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Research Article

EXPLORING THE POTENTIAL OF SYSTEMIC FUNGICIDES AND PLANT EXTRACTS IN SUPPRESSING FUSARIUM WILT OF TOMATO

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ABSTRACT

This comprehensive study has examined the potential of controlling *Fusarium oxysporum* f. sp. *lycopersici* causing tomato wilt using systemic fungicides and plant extracts. For the field evaluation of several fungicides, namely Heritage, Pyranil, Folicur, Medallion, Bloom, Benomyl, Defeater, Chipco, Sporta, and Aliette, and plant extracts including *Citrullus colocynthis*, *Eucalyptus globulus*, *Azadirachta indica*, *Zingiber officinale*, *Allium sativum*, *Nicotiana tabacum*, *Aloe indica*, and *Calendula officinalis*, tomato seeds were cultivated in the greenhouse at the Vegetable Research Area at Ayub Agriculture Research Institute, Faisalabad, during October 2022. The key findings confirmed the significant effectiveness of fungicides such as Chipco, Bloom, Sporta, and Benomyl. These fungicides, at different concentrations, effectively inhibited the growth of the fungal mycelium. The amount of inhibition ranged from 1.75 cm to 5.84 cm, whereas the control group exhibited an increase of 9 cm. The study highlights the significant inhibitory impact of Bloom on fungal development, resulting in a remarkable reduction of fungal mycelial growth by 85.92%, 81.10%, and 79.90% at various concentrations. In addition, plant extracts demonstrated their natural antifungal characteristics, which varied in efficacy based on the concentrations used. The extracts from *A. indica* and *A. sativum* were the most effective, exhibiting the maximum growth inhibition percentage at a concentration of 8%. The present investigation highlighted the potential application of certain fungicides and plant extracts to combat *F. oxysporum* f. sp. *lycopersici*. These alternatives provide an environmentally friendly response to synthetic fungicides for managing the disease. Further research is needed to enhance the understanding of the exact efficiency and cost-effectiveness.

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INTRODUCTION

Fusarium oxysporum f. sp. *lycopersici* is a significant issue for tomato production globally, causing tomato wilt. The development of resistance in this pathogen has emphasized the importance of efficient antifungal methods for combating this devastating disease. Several systemic fungicides have been evaluated for their ability to inhibit the growth of *F. oxysporum* f. sp. *lycopersici* to obtain knowledge about possible methods of control (Amini and Sidovich, 2010; Akram et al., 2018). These fungicides are classified into several chemical groups and have demonstrated variable levels of effectiveness in suppressing the growth of the pathogen (Amini and Sidovich, 2010; Akram et al., 2018). The antifungal activity of these systemic fungicides has received attention due to its implications for developing resistance in fungal populations (Amini and Sidovich, 2010; Akram et al., 2018; Chowdhary and Meis, 2018; Iqbal and Mukhtar, 2020a).

Studies have also investigated the fungicidal characteristics of organic chemicals and compounds obtained from various sources (Iqbal et al., 2014; Shahzaman et al., 2015; Iqbal and Mukhtar, 2020b; Shahbaz et al., 2022). *Tetraclinis articulata* essential oils have exhibited antifungal solid properties against *F. oxysporum* (Khatib et al., 2022). Moreover, examining monoterpenes in crucial oils has uncovered discrepancies in their antifungal properties, indicating the possibility of using these natural chemicals as antifungal agents (Danielli et al., 2019).

In addition, the use of bioactive peptides and surfactants has shown promising antifungal properties against several fungal species, such as *Candida albicans* and *F. oxysporum* (Disetti et al., 2017; Sun et al., 2022). These studies demonstrated that antifungal chemicals control fungal diseases like tomato wilt. Systemic fungicides against *F. oxysporum* f. sp. *lycopersici*, which causes tomato wilt, must be evaluated because the pathogen has evolved resistance (Akram et al., 2018). Multiple studies have assessed the efficacy of various systemic fungicides in treating fungal infections. The antifungal activity of azoxystrobin, a widely used systemic fungicide, has been extensively researched by multiple studies (Koçyiğit-Kaymakçıoğlu et al., 2015; Yao et al., 2018; Kitonde et al., 2019; Yin et al., 2020). The antifungal activity of azoxystrobin has been demonstrated to be superior to that found in conventional formulations, suggesting its potential as a highly effective antifungal drug (Yao et al., 2018). In addition, the co-administration of azoxystrobin with other drugs has been shown to have increased antifungal activity against infections such as *Sclerotinia sclerotiorum* (Yaderets et al., 2021). Strobilurins, a group of fungicides that contains azoxystrobin, have been recognized for their wide-ranging ability to combat numerous plant pathogenic fungi (Kim and Hwang, 2007). Moreover, the ongoing research to find more potent fungicidal drugs can be seen by developing new antifungal compounds, such as 1,3,4-oxadiazole-2-carbohydrazides (Wu et al., 2019).

In vitro, studies have demonstrated that specific compounds have antifungal solid properties against plant-damaging fungi, exceeding commonly used fungicides such as azoxystrobin (Xu et al., 2010; Koçyiğit-Kaymakçıoğlu et al., 2015). The evaluation of novel chemical compounds, such as metal complexes of 8-hydroxyquinoline, has revealed promising antifungal characteristics, suggesting the possibility of developing new fungicidal substances (Yin et al., 2020). Furthermore, the relationship between fungicides such as azoxystrobin and soil microbial communities highlights the significance of comprehending the environmental consequences of these antifungal substances (Adetutu et al., 2008). Traditional management strategies often rely on synthetic fungicides, but their environmental impact and potential resistance development necessitate alternative approaches. In the present investigation, systemic fungicides and plant extracts as were applied an innovative strategy to suppress Fusarium wilt. Exploring the synergistic effects of these treatments was aimed to contribute to sustainable fungal management in tomato cultivation (Yuan, 2021).

Several plant extracts exhibited promising antifungal activities against various fungal diseases. *Eucalyptus globulus* contains 1,8-cineole, which has antifungal properties (Barbosa et al., 2016). Moreover, *Zingiber officinale* has shown inhibitory properties against *Candida albicans* fungus growth (Hasan et al., 2012). Studies have shown many bioactive substances in these plant extracts, including phenols, terpenes, alkaloids, and flavonoids, which enhance their ability to fight against fungal infections (Kuete, 2010). Moreover, the leaves of *E. globulus* are recognized for their antibacterial, antiseptic, antioxidant, and antifungal properties (Álvarez et al., 2021). Moreover, the rhizome extract of *Z. officinale* has exhibited noteworthy antifungal properties against many fungal strains (Prastiyanto et al., 2021).

Hence, the present study explores the antifungal activity of various systemic fungicides against *F. oxysporum* f. sp. *lycopersici*, a fungus associated with tomato wilt. The research also aims to assess the antifungal potential of different plant extracts, providing valuable insights into developing sustainable strategies for managing fungal diseases in agriculture. It aims to develop effective strategies to combat this disease and explore natural alternatives along with synthetic fungicides. Moreover, systemic fungicides can have environmental implications, including ecotoxicity, non-target effects, and potential damage to beneficial fungi and plant health. They can also accumulate in soil, affecting crops and soil microbial communities. Therefore, this current study highlighted the need for further investigation that should emphasize integrated disease management, sustainable alternatives, soil microbiome studies, and risk assessment models.

MATERIALS AND METHODS

Fusarium wilt symptomatic tomato plant parts were collected from the research areas of the Plant Pathology Research Institute (PPRI), Ayub Agriculture Research Institute Faisalabad. The collected disease samples were brought to the Plant Pathology Laboratory of PPRI in Faisalabad (31° 25' 7.3740'' N, 73° 4' 44.7924'' E) in the polythene bags. The pathogen was isolated from infected areas using Potato dextrose agar (PDA) as a growth medium (Chohan et al., 2011). After dividing the affected portions into 4-5 mm fragments, they were washed with tap water and treated with a 3% sodium hypochlorite solution for two minutes. After disinfection, the samples were washed with sterilized distilled water and dried using filter paper. A volume of 10 ml of PDA was aseptically transferred into sterile petri dishes with a diameter of 9 cm using a laminar flow chamber.

The infected leaves were placed on PDA and incubated at 25±2°C for four days, starting when the medium became solid. A single-spore culture was used to produce a pure culture. The identification of fungal species on petri plates after incubation was based on morphological features (Nelson et al., 1983). A sterile fungal culture was stored at a temperature of 4°C for future utilization.

Pathogenicity test

In October 2022, tomato seeds were cultivated in the greenhouse at the Vegetable Research Area at Ayub Agriculture Research Institute Faisalabad. Tomato seedlings measuring 10 inches (Roma) were moved to sterilized soil with a fungal suspension inoculum with a 10^6 spores/ml concentration. This was carried out using a Neubauer haemocytometer, and the seedlings were planted in 12 cm plastic pots in the greenhouse at the Vegetable Research Area at Ayub Agriculture Research Institute in Faisalabad.

The pots were moved to the greenhouse following inoculation. Regular monitoring of symptoms was conducted. After symptoms had manifested, artificial mediums were employed to separate the pathogen from the symptomatic areas. The morphological properties of both the isolated and the source cultures were assessed to fulfill Koch's postulates (Ignjatov et al., 2012).

Management of *F. oxysporum* f. sp. *lycopersici* through fungicides

The antifungal activity of 16 distinct systemic fungicides, commercial formulations from various groups, was assessed against *F. oxysporum* f. sp. *lycopersici* at varying doses (Table 1).

Table 1. List of fungicides used in suppressing fungal growth of *F. oxysporum* f.sp. *lycopersici.*

Sr. No.	Trade name	A.I.	Formulation	Dose/100 L	FRAC group	Manufacturer	Action
1	Heritage	Azoxystrobin	SC	180 ml	11	Syngenta	Systemic
2	Pyranil	Pyrimethanil	SC	300 ml	9	Yantai Keda Chemical Co. Ltd	Systemic
3	Folicur	Tebuconazole	ME	750 ml	3	Pak China Chemicals (Pvt.) Ltd	Systemic
4	Medallion	Fludioxonil	SC	125 g/L	12	Syngenta	Systemic
5	Bloom	Myclobutanil	EC	40 ml	3	Four BrothersBiologic AG, Pakistan	Systemic
6	Benomyl	Benlate	WP	500 g/l	B1		Systemic
7	Defeater	Flumorph	WDG	250 g	33	Bayer Crop Science/Kanzo AG	Systemic
8	Chipco	Bromuconazole	SC	100 g/l)		Bayer Crop Science	Systemic
9	Sporta	Prochloraz	EC	20 mL	3	Bayer	Systemic
10	Aliette	Fosetyl-Al	WDG	250 g	33	Syngenta	Systemic

In vitro antifungal activity of fungicides

A poisoned food technique was used to conduct the antifungal test. Different concentrations of 16 fungicides (Table 1) were applied to PDA and then solidified in sterilized petri plates at concentrations of 20, 60, 80, and 100 µg ml^{-1}. The Petri dishes were inoculated with a sterilized cork borer containing a culture of isolated *F. oxysporum* f.sp. *lycopersici*. The study used a completely randomized design with three replications. The controls consisted of Petri plates inoculated with PDA medium without any tested fungicides. The test fungus exhibited a radial mycelial growth of 9 cm in the petri plates under controlled conditions at a temperature of 25°C for one week. Various fungicide concentrations were evaluated for their impact on the growth of the fungal pathogen's mycelium. The algorithm used by Sahi et al. (2012) calculates the percentage decrease in growth.

$$\mathbf{PD} = \frac{(\mathbf{C} - \mathbf{T})}{(\mathbf{C})} \times \mathbf{100}$$

Where PD represents the percentage drop; C represents the colony growth of Fusarium in the control; and T represents the colony growth of Fusarium in the treated plate.

Management of *F. oxysporum* f.sp. *lycopersici* through plant extracts

Preparation of plant extracts

The eight plant materials (Table 2) were cleaned with tap water, followed by surface sterilization using a 0.1 percent sodium hypochlorite solution. They were then rinsed many times with distilled water and let to dry spontaneously. To prepare extracts, 20 ml of sterile water was mixed with 20 g of chosen plant material and crushed using a pestle and mortar. A 0.1 M w/v stock solution, including all selected plant parts, was filtered using muslin cloth and Whatman filter paper No. 1. The samples were centrifuged at 10,000 revolutions per minute for 5 minutes. Following this, they were sterilized at 40°C for 10 minutes. Finally, the samples were stored at a temperature of 4ºC for future use (Jaganathan and Narasimhan, 1988).

In vitro antifungal activity of plant extracts

The selected plant extracts were employed in the lab aseptically via the poisoned food technique. The 100 percent stock solutions were poured into conical flasks with sterilized PDA medium to make the four concentrations of 2, 4, 6, and 8. PDA medium plates without extract served as controls. After medium solidification, a 5 mm disc of pure culture of target fungus was inoculated with a sterilized cork borer in the center of the Petri plates with sterilized PDA and incubated at 25±2°C. Fungal colony mycelial growth was measured in millimeters every 24 hours until the control plates were completely covered with the pathogenic fungus. As previously mentioned, the percent inhibition equations from Sahi et al. (2012) were used to calculate the effect of all plant extracts on *Fusarium* sp. mycelial growth.

Table 2. Detail of plant materials used for the management of *F. oxysporum* f. sp. *lycopersici.*

Sr. No.	Common Name	Scientific Name	Parts
1	Bitter apple	*Citrullus colocynthis*	Mature fruit
2	Eucalyptus	*Eucalyptus globulus*	Leaves
3	Neem	*Azadirachta indica*	Leaves + Seeds
4	Ginger	*Zingiber officinale*	Rhizome
5	Garlic	*Allium sativum*	Tuber
6	Tobacco	*Nicotiana tabacum*	Leaves
7	Aloe vera	*Aloe indica*	Gel
8	Marigold	*Calendula officinalis*	Leaves

Statistical analysis

The fungal radial growth data from a completely randomized experiment was analyzed using ANOVA with Mintab Ver.19. The treatment averages were compared using Fisher's least significant differences (LSD) test at a significance level of P = 0.05. All treatments showed a reduction in the percentage of fungal radial growth.

RESULTS

Management of *F. oxysporum* f.sp. *lycopersici* through systemic fungicides

The effectiveness of 10 systemic fungicides against *F. oxysporum* f.sp. *lycopersici* is demonstrated in Tables 3 and 4. The results clearly showed that the fungicides significantly decreased the growth of the fungal pathogen, thereby reducing wilt disease to a considerable level. Tables 3 and 4 present comprehensive data on the effectiveness of the tested fungicides in inhibiting mycelial growth. The tables also include the percentage decrease compared to the control treatment for all the fungicides, along with statistical calculations.

Various concentrations of Bromuconazole showed significant efficacy compared to other fungicides tested. It effectively inhibited the growth of the fungal colony by 3.15 cm, 3.75 cm, 2.16 cm, and 1.75 cm at low and high concentrations, respectively. The application of Bloom and Prochloraz resulted in a significant reduction in the growth of the *Fusarium* pathogen. The mycelial growth measurements at several tested concentrations were roughly similar, ranging from 2.16 cm to 3.54 cm, compared to the control, which measured 9 cm. Benomyl at both low and high concentrations resulted in a considerable reduction in fungal mycelial growth, measuring 4.16 cm, 5.84 cm, 4.40 cm, and 5.56 cm. In comparison, Pyranil only reduced the inhibition zones of the fungus to 5.26 cm, 6.55 cm, 7.46 cm, and 6.85 cm at all lower and higher concentrations, respectively. At this dose, Fludioxonil showed a decrease of 4.16 cm in mycelial growth, showing moderate effectiveness. On the other hand, Aliette showed a reduction of 4.74 cm in mycelial growth, indicating a medium to high level of efficacy (Table 3).

Defeater exhibited a decrease of 4.65 cm in the growth of fungal mycelium, demonstrating substantial control comparable to that of Aliette and Benomyl. Azoxystrobin showed a 7.23 cm decrease in fungal mycelial development, demonstrating superior effectiveness at this concentration compared to the other studied fungicides. Tebuconazole decreased by 7.67 cm in mycelial development, indicating comparable effectiveness to Azoxystrobin at low and high dosages (Table 3).

In general, the findings at low concentrations indicate that certain fungicides, including Azoxystrobin and Tebuconazole, have shown significant success in suppressing the growth of fungal mycelium. On the other hand, Pyranil consistently exhibited the lowest level of effectiveness compared to the other fungicides tested.

The percentage of inhibition in the growth of *F. oxysporum* f.sp. *lycopersici* colony growth was calculated in contrast with the control group for all concentrations of fungicides, both low and high. The fungicide Bloom had the highest significance level, decreasing fungal mycelial growth by 85.92%, 81.10%, and 79.90% at concentrations of high concentration 80, low concentration 50, and high concentration 100, respectively, when compared to the control group. This demonstrates its potent inhibitory effect on fungal growth at various doses. Prochloraz at a low concentration of 50 and Bromuconazole at a high concentration of 100 were identified as the second most significant fungicides, demonstrating an inhibition rate of 79.62%. Benomyl and Fludioxonil, at concentrations of 20 and 80, respectively, exhibited higher levels of effectiveness with percent inhibitions of 63.6% and 64.40%, compared to the control (Table 4).

Pyranil at a concentration of 20 and Flare at 100 resulted in reductions of 52.21% and 48.88%, respectively, which were satisfactory. Carbendazim and Epic at a high dosage of 80 showed a relatively low significance level, with a percent inhibition of 1.48%, when compared to all other concentrations of fungicides examined (Table 4). The results demonstrate diverse levels of effectiveness among the tested fungicides. Among them, Bloom, Prochloraz, and Bromuconazole exhibited the most favorable outcomes in preventing the growth of fungal mycelium at various concentrations (Table 4).

In vitro antifungal activity of plant extracts

The *in vitro* antifungal activity of various plant extracts against *F. oxysporum* f.sp. *lycopersici* was evaluated, assessing their growth inhibition percent at different concentrations. The effectiveness of plant extracts in inhibiting the growth of *F. oxysporum* varied across different concentrations. Plant extracts demonstrated varying degrees of antifungal activity, with some showing higher inhibition percentages compared to others. At a concentration of 8%, *A. indica* exhibited notable growth inhibition percent against *F. oxysporum* (Figure 1).

A. sativum showed significant growth inhibition percent at a concentration of 8%, indicating its potential as an antifungal agent against *F. oxysporum*. It was observed that *E. globulus* and *A. indica* demonstrated moderate growth inhibition percent at a concentration of 6%, suggesting their potential antifungal properties. *C. officinalis* and *N. tabacum* exhibited moderate growth inhibition percent at a concentration of 4%, indicating their effectiveness against *F. oxysporum* growth in petri plates (Figure 1).

Table 3. The effects of various concentrations of distinct systemic fungicides on the mycelial growth of *F. oxysporum* f.sp. *lycopersici* on PDA.

Concentration (µg/mL)	Reduction in fungal mycelial growth (cm)									
	Pyranil	Bloom	Fludioxonil	Benomyl	Bromuconazole	Aliette	Defeater	Prochloraz	Azoxystrobin	Tebuconazole
Low concentration 20	5.26 E	3.17 B	4.16 D	4.16 D	3.15 C	4.74 C	4.65 C	3.54 B	7.23 D	7.67 D
Low concentration 50	6.55 D	2.66 C	4.83 C	5.84 B	3.75 B	5.35 B	5.17 B	2.75 C	7.55 C	7.45 D
High concentration 80	7.46 B	2.18 D	4.15 D	4.40 D	2.16 D	4.57 C	4.56 C	2.16 D	7.85 B	8.16 C
High concentration 100	6.85 C	3.07 B	5.74 B	5.56 C	1.75 E	5.55 B	4.25 D	2.76 C	7.97 B	8.45 B
Control	9.00 A	9.00 A	9.00 A	9.00 A	9.00 A	9.00 A	9.00 A	9.00 A	9.00 A	9.00 A

Different letters within the same row denote significant differences ($p < 0.05$) between means according to Tukey’s Honestly Significant Difference (HSD) test.

Table 4. Percentage decrease in fungal growth of *F. oxysporum* f.sp. *lycopersici* on PDA mixed with systemic fungicides at different concentrations

Concentration (µg/mL)	Decrease in fungal mycelial growth (%)									
	Pyranil	Bloom	Fludioxonil	Benomyl	Bromuconazole	Aliette	Defeater	Prochloraz	Azoxystrobin	Tebuconazole
Low concentration 20	51.52 A	75.51 C	63.41 A	62.34 A	62.34 A	63.45 A	57.62 B	69.48 C	75.51 C	12.41 A
Low concentration 50	36.56 B	79.48 B	53.63 B	46.66 B	46.67 B	50.56 C	52.52 C	78.48 A	79.48 B	13.51 A
High concentration 80	33.66 C	83.57 A	63.59 A	64.59 A	64.59 A	58.45 A	58.66 B	77.52 A	83.57 A	5.55 B
High concentration 100	26.91 D	77.65 BC	43.63 C	47.62 B	47.62 B	47.65 C	60.52 A	73.59 B	77.65 BC	3.62 B
Control	0.00 E	0.00 D	0.00 D	0.00 C	0.00 C	0.00 D	0.00 D	0.00 D	0.00 D	0.00 C

Different letters within the same row denote significant differences ($p < 0.05$) between means according to Tukey's Honestly Significant Difference (HSD) test.

C. colocynthis and *Z. officinale* showed moderate growth inhibition percent at a concentration of 2%, suggesting their potential as antifungal agents. These results highlight the potential of various plant extracts as natural antifungal agents against *F. oxysporum*, with their effectiveness varying depending on the concentration used (Figure 1).

Overall, the results indicate that *A. indica* and *A. sativum* were the most effective plant extracts at higher concentrations, while *C. colocynthis* and *Z. officinale* showed relatively lower effectiveness at lower concentrations. The effectiveness of the plant extracts varied depending on their concentration levels, with higher concentrations generally resulting in higher effectiveness in controlling the disease.

DISCUSSION

The control of *F. oxysporum* f.sp. *lycopersici*, which causes tomato wilt, can be effectively achieved using systemic fungicides. This approach has been extensively discussed in plant pathology and agriculture. This study focused on the impact of Pyranil, Bloom, Fludioxonil, Benomyl, Bromuconazole, Aliette, Defeater, Prochloraz, Azoxystrobin, and Tebuconazole on the management of *F. oxysporum* f.sp. *lycopersici*.

Previous studies have acknowledged the effectiveness of systemic fungicides in controlling plant wilt infections, particularly those of the *Fusarium* species (Agrios, 2005). This study aimed to further improve our understanding by investigating the effects of different systemic fungicides on *F. oxysporum* f.sp. *lycopersici*. Our research findings align with earlier literature, specifically the study of Fravel et al. (2003), which suggested that fungicides are effective in managing wilt pathogens. Azoxystrobin and Tebuconazole demonstrated the most pronounced impact on controlling *F. oxysporum* f.sp. *lycopersici* in our study. These findings align with the research conducted by Zhang et al. (2009), which emphasizes the potent efficacy of Azoxystrobin in managing several types of downy mildews, *Botrytis*, and scab diseases. Moreover, the remarkable performance of Tebuconazole aligns with the study conducted by Bartlett et al. (2002), which showed the beneficial effects of this fungicide in managing various fungal diseases.

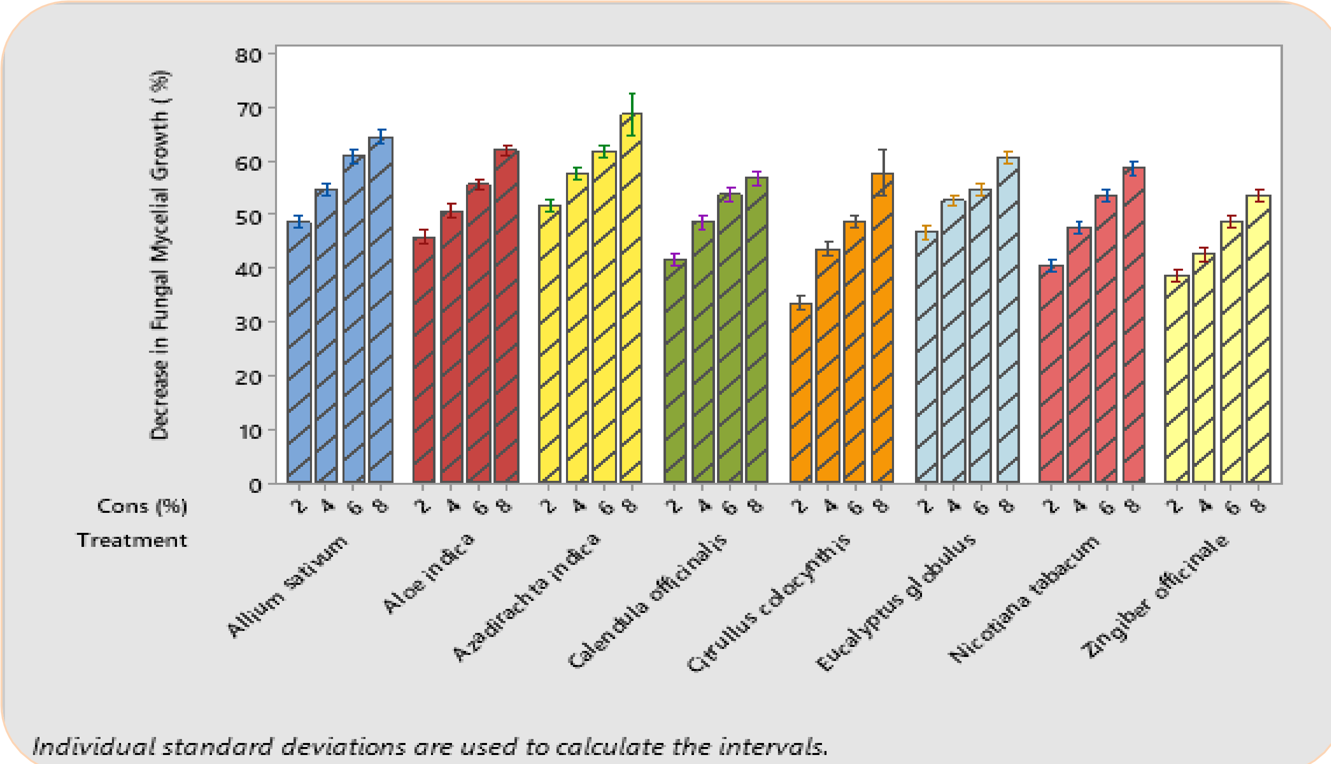

Figure 1. The efficacy of different plant extracts in controlling the *F. oxysporum* f.sp. *lycopersici* assessed at varying concentrations (2%, 4%, 6% and 8%).

Our research also revealed that Pyranil, Bloom, Fludioxonil, Benomyl, Bromuconazole, Aliette, Defeater, and Prochloraz demonstrated effective control of the tomato wilt pathogen. These results are consistent with the study conducted by Kilic-Ekici and Yuen (2004), which found that using Prochloraz could restrict the spread of *F. oxysporum.* Although the results suggest that systemic fungicides can effectively control *F. oxysporum* f.sp. *lycopersici*, it is crucial to be aware of the risk of fungicide resistance among pathogens, which can occur if fungicides are used excessively (Hobbelen et al., 2014). Additional investigation is thus required to formulate sustainable and effective disease control tactics to mitigate the impacts of tomato wilt and other *Fusarium* infections. Our study concludes that systemic fungicides effectively manage *F. oxysporum* f.sp. *lycopersici* and emphasizes the importance of developing comprehensive and sustainable disease management methods.

An extensive study has been conducted on controlling *F. oxysporum* f.sp. *lycopersici*, which is connected to tomato wilt. Diverse studies have investigated various methods to manage this infection, including using systemic fungicides. The effectiveness of various fungicides, including Pyranil, Bloom, Fludioxonil, Benomyl, Bromuconazole, Aliette, Defeater, Prochloraz, Azoxystrobin, and Tebuconazole, in controlling Fusarium wilt in tomatoes has been studied (Amini and Sidovich, 2010; Ahmad et al., 2021a).

Furthermore, this study investigates explicitly several plant extracts to control *F. oxysporum* f.sp. *lycopersici*, a pathogenic fungus that causes wilt disease in tomatoes. Multiple researches have acknowledged that plant extracts contain promising antifungal chemicals that can be employed as bio-control agents against fungal illnesses.

Various researches have emphasized the efficacy of *C. colocynthis* extract in reducing *F. oxysporum*. Rahmy and Gad (2004) demonstrated that the use of *C. colocynthis* effectively suppressed the growth of *F. oxysporum*, indicating its potential for controlling wilt disease.

The present investigation evaluated the effects of plant extracts and systemic fungicides. The combination of Mancozeb, Thiophanate Methyl, and Difenoconazole effectively suppressed the growth and sporulation of *F. oxysporum* f.sp. *lycopersici*. These results were in line with the findings of a previous study (Ahmad et al., 2021a). The plant absorbs these fungicides and plant extracts and translocate them throughout its tissues to combat pathogen infection. The incidence of Fusarium wilt was effectively mitigated with the application of a 15% soil drenching treatment containing

Mancozeb and Thiophanate Methyl (Ahmad et al., 2021b). Fungicides effectively mitigated disease and significantly enhanced crop yields. Further investigation is required to substantiate their ability to impede the growth of Fusarium wilt in tomatoes. Both systemic fungicides and plant extracts can effectively control tomato Fusarium wilt through several mechanisms (Gulya et al., 2023). Researchers and practitioners must explore these methods to enhance the growth and efficiency of crops.

Moreover, reports indicate that *E. globulus* extract displays potent antifungal properties. *Z. officinalis*, *A. sativum*, and *N. tabacum* have shown positive outcomes in recent research investigations (Kumar et al., 2009; Farahat et al., 2015). The medicinal capabilities of *A. indica* and *C. officinalis* extracts are widely recognized, and recent research has indicated their potential for reducing *F. oxysporum* (Dixit et al., 2017). Furthermore, *A. indica* has long been employed for its bioactive substances in preventing several plant diseases. A study conducted by Rani and Devi (2018) showed these extracts' efficacy in controlling *F. oxysporum* f.sp. *lycopersici*, indicating the possibility of these plant extracts as a substitute for synthetic fungicides.

CONCLUSION

The research concluded that Bromuconazole, among the tested fungicides, significantly inhibited the growth of *Fusarium oxysporum* f.sp. *Lycopersici*, followed closely by Bloom and Prochloraz. Similarly, in the case of plant extracts, *Azadirachta indica* and *Allium sativum* demonstrated the highest inhibitory effect on the fungal growth, with effectiveness improving as concentration increased. Hence, the study suggests the potential of fungicides and plant extracts in managing the wilt disease associated with *F. oxysporum* f.sp. *lycopersici*.

AUTHORS' CONTRIBUTIONS

AM, and SN designed, formulated and laid out the study; AM, SN, and SS conducted the experiments; SA and US collected, arranged and analyzed the data; AAK, and MU provided technical assistance; AM and RK supervised the work; SN and YA wrote the manuscript; YA proofread the paper.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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