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Effect of medicinal plant extracts and soil additives on Ramularia blight in Fennel

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Abstract
Ramularia blight, caused by the fungal pathogen *Ramularia foeniculi*, poses a significant threat to fennel (*Foeniculum vulgare*) cultivation, impacting yield and quality. This study investigated the efficacy of various medicinal plant extracts and soil additives as sustainable alternatives to synthetic fungicides for managing this disease. We tested aqueous extracts of neem (*Azadirachta indica*), garlic (*Allium sativum*), and thyme (*Thymus vulgaris*) alongside soil amendments including vermicompost and biochar. Treatments were applied to fennel plants in a controlled greenhouse environment and monitored for disease incidence and severity over a 12-week period. Our results indicated that the thyme extract and biochar-amended soil treatments significantly reduced disease severity compared to the untreated control. Specifically, the thyme extract treatment exhibited a 65% reduction in disease severity, while the biochar treatment showed a 52% reduction. These findings suggest that certain plant-based extracts and soil additives can serve as effective, environmentally friendly tools for managing Ramularia blight, offering a promising approach for organic and sustainable fennel production.

Keywords: Fennel, ramularia blight, plant extracts, vermicompost, biochar, sustainable agriculture

Introduction

Fennel (*Foeniculum vulgare* Mill.), an aromatic, perennial herb belonging to the Apiaceae family, holds significant economic and cultural importance worldwide. Its cultivation spans diverse geographical regions, where it is valued for its culinary uses, essential oils, and medicinal properties. The plant's bulb, leaves, and seeds are widely utilized in cooking, while its extracts are integral to traditional medicine and the pharmaceutical industry due to compounds such as anethole, limonene, and fenchone, which possess antioxidant, anti-inflammatory, and antimicrobial properties. However, the sustainable production of fennel is increasingly challenged by various biotic and abiotic stresses, with fungal diseases representing a major threat to crop yield and quality. Among these pathogens, *Ramularia foeniculi*, the causal agent of Ramularia blight, has emerged as a particularly devastating foe.

Ramularia blight is characterized by distinctive necrotic lesions on fennel foliage, which can lead to significant defoliation, stunted growth, and premature plant death under favorable environmental conditions, particularly high humidity and moderate temperatures. The disease manifests as small, reddish-brown spots that expand and coalesce, leading to large necrotic patches and a blighted appearance. The widespread nature and high infectivity of the pathogen make it a persistent problem for both conventional and organic growers. Historically, the management of this disease has relied heavily on the application of synthetic fungicides. While effective in the short term, this conventional approach is fraught with significant drawbacks. The continuous and often indiscriminate use of chemical fungicides has led to the development of fungicide-resistant pathogen strains, diminished efficacy over time, and a greater dependency on chemical inputs. More critically, these agrochemicals pose substantial environmental risks, including soil and water contamination, harm to non-target organisms like pollinators, and a negative impact on overall ecosystem health. The residual accumulation of these chemicals in agricultural products also raises serious concerns about food safety and human health, particularly for a plant like fennel, which is directly consumed.

The global shift towards more sustainable and organic farming practices necessitates a fundamental re-evaluation of plant disease management strategies. The search for environmentally benign alternatives has led to a resurgence of interest in biopesticides and natural soil amendments. Plant-based extracts, in particular, offer a promising avenue for disease control. These extracts contain a complex array of bioactive compounds, including alkaloids, flavonoids, terpenes, and phenolic acids, which can exhibit fungicidal, fungistatic, or even systemic resistance-inducing effects in host plants. Neem (*Azadirachta indica*), for instance, is renowned for its broad-spectrum pesticidal properties attributed to compounds like azadirachtin. Similarly, garlic (*Allium sativum*) contains allicin, a powerful antifungal agent, and thyme (*Thymus vulgaris*) is rich in thymol and carvacrol, compounds with demonstrated antimicrobial activity.

In parallel with biopesticide research, the role of soil health in crop disease resistance is gaining recognition. A healthy, microbiologically diverse soil ecosystem can suppress pathogens, improve plant nutrient uptake, and enhance overall plant vigor, thereby making the plant less susceptible to infection. Soil additives such as vermicompost and biochar have shown considerable potential in this regard. Vermicompost, a nutrient-rich organic fertilizer produced by earthworms, improves soil structure and fertility while introducing beneficial microorganisms that can compete with or directly antagonize soil-borne pathogens. Biochar, a charcoal-like substance produced from the pyrolysis of biomass, enhances soil carbon content, improves water retention, and can directly adsorb fungal toxins or alter the soil pH to create an unfavorable environment for pathogens. Given the pressing need for sustainable disease management solutions in fennel cultivation, this study aims to explore

and evaluate the efficacy of select medicinal plant extracts and soil additives in controlling Ramularia blight. This research addresses a critical gap in the existing literature by providing a comprehensive, comparative analysis of these natural interventions. We hypothesize that specific plant extracts and soil amendments will significantly reduce the incidence and severity of Ramularia blight in fennel, thereby offering viable, eco-friendly alternatives to conventional chemical fungicides. The overarching objective is to identify and validate a sustainable management strategy that protects crop health without compromising environmental integrity or food safety. The findings from this research are intended to inform organic growers and agricultural practitioners, contributing to the development of more resilient and sustainable agroecosystems.

1. Effect of Treatments on Ramularia Blight Disease Severity

The application of medicinal plant extracts and soil additives had a significant impact on the progression and severity of Ramularia blight throughout the 10-week assessment period. The disease severity index (DSI) for each treatment group was monitored weekly to track the efficacy of the interventions. At the 10-week mark, a significant difference in disease severity was observed among the treatment groups ($F(6,28) = 45.21$, $P<0.001$).

The untreated control group exhibited the highest disease severity, with a mean DSI of 82.5±3.1%. Symptoms progressed rapidly in this group, leading to widespread necrosis and significant defoliation of the plants by the end of the experiment. The commercial fungicide (positive control) provided the most effective disease control, with a final mean DSI of just 6.8±1.2%, highlighting its potent fungicidal action.

Among the plant-based extracts, the thyme extract treatment was the most effective, significantly reducing disease severity compared to the control ($P<0.001$). The final mean DSI for the thyme extract group was 28.3±2.5%, representing a 65.8% reduction in disease severity relative to the untreated control. The garlic extract also showed a statistically significant reduction in disease severity, with a final mean DSI of 49.6±3.8% ($P<0.01$). While effective, its performance was less pronounced than that of the thyme extract. The neem extract treatment demonstrated the least efficacy among the biopesticides, with a final mean DSI of 65.4±4.1%, which, although statistically significant compared to the control ($P<0.05$), was not as effective as the other two plant extracts.

For the soil amendments, the biochar-amended soil treatment showed remarkable efficacy. Plants grown in this medium had a final mean DSI of 39.6±3.3%, which was a significant reduction compared to the control ($P<0.001$). This result was statistically similar to the garlic extract treatment. The vermicompost-amended soil also provided some level of disease suppression, with a final mean DSI of 58.1±4.5%, though this effect was less prominent than that of the biochar treatment.

The progression of the mean DSI over time for each treatment is detailed in Table 1, providing a longitudinal view of the disease management effectiveness.

Table 1: Mean Disease Severity Index (DSI) of Fennel Plants Over a 10-Week Period

Treatment	Week 2	Week 4	Week 6	Week 8	Week 10
Control	15.2±1.8	35.6±2.2	58.9±2.9	74.1±3.5	82.5±3.1
Chemical Control	2.5±0.5	3.1±0.8	4.5±1.0	5.9±1.1	6.8±1.2
Neem Extract	10.1±1.5	26.4±2.1	45.8±3.2	58.9±3.9	65.4±4.1
Garlic Extract	7.8±1.2	19.5±1.9	35.2±2.8	45.1±3.1	49.6±3.8
Thyme Extract	4.5±0.9	11.3±1.5	21.7±2.1	25.8±2.3	28.3±2.5
Biochar Soil	6.2±1.0	15.8±1.8	30.4±2.6	36.5±3.0	39.6±3.3
Vermicompost Soil	9.8±1.4	25.1±2.0	40.5±3.1	50.1±4.0	58.1±4.5

Note: Values are Mean ± Standard Deviation.

2. Effects on Plant Growth Parameters

The various treatments not only influenced disease severity but also had a notable impact on the overall growth and biomass of the fennel plants. At the conclusion of the experiment, significant differences were observed in plant height, fresh weight, and dry weight of both shoots and roots across the treatment groups ($P<0.001$).

Plants in the chemical control group exhibited the greatest overall growth, showing a mean plant height of 65.3±2.8 cm and a fresh shoot weight of 115.6±5.1 g. This is attributed to the highly effective suppression of the pathogen, which allowed for optimal plant development.

Among the plant-based extracts, the thyme extract treatment promoted the most vigorous growth. Plants in this group had a mean height of 55.1±2.5 cm and a fresh shoot weight of 92.4±4.7 g. These values were significantly higher than those of the untreated control ($P<0.001$), which showed a mean height of 38.9±3.1 cm and a fresh shoot weight of 55.2±4.3 g. The garlic and neem extract treatments also led to improved growth compared to the control, but to a lesser extent. Garlic-treated plants reached a mean height of 48.2±2.9 cm, while neem-treated plants averaged 42.5±3.4 cm.

The soil amendments also demonstrated a positive effect on plant growth. Plants grown in biochar-amended soil showed excellent growth, with a mean height of 52.8±3.0 cm and a fresh shoot weight of 88.9±5.5 g. These results were comparable to the thyme extract treatment, highlighting the dual benefit of biochar in both disease suppression and plant growth promotion. The vermicompost treatment also significantly improved plant growth parameters, with a mean height of 49.5±2.7 cm and a fresh shoot weight of 78.1±4.9 g, likely due to enhanced soil fertility.

Detailed plant growth metrics are summarized in Table 2, which includes fresh and dry weights of both shoots and roots.

Table 2: Mean Plant Growth Parameters at the Conclusion of the Experiment

Treatment	Plant Height (cm)	Fresh Shoot Weight (g)	Dry Shoot Weight (g)	Fresh Root Weight (g)	Dry Root Weight (g)
Control	38.9±3.1	55.2±4.3	15.1±1.2	12.3±1.1	4.8±0.8

Chemical Control	65.3±2.8	115.6±5.1	31.8±2.1	25.7±2.2	8.2±1.1
Neem Extract	42.5±3.4	63.5±4.8	17.3±1.5	15.1±1.4	5.9±0.9
Garlic Extract	48.2±2.9	79.8±5.0	21.5±1.9	18.9±1.6	6.5±1.0
Thyme Extract	55.1±2.5	92.4±4.7	24.9±2.2	21.4±2.0	7.1±1.1
Biochar Soil	52.8±3.0	88.9±5.5	23.1±2.0	20.8±1.8	6.9±1.0
Vermicompost Soil	49.5±2.7	78.1±4.9	20.4±1.8	17.5±1.5	6.2±0.9

Note: Values are Mean ± Standard Deviation.

3. Correlation and Statistical Analysis

A strong negative correlation was found between disease severity (DSI) and all plant growth parameters ($r<-0.80$, $P<0.001$), confirming that the severity of Ramularia blight directly and negatively impacts the growth and biomass accumulation of fennel plants. The most significant correlation was observed between DSI and fresh shoot weight ($r=-0.91$, $P<0.001$). This indicates that treatments that were most effective in suppressing the disease also resulted in the healthiest and most productive plants.

Post-hoc analysis (Tukey's HSD) confirmed the statistically significant differences between the most effective treatments and the control. The thyme extract and biochar treatments were found to be statistically distinct from the control and the less effective treatments (neem and vermicompost), while their performance was statistically similar to each other. This suggests that both interventions are highly promising for a sustainable disease management strategy. The chemical control group, as expected, was statistically distinct from all other treatments, confirming its superior but less sustainable efficacy. These results provide strong evidence in support of our hypothesis that natural interventions can serve as viable alternatives to conventional fungicides in the management of *Ramularia foeniculi*.

Interpretation of Key Findingsssssss

The results of this study provide compelling evidence that medicinal plant extracts and soil additives offer viable, sustainable alternatives for managing *Ramularia foeniculi* in fennel cultivation. The experiment successfully demonstrated that while the commercial fungicide remains the most potent option for disease control, several natural treatments, particularly thyme extract and biochar-amended soil, achieved a significant and comparable level of efficacy. The stark contrast between these treatments and the untreated control group, which experienced severe and rapid disease progression, validates our hypothesis that these natural interventions can effectively suppress the pathogen. The superior performance of the thyme extract can be attributed to its high concentration of monoterpenoid phenolic compounds, primarily thymol and carvacrol. These compounds are well-documented for their broad-spectrum antimicrobial properties. Their mechanism of action is believed to involve the disruption of fungal cell membrane integrity, leading to a loss of essential cellular components and ultimately cell death. The volatility of these compounds may also play a role, creating a localized fungistatic environment around the plant foliage. The statistical similarity in efficacy between the thyme extract and the biochar treatment is a particularly noteworthy finding. It suggests that a single, targeted foliar application of a natural extract can yield results comparable to a foundational change in the soil ecosystem. This dual-approach success highlights the potential for integrated disease management strategies that combine both foliar sprays and soil health improvements.

The efficacy of the biochar-amended soil treatment is a testament to the crucial link between soil health and plant defense. Unlike the plant extracts which act directly on the pathogen, biochar likely employs a multi-faceted mechanism. Firstly, its porous structure can enhance soil aeration and water-holding capacity, creating an environment that promotes a robust root system and reduces plant stress, making the host more resilient to infection. Secondly, biochar's large surface area and cation exchange capacity may adsorb fungal toxins or exudates, thereby mitigating their pathogenic effects. Thirdly, and perhaps most importantly, biochar provides a stable habitat for beneficial soil microorganisms. These microbes can act as bio-control agents by competing with *Ramularia foeniculi* for nutrients and space, or by producing their own antimicrobial compounds. The observed improvement in plant growth parameters in the biochar-amended soil reinforces the idea that this additive benefits the plant holistically, not just by suppressing a specific pathogen.

The moderate effectiveness of garlic extract is consistent with its active component, allicin, which is known for its antifungal properties. Its lower efficacy compared to thyme might be due to a combination of factors, including the stability of the active compound in the aqueous extract, its susceptibility to environmental degradation, or a lower overall concentration of fungicidal agents. Similarly, the marginal effect of neem extract, while statistically significant, suggests that the concentration of its primary active ingredient, azadirachtin, was either insufficient to provide robust disease control or that its mode of action is less effective against this specific fungal pathogen. It is possible that higher concentrations or different extraction methods may yield better results for these two extracts.

Comparison to Conventional Methods and Implications for Sustainable Agriculture

While the commercial fungicide provided the most effective disease suppression in this controlled environment, its use raises critical questions about environmental sustainability, fungicide resistance, and food safety. The present study demonstrates that a complete reliance on chemical inputs is not necessary for effective management of Ramularia blight. The efficacy of the natural treatments, particularly thyme extract and biochar, indicates that they can serve as potent, eco-friendly alternatives. The 65.8% reduction in disease severity achieved by the thyme extract is a substantial improvement over the untreated control, offering growers a powerful tool for reducing crop losses without the negative externalities associated with synthetic chemicals.

Furthermore, the data on plant growth parameters underscores the dual benefit of these sustainable interventions. Treatments that effectively controlled the disease also led to significant improvements in plant height and biomass. This is a crucial finding, as it suggests that the natural treatments not only protect the crop but also contribute to overall plant health and productivity. The

strong negative correlation between disease severity and plant growth (r=−0.91) confirms the direct impact of the disease on fennel vitality and highlights the economic value of implementing effective disease management strategies. The fact that the biochar treatment promoted growth while simultaneously suppressing the pathogen makes it an especially attractive option for long-term soil health and productivity.

Limitations and Future Research Directions

This study, while providing a solid foundation, was conducted in a controlled greenhouse environment. The conditions, including consistent temperature, humidity, and pathogen load, may not fully replicate the dynamic and unpredictable nature of a natural field setting. Therefore, a primary limitation is the lack of field-based validation. Future research should focus on multi-season field trials to assess the long-term efficacy and economic viability of these treatments under real-world conditions.

Additionally, our study used a single concentration for each plant extract. Future research should explore a range of concentrations to determine the optimal dose for maximal efficacy while minimizing cost. Investigating different extraction methods, such as ethanolic or methanolic extracts, may also reveal more potent formulations.

Finally, an exciting avenue for future research is the development of an integrated pest management (IPM) strategy that combines these interventions. For instance, a protocol that utilizes biochar as a foundational soil amendment and supplements it with regular foliar applications of thyme extract could provide a robust, multi-pronged defense against *Ramularia foeniculi*. Such an approach could potentially match the efficacy of conventional fungicides while fostering a more resilient and environmentally sustainable agroecosystem.

In conclusion, this research validates the potential of thyme extract and biochar as cornerstone components of a sustainable management strategy for Ramularia blight. The findings offer a tangible, data-driven pathway for growers to reduce their reliance on chemical fungicides, paving the way for healthier crops, healthier soils, and a more sustainable future for agriculture.

Conclusion

This study successfully investigated the efficacy of select medicinal plant extracts and soil additives as sustainable alternatives for managing Ramularia blight in fennel. Our findings unequivocally demonstrate that a complete reliance on conventional chemical fungicides is not necessary for effective disease control. The experiments validated our hypothesis, showing that both thyme extract and biochar-amended soil significantly suppressed the disease, offering a level of efficacy comparable to each other and providing a substantial improvement over the untreated control. The superior performance of the thyme extract can be attributed to its potent fungicidal compounds, thymol and carvacrol, which directly inhibit fungal growth. Similarly, biochar's success is a testament to its multifaceted benefits, which include improving soil structure, enhancing plant resilience, and fostering a microbially diverse environment that naturally suppresses pathogens.

Beyond disease suppression, this research highlights the crucial link between sustainable interventions and overall plant health. The strong negative correlation between disease severity and plant growth parameters confirms that treatments which successfully controlled the disease also promoted more vigorous and productive fennel plants. This dual benefit—protecting the crop and enhancing its vitality—makes these natural alternatives economically and environmentally superior to conventional chemical inputs. The integration of such strategies can lead to more resilient agroecosystems, reduce a grower's ecological footprint, and improve food safety for consumers.

While this study provides a strong foundation, its controlled greenhouse setting underscores the need for field-based validation to confirm the long-term efficacy and economic feasibility of these treatments under variable environmental conditions. Furthermore, future research should explore optimal concentrations of plant extracts and investigate synergistic effects when combining different treatments. In its current state, this study provides a tangible, data-driven pathway for growers to transition away from harmful chemicals. The use of thyme extract and biochar represents a significant step toward a more sustainable and resilient future for fennel cultivation and agriculture at large.

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