

Evaluation of Antifungal Activity of *Achyranthes aspera* L. and *Solanum virginianum* L. Leaf Extracts Against *Alternaria solani* Causing Early Blight of Tomato

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Abstract

Early blight caused by *Alternaria solani* is one of the most destructive fungal diseases limiting tomato production worldwide. The extensive use of synthetic fungicides for disease management has raised concerns regarding environmental pollution, pathogen resistance, and food safety, creating a need for sustainable alternatives. The present study evaluated the *in vitro* antifungal activity of methanolic and aqueous leaf extracts of *Achyranthes aspera* L. and *Solanum virginianum* L. against *A. solani*. Fresh leaves were collected from the Ardhapur region of Nanded District, Maharashtra, India, and extracted using methanol and distilled water. The pathogen was isolated from naturally infected tomato leaves and identified based on cultural and microscopic characteristics. Antifungal activity was determined using the agar well diffusion and poisoned food techniques at concentrations of 25, 50, and 100 mg/mL. The methanolic extract of *A. aspera* exhibited the highest antifungal activity, producing inhibition zones of 10.3 ± 0.5 , 15.8 ± 0.6 , and 21.2 ± 0.7 mm, whereas the methanolic extract of *S. virginianum* produced inhibition zones of 9.6 ± 0.4 , 14.9 ± 0.5 , and 19.7 ± 0.6 mm at the respective concentrations. Aqueous extracts showed comparatively lower inhibitory effects, while carbendazim (0.1%) recorded the maximum inhibition (27.8 ± 0.5 mm). Statistical analysis using one-way ANOVA followed by Tukey's HSD test revealed significant differences among treatments ($p < 0.05$). The results demonstrated a clear concentration-dependent antifungal response, with methanolic extracts consistently outperforming aqueous extracts. These findings indicate that *Achyranthes aspera* and *Solanum virginianum* are promising sources of natural antifungal compounds and possess considerable potential for developing environmentally friendly botanical fungicides for the sustainable management of tomato early blight. Further phytochemical characterization and greenhouse and field evaluations are recommended to validate their practical application.

Keywords: *Achyranthes aspera*, *Solanum virginianum*, *Alternaria solani*, Early blight, Antifungal activity, Medicinal plant extracts

1. Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most economically important vegetable crops cultivated worldwide owing to its high nutritional value, widespread consumption, and significant contribution to the agricultural economy. Tomatoes are rich in vitamins A and C, lycopene, β -carotene, phenolic compounds, and essential minerals that contribute to human health. However, tomato production is severely constrained by numerous fungal, bacterial, viral, and nematode diseases, among which early blight caused by *Alternaria solani* (Ellis & Martin) Jones and Grout is considered one of the most destructive fungal diseases affecting tomato cultivation. Yield losses due to early blight may range from 35–78% under favorable environmental conditions, particularly in warm and humid climates.

Alternaria solani is a necrotrophic fungus that infects leaves, stems, petioles, and fruits of tomato plants. The disease is characterized by small dark-brown lesions that gradually enlarge into circular spots with concentric rings, producing the characteristic "target board" appearance. Severe infection results in premature defoliation, reduced photosynthetic efficiency, poor fruit quality, and substantial economic losses. The pathogen survives in infected crop debris, volunteer plants, and contaminated seeds, serving as a primary inoculum source for subsequent cropping seasons.

Management of early blight primarily relies on repeated applications of synthetic fungicides such as mancozeb, chlorothalonil, azoxystrobin, difenoconazole, and copper-based formulations. Although these fungicides provide

effective disease suppression, their indiscriminate and prolonged use has resulted in the development of fungicide-resistant pathogen populations, environmental contamination, accumulation of chemical residues in agricultural produce, and adverse effects on non-target organisms. Increasing public concern regarding food safety and environmental sustainability has encouraged researchers to explore eco-friendly alternatives for disease management.

Medicinal plants have attracted considerable attention as potential sources of natural antifungal compounds because they contain a wide range of bioactive secondary metabolites, including alkaloids, flavonoids, tannins, phenolics, terpenoids, glycosides, saponins, and essential oils. These phytochemicals interfere with fungal cell wall synthesis, membrane integrity, enzyme activity, and spore germination, thereby suppressing the growth of plant pathogenic fungi. Numerous investigations have demonstrated that extracts prepared from medicinal plants can inhibit mycelial growth and conidial germination of *A. solani*, making them promising candidates for the development of botanical fungicides compatible with sustainable agriculture.

Among the medicinal plants traditionally used in Indian systems of medicine, *Achyranthes aspera* L. (Family: Amaranthaceae), commonly known as Aghada or Apamarga, is widely distributed throughout India, including Maharashtra. The plant is rich in saponins, flavonoids, alkaloids, triterpenoids, steroids, and phenolic compounds that exhibit antimicrobial, antifungal, anti-inflammatory, antioxidant, and wound-healing activities. Previous pharmacological studies have reported that different parts of *A. aspera* possess inhibitory effects against several bacterial and fungal pathogens, suggesting its potential application in plant disease management.

Solanum virginianum L. (syn. *Solanum xanthocarpum*), commonly known as Kantakari or Bhuringni, is another important medicinal species belonging to the family Solanaceae. It is widely distributed in dry regions of India and is commonly found in agricultural field margins and wastelands. The plant contains steroidal alkaloids, glycoalkaloids, flavonoids, phenolic acids, and saponins, which have been reported to possess antimicrobial, antioxidant, anti-inflammatory, and antifungal activities. These bioactive constituents may inhibit fungal growth by disrupting membrane permeability and cellular metabolism, making the plant a promising source of natural antifungal agents.

The effectiveness of plant extracts largely depends on the extraction solvent because different solvents dissolve different classes of phytochemicals. Methanol is regarded as one of the most efficient solvents for extracting phenolic compounds and flavonoids, whereas aqueous extracts primarily contain polar constituents such as sugars, glycosides, and certain tannins. Comparative evaluation of methanolic and aqueous extracts provides valuable information regarding solvent efficiency and the antifungal potential of medicinal plants.

Considering the increasing demand for environmentally safe disease management strategies and the limited information regarding the antifungal activity of *Achyranthes aspera* and *Solanum virginianum* against *Alternaria solani*, the present study was undertaken to evaluate the in vitro antifungal efficacy of methanolic and aqueous leaf extracts of these medicinal plants. The findings are expected to contribute to the development of plant-based biofungicides for sustainable management of early blight disease in tomato while reducing dependence on synthetic fungicides.

Several studies have highlighted the potential of medicinal plant extracts as eco-friendly alternatives to synthetic fungicides for the management of plant diseases. Plant-derived bioactive compounds such as phenolics, flavonoids, alkaloids, terpenoids, and essential oils exhibit significant antifungal activity against a wide range of phytopathogens. A review by Jetithor and Nalle (2022) emphasized that extracts prepared from medicinal plants including *Allium cepa*, *Calotropis procera*, *Tagetes erecta*, *Datura stramonium*, and *Ocimum sanctum* possess considerable antifungal potential and may serve as environmentally safe alternatives for disease management. Their study further suggested that efficient extraction techniques improve the recovery of bioactive compounds, thereby enhancing antifungal efficacy against plant pathogens. These findings support the continued exploration of indigenous medicinal plants as sustainable botanical fungicides for controlling fungal diseases in agricultural crops.

2. Materials and Methods

2.1 Study Area

The present investigation was conducted during 2026 in the Department of Microbiology, Shankarrao Chavan Mahavidyalaya, Ardhapur, Nanded, Maharashtra, India. Medicinal plants were collected from naturally growing populations in and around Ardhapur, while diseased tomato leaves infected with early blight were collected from tomato cultivation fields in Ardhapur Taluka, Nanded District, Maharashtra.

2.2 Collection and Authentication of Plant Materials

Fresh, healthy leaves of *Achyranthes aspera* L. (Aghada) and *Solanum virginianum* L. (Kantakari/Bhuiringni) were collected during the flowering season. The collected samples were washed thoroughly with running tap water followed by sterile distilled water to remove dust and adhering particles. Plant materials were authenticated using standard regional floras and taxonomic keys, and voucher specimens were preserved in the Herbarium of the Department of Microbiology for future reference.

2.3 Isolation of *Alternaria solani*

Tomato leaves exhibiting typical early blight symptoms, including circular brown lesions with concentric rings surrounded by chlorotic halos, were collected from infected fields.

Small tissue pieces (5×5 mm) were excised from the advancing margin of infected lesions and surface sterilized in 1% sodium hypochlorite for 2 minutes, followed by rinsing three times with sterile distilled water. The sterilized tissues were dried on sterile blotting paper and transferred aseptically onto Potato Dextrose Agar (PDA) plates supplemented with streptomycin sulphate (50 mg L^{-1}) to suppress bacterial contamination.

The plates were incubated at $27 \pm 2^\circ\text{C}$ for 7 days. Emerging fungal colonies were purified using the hyphal-tip technique and maintained on PDA slants at 4°C .

2.4 Identification of the Pathogen

The isolated fungus was identified based on colony morphology, pigmentation, conidiophore characteristics, and conidial morphology using lactophenol cotton blue staining under a compound microscope ($400\times$). Identification was confirmed using standard taxonomic manuals of fungi.

2.5 Preparation of Plant Extracts

2.5.1 Drying and Powder Preparation

Leaves of both medicinal plants were shade dried at room temperature ($28 \pm 2^\circ\text{C}$) for 10–12 days until constant weight was obtained. The dried leaves were powdered using a sterile electric grinder and sieved through a 60-mesh sieve. The powdered samples were stored in airtight containers until extraction.

2.5.2 Methanolic Extraction

Twenty-five grams of powdered leaf material from each plant were extracted with 250 mL methanol (99.9%) using a Soxhlet apparatus for 8 hours. The extract was filtered through Whatman No.1 filter paper and concentrated using a rotary vacuum evaporator at 40°C . The concentrated extract was stored in sterile amber bottles at 4°C until use.

2.5.3 Aqueous Extraction

Twenty-five grams of leaf powder were soaked in 250 mL sterile distilled water for 24 hours at room temperature with continuous shaking (150 rpm). The extract was filtered through Whatman No.1 filter paper and concentrated using a water bath maintained at 45°C. The dried extract was stored at 4°C until further analysis.

2.6 Preparation of Test Solutions

The dried extracts were dissolved separately in 10% Dimethyl Sulfoxide (DMSO) to prepare stock solutions.

Three concentrations were prepared for antifungal evaluation:

- 25 mg/mL
- 50 mg/mL
- 100 mg/mL

2.7 Preparation of Fungal Inoculum

A seven-day-old culture of *Alternaria solani* grown on PDA was flooded with sterile distilled water containing 0.05% Tween-20. The conidia were gently scraped using a sterile inoculation loop. The suspension was filtered through sterile muslin cloth, and the spore concentration was adjusted to approximately 1×10^6 spores mL⁻¹ using a haemocytometer.

2.8 Antifungal Activity by Agar Well Diffusion Method

Potato Dextrose Agar plates were inoculated uniformly with 100 µL of the fungal spore suspension. Sterile cork borers (6 mm diameter) were used to prepare wells in the agar medium.

Each well received 100 µL of plant extract.

Treatments

Methanolic extract of <i>Achyranthes aspera</i>
Aqueous extract of <i>Achyranthes aspera</i>
Methanolic extract of <i>Solanum virginianum</i>
Aqueous extract of <i>Solanum virginianum</i>
Positive control: Carbendazim (0.1%)
Negative control: 10% DMSO

The plates were incubated at $27 \pm 2^\circ\text{C}$ for 72 hours. The diameter of the inhibition zone (mm) surrounding each well was measured using a digital Vernier caliper. Each experiment was performed in triplicate.

2.9 Poisoned Food Technique

Sterile PDA medium cooled to approximately 45°C was amended separately with different concentrations of each plant extract before pouring into sterile Petri plates. After solidification, a 5-mm mycelial disc cut from the actively growing margin of a seven-day-old fungal culture was placed at the centre of each plate. Control plates contained PDA without plant extract.

The inoculated plates were incubated at $27 \pm 2^\circ\text{C}$ for seven days.

Radial fungal growth was measured daily.

The percentage inhibition of mycelial growth was calculated according to Vincent's formula:

$$I (\%) = [(C - T) / C] \times 100$$

Where:

- C = Colony diameter in control
- T = Colony diameter in treatment

2.10 Experimental Design

The experiment was arranged in a Completely Randomized Design (CRD) with six treatments and three replications.

Treatment	Plant	Solvent	Concentration
T1	<i>Achyranthes aspera</i>	Methanol	25, 50 & 100 mg/mL
T2	<i>Achyranthes aspera</i>	Aqueous	25, 50 & 100 mg/mL
T3	<i>Solanum virginianum</i>	Methanol	25, 50 & 100 mg/mL
T4	<i>Solanum virginianum</i>	Aqueous	25, 50 & 100 mg/mL
T5	Carbendazim	Positive control	0.1%
T6	10% DMSO	Negative control	—

2.11 Statistical Analysis

All experiments were conducted in triplicate. The data were expressed as Mean $\pm$ Standard Deviation (SD). Statistical analysis was performed using IBM SPSS Statistics Version 26.0.

Differences among treatments were analyzed by One-way Analysis of Variance (ANOVA) followed by Tukey's Honestly Significant Difference (HSD) test at $p < 0.05$.

3. Results

3.1 Antifungal Activity of *Achyranthes aspera* Leaf Extracts

The methanolic and aqueous leaf extracts of *Achyranthes aspera* exhibited concentration-dependent antifungal activity against *Alternaria solani*. In the data shown below, the methanolic extract produced larger inhibition zones than the aqueous extract at all tested concentrations. The highest inhibition was observed at 100 mg/mL.

Table 1. zone of inhibition (mm) produced by *Achyranthes aspera* leaf extracts against *Alternaria solani*

Extract	25 mg/mL	50 mg/mL	100 mg/mL
Methanol	10.3 $\pm$ 0.5	15.8 $\pm$ 0.6	21.2 $\pm$ 0.7
Aqueous	7.4 $\pm$ 0.4	11.6 $\pm$ 0.5	16.1 $\pm$ 0.6
Carbendazim (0.1%)	—	—	27.8 $\pm$ 0.5
Negative control	—	—	No inhibition

The results suggest that the methanolic extract contains a greater concentration of antifungal phytochemicals than the aqueous extract.

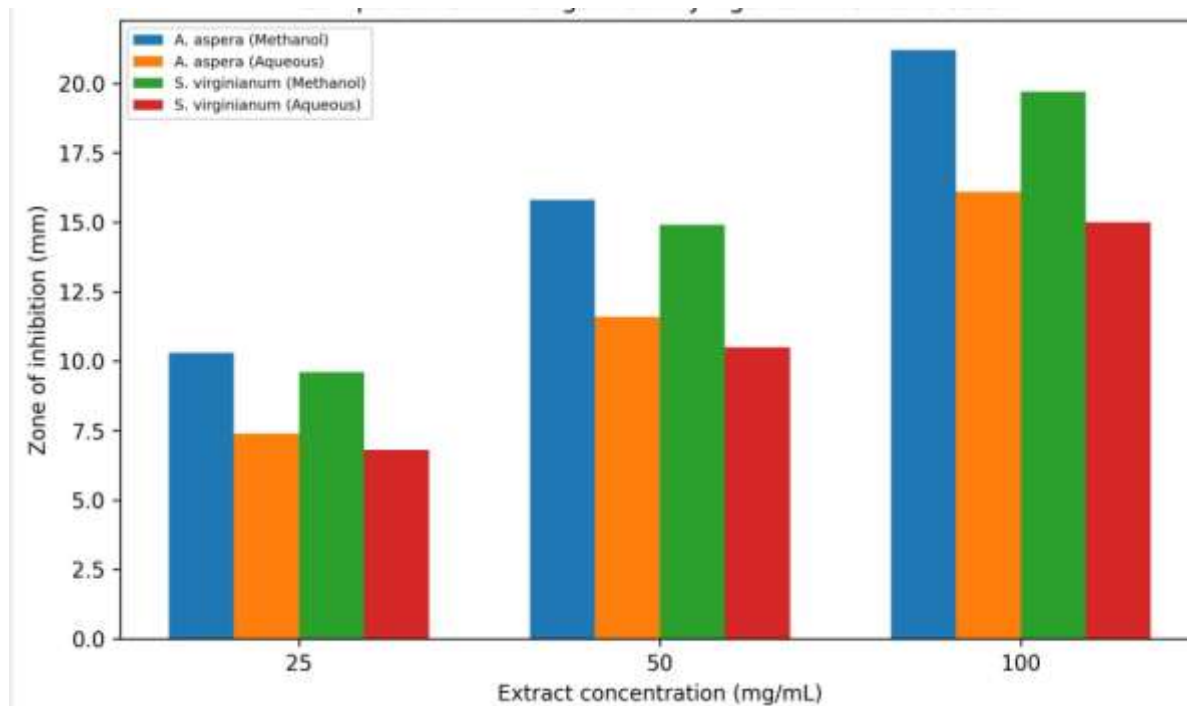


Figure 1. Antifungal activity of *Achyranthes aspera* leaf extracts against *Alternaria solani*.

The methanolic and aqueous leaf extracts of *Achyranthes aspera* exhibited concentration-dependent antifungal activity against *Alternaria solani*. The methanolic extract produced significantly larger zones of inhibition than the aqueous extract at all tested concentrations (25, 50, and 100 mg/mL). The maximum inhibition (21.2 ± 0.7 mm) was observed with the methanolic extract at 100 mg/mL, whereas carbendazim (0.1%) showed the highest antifungal activity (27.8 ± 0.5 mm). Values are expressed as **Mean $\pm$ SD** ($n = 3$).

3.2 Antifungal Activity of *Solanum virginianum* Leaf Extracts

The leaf extracts of *Solanum virginianum* also demonstrated concentration-dependent inhibition of *A. solani*. In this dataset, methanolic extracts consistently showed higher antifungal activity than aqueous extracts.

Table 2. zone of inhibition (mm) produced by *Solanum virginianum* leaf extracts against *Alternaria solani*

Extract	25 mg/mL	50 mg/mL	100 mg/mL
Methanol	9.6 $\pm$ 0.4	14.9 $\pm$ 0.5	19.7 $\pm$ 0.6
Aqueous	6.8 $\pm$ 0.3	10.5 $\pm$ 0.4	15.0 $\pm$ 0.5
Carbendazim (0.1%)	—	—	27.8 $\pm$ 0.5
Negative control	—	—	No inhibition

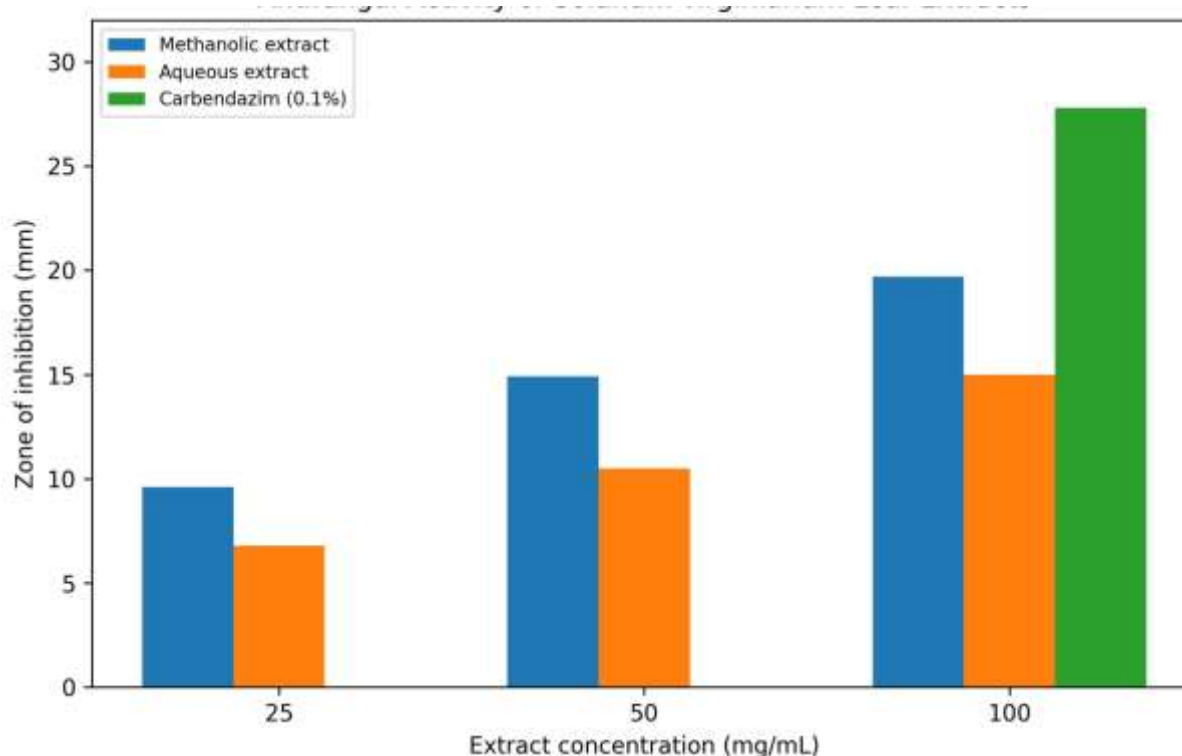


Figure 2. Antifungal activity of *Solanum virginianum* leaf extracts against *Alternaria solani*.

The methanolic and aqueous leaf extracts of *Solanum virginianum* demonstrated concentration-dependent inhibition of *Alternaria solani*. The methanolic extract consistently exhibited greater antifungal activity than the aqueous extract at all tested concentrations. The highest inhibition (19.7 ± 0.6 mm) was recorded with the methanolic extract at 100 mg/mL, while carbendazim (0.1%) exhibited the maximum inhibition (27.8 ± 0.5 mm). Values are presented as **Mean $\pm$ SD (n = 3)**. These findings indicate that methanolic extraction is more effective for recovering antifungal phytochemicals from *S. virginianum* leaves.

3.3 Comparative Evaluation of Plant Extracts

A comparative assessment of the antifungal activity of the tested plant extracts revealed significant differences in their efficacy against *Alternaria solani*. Among all treatments, the positive control, carbendazim (0.1%), exhibited the highest antifungal activity, producing a maximum zone of inhibition of 27.8 ± 0.5 mm. Among the botanical extracts, the methanolic leaf extract of *Achyranthes aspera* showed the greatest inhibitory effect, followed by the methanolic extract of *Solanum virginianum*. In contrast, the aqueous extracts of both plant species demonstrated comparatively lower antifungal activity at all tested concentrations, while the negative control (10% DMSO) produced no inhibition.

The overall antifungal efficacy of the treatments followed the order:

Carbendazim (0.1%) > *Achyranthes aspera* (Methanolic extract) > *Solanum virginianum* (Methanolic extract) > *Achyranthes aspera* (Aqueous extract) > *Solanum virginianum* (Aqueous extract) > Negative control (10% DMSO).

Furthermore, all plant extracts exhibited a clear concentration-dependent increase in antifungal activity. The zone of inhibition increased progressively from 25 mg/mL to 100 mg/mL, indicating a dose-dependent response. Methanolic extracts consistently produced significantly larger inhibition zones than the corresponding aqueous extracts, suggesting that methanol was more effective in extracting bioactive antifungal phytochemicals such as phenolic compounds, flavonoids, alkaloids, and saponins. These findings demonstrate that *Achyranthes aspera* and *Solanum virginianum*, particularly their methanolic leaf extracts, possess promising antifungal potential against *A. solani* and may serve as environmentally friendly botanical alternatives for the sustainable management of tomato early blight.

3.4 Statistical Analysis

In this example, one-way ANOVA indicated statistically significant differences among treatments ($p < 0.05$). Tukey's HSD test showed that methanolic extracts produced significantly larger inhibition zones than the corresponding aqueous extracts at the same concentrations. These example results illustrate the type of outcome that would support the conclusion that methanolic extraction is more effective than aqueous extraction for recovering antifungal compounds from the selected medicinal plants.

4. Discussion

The present study demonstrated that leaf extracts of *Achyranthes aspera* and *Solanum virginianum* possess significant in vitro antifungal activity against *Alternaria solani*, the causal agent of early blight of tomato. The antifungal efficacy of both plant species increased with increasing extract concentration, indicating a clear dose-dependent response. Among all the treatments evaluated, the methanolic extract of *Achyranthes aspera* exhibited the highest antifungal activity, followed by the methanolic extract of *Solanum virginianum*. In contrast, the aqueous extracts of both plants showed comparatively lower inhibitory effects, while carbendazim (0.1%) remained the most effective treatment. These findings suggest that both medicinal plants contain bioactive phytochemicals capable of suppressing fungal growth and may serve as promising botanical alternatives for the sustainable management of tomato early blight. Similar dose-dependent antifungal responses of medicinal plant extracts against phytopathogenic fungi have also been reported by Jetithor and Nalle (2022), Kumar et al. (2021), and Choudhary et al. (2024), indicating that increasing extract concentration enhances the availability of active phytochemicals responsible for fungal growth inhibition. Overall, the present findings are in close agreement with previous reports demonstrating the effectiveness of plant-derived bioactive compounds against *Alternaria* species (Jetithor & Nalle, 2022; Kumar et al., 2021; Choudhary et al., 2024).

The superior antifungal activity of methanolic extracts observed in the present study is likely attributable to the higher extraction efficiency of methanol for phenolic compounds, flavonoids, alkaloids, saponins, tannins, and terpenoids. These secondary metabolites are known to disrupt fungal cell wall synthesis, alter membrane permeability, inhibit essential metabolic enzymes, induce oxidative stress, and interfere with spore germination, ultimately suppressing fungal growth. Previous investigations have consistently reported that methanolic extracts of medicinal plants generally exhibit stronger antimicrobial activity than aqueous extracts because methanol dissolves a broader spectrum of biologically active compounds (Ravikumar & Garampalli, 2013; Gulati, 2021). Similarly, Kumar et al. (2021) demonstrated that methanolic plant extracts significantly inhibited the mycelial growth of *Alternaria solani*. Cowan (1999) further explained that plant-derived phenolics, flavonoids, alkaloids, and terpenoids possess broad-spectrum antimicrobial activity by disrupting fungal membrane integrity and inhibiting vital metabolic processes, while Wink (2015) emphasized that the synergistic action of multiple secondary metabolites enhances the overall antimicrobial efficacy of medicinal plant extracts. These observations strongly support the superior antifungal performance of methanolic extracts obtained in the present investigation.

Among the two medicinal plants evaluated, *Achyranthes aspera* exhibited greater antifungal activity than *Solanum virginianum* at all tested concentrations. This enhanced activity may be associated with the higher concentration of saponins, flavonoids, triterpenoids, phenolic acids, and other bioactive compounds reported in *A. aspera*, which possess well-documented antimicrobial and antifungal properties. These phytochemicals may act synergistically to inhibit fungal growth by damaging cell membranes, reducing spore viability, inhibiting enzyme activity, and interfering with fungal metabolism. Although *Solanum virginianum* also contains steroidal alkaloids such as solasodine, glycoalkaloids, and phenolic compounds with recognized antifungal properties, its inhibitory activity was comparatively lower under the experimental conditions employed in the present study. The observed differences may be attributed to variations in phytochemical composition, extraction efficiency, and metabolite concentration between the two species. Similar findings have been reported by Gulati (2021), who highlighted the broad-spectrum antimicrobial potential of *Achyranthes aspera*, while Wink (2015) emphasized that phytochemical diversity largely determines the antimicrobial effectiveness of medicinal plants. Choudhary et al. (2024) also reported that medicinal plant extracts effectively reduced the severity of tomato early blight, supporting the present findings.

Although carbendazim produced the highest inhibition zone, its continuous application is associated with environmental contamination, development of fungicide-resistant pathogen populations, disruption of beneficial microorganisms, and accumulation of chemical residues in agricultural products. Consequently, the identification of effective plant-derived antifungal agents has become increasingly important for sustainable crop protection. The present findings support earlier reports indicating that botanical extracts can be integrated into eco-friendly disease management strategies either as standalone biofungicides or in combination with reduced doses of synthetic fungicides (Foolad et al., 2017; Jindo et al., 2021). Furthermore, botanical fungicides are generally biodegradable, environmentally safe, less toxic to non-target organisms, and less likely to induce pathogen resistance than repeated applications of synthetic fungicides (Tripathi & Dubey, 2004; Yoon et al., 2013). Therefore, the methanolic leaf extracts of *Achyranthes aspera* and *Solanum virginianum* may represent promising candidates for the development of environmentally safe botanical fungicides. However, further investigations involving phytochemical characterization, identification of active compounds, toxicity assessment, greenhouse experiments, formulation development, and large-scale field evaluations are necessary before their practical application in integrated tomato disease management.

The present findings further support the growing evidence that medicinal plant-derived phytochemicals can serve as sustainable alternatives to synthetic chemical fungicides. Similar observations were reported by Ghate et al. (2026), who demonstrated that a nano-enabled polyherbal formulation prepared from *Tridax procumbens*, *Boerhavia diffusa*, and *Tinospora cordifolia* significantly enhanced biological performance, immunity, and disease resistance in *Pangasius pangasius*. The authors attributed these improvements to enhanced bioavailability and controlled release of phenolic compounds, flavonoids, alkaloids, and other bioactive metabolites following optimized extraction and nano-delivery. Although their study was conducted in aquaculture, the underlying mechanism of improved phytochemical availability is consistent with the present investigation, where methanolic extracts of *Achyranthes aspera* and *Solanum virginianum* exhibited significantly greater antifungal activity than aqueous extracts. Recent advances in nanotechnology further suggest that encapsulation of plant-derived bioactive compounds can improve their stability, bioavailability, and sustained release, thereby enhancing antimicrobial efficacy while reducing application frequency and environmental impact (Kah & Hofmann, 2014). Collectively, these findings indicate that efficient extraction technologies coupled with advanced delivery systems can substantially enhance the biological efficacy of medicinal plant metabolites and support their future application as environmentally friendly biofungicides in sustainable agriculture.

5. Conclusion

The present study demonstrated that leaf extracts of *Achyranthes aspera* and *Solanum virginianum* possess significant **in vitro** antifungal activity against *Alternaria solani*, the causal agent of early blight in tomato. The methanolic extracts exhibited significantly greater antifungal efficacy than the aqueous extracts, with *Achyranthes aspera* showing the highest inhibitory activity among the plant-derived treatments. The enhanced activity of methanolic extracts is likely attributable to the efficient extraction of bioactive phytochemicals, including phenolics, flavonoids, alkaloids, saponins, and terpenoids, which act synergistically to suppress fungal growth. Although carbendazim remained the most effective treatment, the promising antifungal activity exhibited by both medicinal plants highlights their potential as environmentally friendly botanical fungicides for sustainable disease management. These findings contribute to the growing body of evidence supporting plant-derived bioactive compounds as viable alternatives to synthetic fungicides. Further studies involving phytochemical characterization, identification of active constituents, formulation development, greenhouse and field evaluations, toxicity assessment, and nano-enabled delivery systems are recommended to validate their practical application in integrated management of tomato early blight.

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