have not used any AI tool for the preparation of this manuscript.

Conflict of interest

The authors declare no conflict of interest.

Author's Contribution

Asghar Ali: Conceptulization
Safdar Ali: Supervision
Luqman Amrao: Visualization
Yasir Iftikhar: Methodology
Muhammad Usman Ghani: Formal Analysis
Salma Malik: Writing review and Editing

Fahad Hussain G Mohammed Yar: Improved Discussion
Muhammad Ahmad Zeshan: Writing original draft

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