Research Horizon

ISSN: 2808-0696 (p), 2807-9531 (e)

Research Horizon
Volume: 06
Issue: 04
Year: 2026
Page: 1769-1782

Citation:
Sipayung, A. C. N. A., Sudiarta, I. P., & Phabiola, T. A. (2026). Effectiveness of lemongrass against *Fusarium oxysporum* wilt disease in tomato. *Research Horizon*, *6*(4), 1769-1782.

Article History:
Received: July 20, 2026
Revised: August 7, 2026
Accepted: August 20, 2026
Online since: August 25, 2026

Effectiveness of Lemongrass Against *Fusarium oxysporum* Wilt Disease in Tomato

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Abstract

Tomato (*Solanum lycopersicum*) production is severely constrained by *Fusarium* wilt caused by *Fusarium oxysporum*, a soil-borne pathogen that disrupts vascular tissues and reduces plant growth and productivity. Although synthetic fungicides are widely used, their environmental impacts have encouraged the development of sustainable alternatives. This study aimed to evaluate the effectiveness of citronella (*Cymbopogon citratus*) essential oil as a botanical pesticide for suppressing *Fusarium* wilt and improving tomato plant growth under greenhouse conditions. The experiment employed a Randomized Block Design consisting of five treatments (0, 0.25, 0.50, 0.75, and 1.00% Lemongrass) with five replications. Disease incidence and plant height were measured, and the data were analyzed using analysis of variance followed by Duncan's Multiple Range Test at the 5% significance level. The results showed that Lemongrass significantly reduced disease incidence while enhancing plant growth. The 1.00% treatment produced the lowest disease incidence (10.00%) and the greatest plant height (25.00 cm), whereas the control treatment exhibited 100.00% disease incidence and the lowest plant height (7.00 cm). These findings indicate that citronella essential oil is a promising environmentally friendly botanical pesticide for managing *Fusarium* wilt while supporting tomato growth.

Keywords

Botanical Pesticide, *Cymbopogon citratus*, *Fusarium oxysporum*, *Solanum lycopersicum*, Wilt Disease.

1. Introduction

Tomato (*Solanum lycopersicum*) is one of the important horticultural commodities with high economic value and a significant role in fulfilling food and nutritional needs. Tomatoes are widely consumed as fresh food products and utilized as raw materials in various food industries due to their nutritional composition, including vitamin A, vitamin C, and lycopene, which provide beneficial effects for human health. The increasing market demand has positioned tomatoes as one of the most widely cultivated vegetable crops in Indonesia. However, tomato production continues to encounter several constraints, particularly biotic stresses caused by plant pathogens that significantly affect crop productivity and quality (Laoth et al., 2026). According to the Central Statistics Agency (*Badan Pusat Statistik/*BPS), tomato production in Lampung Province declined from 24,490 tons in 2015 to 19,604 tons in 2019, with plant disease incidence being one of the contributing factors to this reduction (Badan Pusat Statistik, 2019).

One of the major diseases affecting tomato cultivation is *Fusarium* wilt, which is caused by the soil-borne pathogen *Fusarium oxysporum.* This pathogen is considered highly destructive because it can survive in soil for extended periods through the formation of resistant structures such as chlamydospores, allowing it to persist even in the absence of susceptible hosts. The infection process begins when fungal propagules penetrate plant roots and subsequently colonize the xylem vessels, resulting in disruption of water and nutrient transport within the plant. Infected plants commonly exhibit symptoms including leaf chlorosis, vascular discoloration, wilting, reduced vegetative growth, and plant death under severe infection conditions (Agrios, 2005; Michielse & Rep, 2009). Yield losses caused by *Fusarium* wilt may reach 30–80%, depending on pathogen population density, environmental conditions, plant resistance level, and cultivation practices (Jones et al., 2014).

The management of *Fusarium* wilt disease has primarily relied on synthetic fungicides due to their rapid and effective pathogen suppression capabilities. Nevertheless, the continuous and excessive application of chemical fungicides has raised concerns regarding the development of fungicide-resistant pathogen populations, accumulation of chemical residues in agricultural products, environmental contamination, and disruption of beneficial soil microbial communities that contribute to ecosystem stability (McGovern, 2015). These limitations have encouraged the exploration of environmentally sustainable disease management strategies, including the utilization of botanical pesticides derived from plant-based bioactive compounds. Botanical pesticides are considered promising alternatives because they generally exhibit biodegradability, lower environmental risks, and diverse mechanisms of antimicrobial action (Bakkali et al., 2008; Shaaban et al., 2022).

Lemongrass (*Cymbopogon citratus*) essential oil is one of the botanical resources with considerable potential as an antifungal agent. This essential oil contains various bioactive compounds, particularly citral, geraniol, and citronellal, which exhibit antimicrobial properties against several fungal pathogens. These compounds can interfere with fungal cell membrane integrity, increase membrane permeability, disrupt cellular metabolism, and ultimately inhibit fungal growth and development (Bakkali et al., 2008; Tajkarimi et al., 2010). Previous studies by Somda et al. (2007) have demonstrated the antifungal activity of lemongrass oil against several plant-associated fungi, indicating its potential application as an environmentally friendly component in integrated disease management strategies.

Although previous studies by Boukhatem et al. (2014) have reported the antifungal properties of lemongrass essential oil, comprehensive evaluation of its effectiveness against *Fusarium oxysporum* under plant cultivation conditions remains limited. Most existing studies have focused primarily on in vitro inhibition of fungal growth, whereas the effectiveness of botanical pesticides should also be assessed based on their ability to reduce disease development and maintain plant growth under infected conditions. The evaluation of plant responses is essential because successful disease management is not only determined by pathogen suppression but also by the capacity of treatment applications to preserve plant health and productivity.

Therefore, this study aims to evaluate the effectiveness of lemongrass (*Cymbopogon citratus*) essential oil as a botanical pesticide in suppressing *Fusarium* wilt disease caused by *Fusarium oxysporum* and improving the growth performance of tomato plants (*Solanum lycopersicum*) under greenhouse conditions. This research contributes to the development of sustainable plant disease management practices by providing scientific evidence regarding the potential use of lemongrass essential oil as an environmentally friendly alternative for controlling soil-borne pathogens.

2. Literature Review

2.1. *Fusarium* Wilt Disease in Tomato Plants

Fusarium oxysporum is a destructive soil-borne fungal pathogen responsible for *Fusarium* wilt disease in tomato plants (*Solanum lycopersicum*). The pathogen survives in agricultural soils for long periods through resistant structures and infects plants primarily through the root system. After penetrating the roots, *F. oxysporum* colonizes the xylem vessels, interfering with water and nutrient transportation throughout the plant. This vascular colonization causes physiological disruption, resulting in reduced plant vigor, chlorosis, wilting, and growth inhibition. The disease development generally begins with root infection, followed by vascular discoloration, leaf yellowing, and progressive wilting that may lead to plant death under severe infection conditions (Attia et al., 2022; Rao et al., 2022). Mosa and El-Abeid (2023) reported that the severity of *Fusarium* wilt is influenced by pathogen aggressiveness, environmental conditions, and the susceptibility of tomato plants, making the disease a major limiting factor in tomato production.

The impact of *Fusarium* wilt is not only associated with visible disease symptoms but also with reduced plant growth and yield performance. Akram et al. (2024) reported that infection by *F. oxysporum* can decrease root function, impair nutrient uptake, and disturb physiological processes required for optimal plant development. Simamora et al. (2022) and Taruna et al. (2024) reported that *Fusarium* wilt remains a significant challenge in tomato cultivation, prompting the exploration of sustainable management approaches, including biological control agents and plant growth-promoting microorganisms. The application of beneficial microorganisms, such as *Trichoderma*, *Bacillus*, and *Pseudomonas*, has been shown to reduce pathogen development and improve plant resistance against *Fusarium* wilt (Sriwahyuni et al., 2023; Resti & Marsuni, 2026). Therefore, understanding the infection mechanism, symptom development, and effects of *F. oxysporum* infection is essential for developing effective and environmentally friendly disease management strategies.

2.2. Lemongrass Essential Oil as a Botanical Pesticide

Lemongrass (*Cymbopogon citratus*) essential oil has gained attention as a botanical pesticide due to its bioactive compounds and diverse biological activities. The essential oil contains several phytochemical constituents, including citral, geraniol, citronellal, and other terpenoid compounds that contribute to its antimicrobial properties (Sari et al., 2025). According to Saulie et al. (2024), phytochemical screening of lemongrass (*Cymbopogon citratus*) revealed the presence of bioactive compounds with potential biological activities, while Adiwiguna et al. (2025) emphasized that lemongrass compounds have been widely utilized due to their antioxidant, antimicrobial, and protective properties. Furthermore, Ahmed and Abdelwines (2024) reported that lemongrass essential oil exhibited biological activity against arthropod pests, demonstrating its potential as a natural control agent. The effectiveness of essential oils as botanical pesticides is also influenced by their chemical composition and formulation, as demonstrated by Idris et al. (2022), who found that essential oil formulations significantly affected antifungal activity. These findings indicate that lemongrass essential oil has potential as an environmentally friendly alternative for agricultural pest and disease management.

The antifungal mechanism of lemongrass essential oil is mainly associated with the disruption of fungal cellular structures and inhibition of pathogen development. Nurmansyah et al. (2023) reported that essential oils have potential in suppressing *Fusarium oxysporum* through antifungal mechanisms involving inhibition of fungal growth and mycelial development. Similarly, Pratiwi et al. (2025) demonstrated that lemongrass oil exhibited fungicidal activity against *Fusarium oxysporum* in chili plants, reducing pathogen development and disease severity. In addition, Baranová et al. (2025) highlighted that lemongrass essential oil possesses biological activity due to its secondary metabolites, supporting its application as a natural plant protection agent. By reducing pathogen infection, lemongrass essential oil can help maintain plant physiological processes, including water and nutrient uptake, thereby supporting plant growth. Therefore, lemongrass essential oil has considerable potential as a sustainable botanical pesticide for managing *Fusarium* wilt disease.

3. Methods

The research was conducted from April to July 2026 in the Experimental Garden Greenhouse and Plant Disease Laboratory, Faculty of Agriculture, Udayana University. The research activities included the preparation of *Fusarium oxysporum* inoculum, application of citronella (*Cymbopogon citratus*) oil as a botanical pesticide, and observation of disease development and tomato plant growth responses under greenhouse conditions. The materials used in this study included *Fusarium oxysporum* isolates, Lemongrass (*Cymbopogon citratus*), tomato seeds (*Solanum lycopersicum*), sterile soil, manure, sterile distilled water, 70% alcohol, Tween 80, and other supporting materials. The equipment used consisted of a laminar airflow cabinet, autoclave, incubator, micropipettes, measuring cylinders, Erlenmeyer flasks, sprayers, polybags, rulers, analytical balances, cameras, and other supporting laboratory and cultivation equipment.

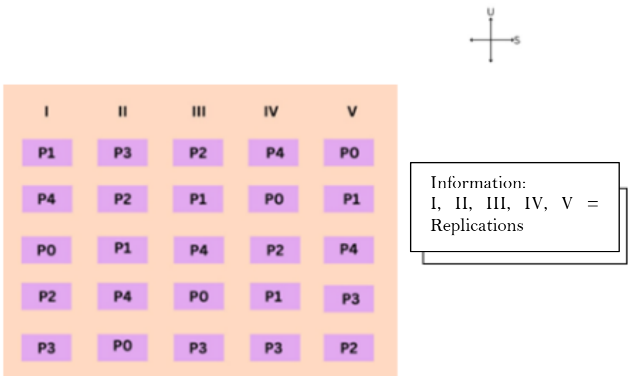

Figure 1. Experimental Layout

The experiment was arranged using a Randomized Block Design (RBD) with five treatments and five replications, in shown in Figure 1. Each treatment consisted of four polybags, resulting in a total of 100 experimental units (5 treatments × 5 replications × 4 polybags). Lemongrass solutions were applied periodically by watering the growing medium on days 1, 7, 14, and 21 after planting. The treatments consisted of P0 (soil + 10 ml *Fusarium* sp. suspension), P1 (soil + 0.25% Lemongrass solution + 10 ml *Fusarium* sp. suspension), P2 (soil + 0.50% Lemongrass solution + 10 ml *Fusarium* sp. suspension), P3 (soil + 0.75% Lemongrass solution + 10 ml *Fusarium* sp. suspension), and P4 (soil + 1.00% Lemongrass solution + 10 ml *Fusarium* sp. suspension).

The percentage of *Fusarium* wilt disease incidence was evaluated to determine the effectiveness of Lemongrass in suppressing disease development in tomato plants. Disease observations were conducted every three days from 0 to 21 days after pathogen inoculation. The percentage of disease incidence was calculated by comparing the number of plants showing wilt symptoms with the total number of plants observed in each treatment. The calculation was performed using the following formula:

$$P = \frac{A}{N} \times 100\%$$

Information:
P = Percentage of disease incidence (%)
A = Number of plants showing wilt symptoms in each treatment
N = Total number of plants observed in each treatment

The percentage calculation was used to assess the ability of Lemongrass treatments to reduce *Fusarium* wilt development during the observation period, based on the plant disease epidemiology approach described by Gottwald (1995) and Campbell and Madden (1990). Plant growth responses were evaluated through plant height measurements. Plant height was measured from the surface of the growing medium to the highest point of each plant using a ruler. Measurements were conducted periodically throughout the experimental period to evaluate the effect of Lemongrass application on tomato growth under *Fusarium oxysporum* infection conditions. The obtained data were analyzed using Analysis of Variance (ANOVA). When significant differences were detected, treatment comparisons were further analyzed using Duncan's Multiple Range Test (DMRT) at a 5% significance level.

4. Results

4.1. Disease Symptoms after *Fusarium oxysporum* Inoculation

Following *Fusarium oxysporum* inoculation, tomato plants exhibited a gradual development of *Fusarium* wilt symptoms. The initial symptoms were observed as root discoloration, changing from white to brown, followed by browning at the stem base, leaf chlorosis, and eventually wilting of the entire plant in Figure 2. The sequential development of these symptoms indicates that the pathogen infects tomato plants through the root system and subsequently colonizes the xylem vascular tissue, resulting in disruption of water and nutrient transport. This vascular blockage causes physiological disturbances, including reduced turgor pressure, chlorosis, and irreversible wilting. These findings are consistent with Agrios (2005), who reported that *Fusarium* wilt symptoms develop progressively as *F. oxysporum* spreads and colonizes the xylem vessels.

The brown discoloration observed in infected roots is associated with pathogen colonization and damage to root tissues. Similarly, discoloration at the stem base indicates the progression of pathogen invasion into the vascular system. The colonization of xylem vessels by *F. oxysporum* restricts water movement within the plant, leading to impaired physiological functions and visible symptoms such as leaf chlorosis, loss of turgidity, and wilting. This condition occurs due to the accumulation of fungal mycelium and plant defense responses that contribute to xylem vessel obstruction, thereby reducing water transport efficiency (Beckman, 1987; Agrios, 2005).

At advanced stages of infection, tomato plants showed severe symptoms characterized by permanent wilting and plant death. In addition to physical blockage of xylem vessels, *F. oxysporum* can produce toxic metabolites that accelerate tissue damage and interfere with normal plant physiological processes (Bacon et al., 1996; Michielse & Rep, 2009). Therefore, the progression of disease symptoms observed in this study, beginning from the roots, extending to the stem base, leaves, and finally the entire plant, represents the typical infection pattern of *F. oxysporum* as a vascular wilt pathogen.

Figure 2. (a) Wilting Symptoms of the Whole Plant (b) Leaf Chlorosis (c) Brown Discoloration of the Roots (d) Brown Discoloration of the Stem Base

Figure 2 illustrates the visible symptoms of plant damage, including whole-plant wilting (a), leaf chlorosis (b), brown discoloration of roots (c), and brown discoloration at the stem base (d). The wilted appearance indicates impaired plant water uptake, while chlorosis reflects reduced leaf health and possible nutrient or physiological stress. The browning of roots and stem tissues suggests tissue deterioration associated with pathogen infection or environmental stress, indicating a decline in overall plant vigor.

4.2. Percentage of Disease Incidence in Tomato Plants

Observations revealed that the application of lemongrass (*Cymbopogon citratus*) oil significantly reduced the incidence of *Fusarium* wilt disease caused by *Fusarium oxysporum* in tomato plants. Disease incidence was monitored every three days up to 21 Days After Inoculation (DAI), and the average percentage of disease incidence at the end of the observation period is presented in Table 1.

Table 1. Average Percentage of *Fusarium Oxysporum* Wilt Disease in Tomato Plants

Lemongrass Concentration (%)	Disease Incidence (%)
Control	100.00 e
0.25	55.00 d
0.50	35.00 c
0.75	20.00 b
1.00	10.00 a

Based on Table 1, the application of Lemongrass significantly reduced the incidence of *Fusarium* wilt disease compared with the control treatment. At the end of the observation period, all plants in the control treatment exhibited disease symptoms, resulting in a disease incidence of 100.00%. In contrast, the application of Lemongrass progressively decreased disease incidence as the concentration increased. The lowest disease incidence was recorded in the 1.00% Lemongrass treatment, with only 10.00% of plants showing symptoms. The results of the DMRT test at the 5% significance level indicated that all treatments differed significantly, demonstrating that different concentrations of Lemongrass provided varying levels of effectiveness in suppressing the development of *Fusarium* wilt disease.

The ability of Lemongrass to reduce disease incidence is likely associated with its bioactive compounds, including citral, citronellal, geraniol, and citronellol, which possess antifungal properties. These compounds can disrupt fungal cell membrane integrity, increase membrane permeability, interfere with cellular metabolism, and inhibit mycelial growth, thereby reducing the pathogenic ability of *Fusarium oxysporum* (Bakkali et al., 2008; Tajkarimi et al., 2010). Furthermore, early suppression of pathogen growth may limit fungal colonization within xylem vascular tissues, consequently reducing the severity and incidence of *Fusarium* wilt symptoms in infected plants (Agrios, 2005).

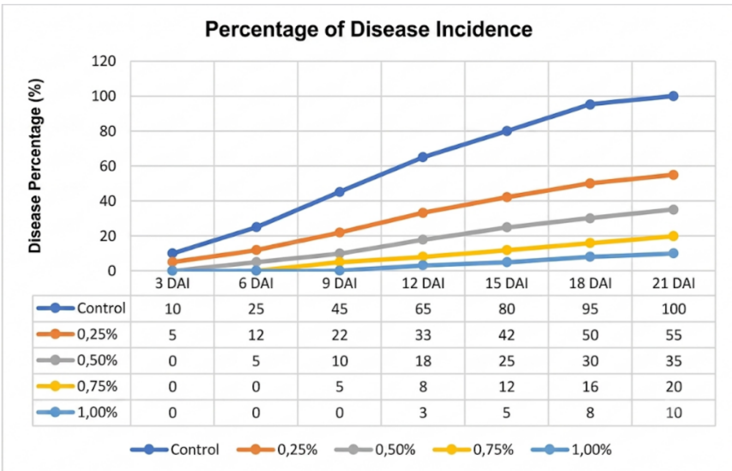

Figure 3. Development of *Fusarium oxysporum* wilt disease incidence in tomato plants during the observation period

The progression of disease incidence throughout the observation period is presented in Figure 3. Disease incidence increased gradually in all treatments as the observation period progressed; however, the rate of disease development differed among Lemongrass concentrations. The control treatment exhibited the most rapid disease progression, reaching 100% incidence at 21 days after inoculation. Conversely, Lemongrass treatments, particularly at concentrations of 0.75% and 1.00%, effectively delayed disease development and maintained lower disease incidence throughout the observation period. These results indicate that higher concentrations of Lemongrass provided greater suppression of *F. oxysporum* infection in tomato plants.

The results of this study are consistent with the findings of Shaaban et al. (2022), who reported that lemongrass oil (*Cymbopogon citratus*) contains bioactive compounds, including citral, geraniol, and citronellal, which exhibit antifungal activity through mechanisms involving fungal cell membrane disruption, increased membrane permeability, and inhibition of cellular metabolism. These findings are further supported by Somda et al. (2007), who demonstrated that lemongrass oil effectively suppresses the growth of several plant pathogenic fungi by inhibiting mycelial development and spore germination. Therefore, lemongrass oil has considerable potential as an effective and environmentally friendly botanical pesticide for controlling *Fusarium* wilt disease caused by *Fusarium oxysporum* in tomato plants.

4.3. Tomato Plant Height

The observations indicated that the application of Lemongrass (*Cymbopogon citratus*) had a significant effect on the height of tomato plants inoculated with *Fusarium oxysporum.* The mean plant height values for each treatment are presented in Table 2.

Table 2. Average height of tomato plants.

Lemongrass Concentration (%)	Plant Height (cm)
Control	7.00 e
0.25	15.00 d
0.50	20.00 c
0.75	23.00 b
1.00	25.00 a

Description: Numbers followed by different letters in the same column indicate significant differences based on the DMRT test at the 5% level.

Based on Table 2, the application of Lemongrass significantly increased tomato plant height compared with the control treatment. The control plants exhibited the lowest average height (7.00 cm), whereas plants treated with 1.00% Lemongrass showed the highest average height (25.00 cm). The results of the DMRT test at the 5% significance level indicated that all treatments were significantly different from each other, suggesting that increasing Lemongrass concentrations resulted in varying effects on tomato plant growth.

Figure 4. Final condition of tomato plants after Lemongrass (*Cymbopogon citratus*) application and *Fusarium oxysporum* inoculation. Treatments from left to right: P4 (1.00%), P3 (0.75%), P2 (0.50%), P1 (0.25%), and control.

The growth conditions of tomato plants under each treatment are presented in Figure 4. Plants treated with Lemongrass, particularly at concentrations of 0.75% and 1.00%, exhibited better growth performance, characterized by straighter stems and greener leaves compared with the control plants. In contrast, control plants showed more severe wilting symptoms, with most plants displaying stunted growth, leaf chlorosis, and extensive wilting associated with *Fusarium oxysporum* infection.

The increase in plant height is presumed to be associated with the ability of lemongrass oil to suppress the growth of *Fusarium oxysporum*, thereby minimizing damage to the root system and vascular tissues. This condition enables more efficient water and nutrient uptake, which subsequently supports optimal vegetative growth of tomato plants (Agrios, 2005; Jones et al., 2014). The antifungal activity of lemongrass oil is attributed to its bioactive compounds, including citral, citronellal, geraniol, and citronellol, which inhibit fungal development through mechanisms involving cell membrane disruption, increased membrane permeability, and interference with fungal metabolism (Bakkali et al., 2008; Tajkarimi et al., 2010).

The findings of this study are consistent with those reported by Shaaban et al. (2022), who stated that the antifungal properties of lemongrass oil can inhibit pathogen development, allowing plants treated with lemongrass oil to maintain better growth performance compared with untreated plants. Similar findings were reported by Somda et al. (2007), who demonstrated that lemongrass oil exhibits antifungal activity against various plant pathogens, highlighting its potential for development as a botanical pesticide. Therefore, Lemongrass has considerable potential as a botanical pesticide that not only suppresses *Fusarium* wilt disease but also contributes to maintaining and improving tomato plant growth.

5. Discussion

The findings of this study demonstrate that Lemongrass (*Cymbopogon citratus*) has a promising role in suppressing *Fusarium* wilt disease and maintaining tomato plant growth under *Fusarium oxysporum* infection. The reduction in disease incidence observed following Lemongrass application indicates that the essential oil possesses protective properties against vascular pathogens. The effectiveness of Lemongrass in reducing disease development is likely related to its ability to inhibit pathogen establishment during the early stages of infection, thereby limiting fungal colonization and preventing extensive damage to plant tissues. Since *F. oxysporum* is a soil-borne pathogen that primarily invades plants through the roots and spreads through xylem vessels, early inhibition of fungal growth is critical for reducing disease severity (Agrios, 2005).

The antifungal activity of Lemongrass is mainly associated with its phytochemical constituents, particularly citral, citronellal, geraniol, and citronellol. These compounds have been reported to exhibit strong antimicrobial properties by affecting fungal cell membrane structure and function. According to Bakkali et al. (2008), essential oil components can penetrate fungal cell membranes, causing increased permeability, leakage of cellular components, and disruption of essential metabolic processes. Similarly, Tajkarimi et al. (2010) explained that plant-derived essential oils can interfere with fungal respiration and enzyme activity, resulting in inhibited mycelial growth and reduced pathogen viability. Therefore, the suppressive effect of Lemongrass against *F. oxysporum* may occur through multiple antifungal mechanisms rather than a single mode of action.

The ability of Lemongrass to suppress *Fusarium* wilt is consistent with previous studies reporting the antifungal potential of lemongrass-derived essential oils against plant pathogens. Shaaban et al. (2022) demonstrated that lemongrass oil contains bioactive compounds capable of inhibiting fungal development through membrane disruption and metabolic interference. Furthermore, Somda et al. (2007) reported that lemongrass oil exhibited inhibitory activity against several phytopathogenic fungi by restricting mycelial growth and spore germination. These findings support the potential application of Lemongrass as a botanical pesticide that can provide an environmentally safer alternative to synthetic fungicides.

In addition to reducing disease development, the application of Lemongrass contributed to improved tomato plant growth under pathogen pressure. Plants infected with *F. oxysporum* commonly experience growth inhibition due to vascular obstruction, impaired water transport, and reduced nutrient availability. The improved growth performance observed in Lemongrass-treated plants suggests that suppression of pathogen activity helped maintain physiological functions, particularly water and nutrient uptake. Beckman (1987) reported that *Fusarium* wilt development is strongly associated with xylem colonization, which disrupts the movement of water within plants and causes physiological stress. By limiting fungal colonization, Lemongrass may indirectly preserve vascular function and support continued vegetative development.

The positive response of tomato plants to increasing Lemongrass concentrations also indicates a concentration-dependent relationship between essential oil application and disease suppression. Higher concentrations likely provided greater amounts of antifungal compounds, resulting in stronger inhibition of pathogen activity. However, the effectiveness of botanical pesticides depends not only on compound concentration but also on their ability to interact with plant and pathogen systems without causing phytotoxic effects. The results suggest that Lemongrass at appropriate concentrations can achieve a balance between pathogen suppression and plant growth support. This study strengthens previous evidence regarding the potential of *Cymbopogon citratus* essential oil as a botanical control agent against *F. oxysporum.* Its dual function in reducing *Fusarium* wilt development and maintaining tomato plant growth highlights its potential for sustainable disease management strategies. Further studies involving field-scale application, formulation optimization, and evaluation of long-term effects are needed to support its practical use in agricultural production systems.

6. Conclusion

This study demonstrated that citronella (*Cymbopogon citratus*) essential oil is effective as a botanical pesticide for suppressing *Fusarium* wilt caused by *Fusarium oxysporum* while simultaneously improving the growth performance of tomato plants. The application of Lemongrass significantly reduced disease incidence and increased plant height compared with the untreated control. Among the tested concentrations, 1.00% Lemongrass provided the greatest effectiveness, resulting in the lowest disease incidence and the highest plant height. These findings indicate that the bioactive compounds present in Lemongrass, including citral, citronellal, geraniol, and citronellol, play an important role in inhibiting pathogen development, thereby preserving plant vascular function and supporting normal physiological processes. The dual ability of Lemongrass to reduce disease pressure while promoting plant growth highlights its potential as an environmentally friendly alternative to synthetic fungicides and supports its application in sustainable tomato disease management.

Despite these promising findings, several limitations should be considered. This study was conducted under greenhouse conditions, which may not fully represent the environmental variability encountered under field cultivation. In addition, only a single source of citronella essential oil and a limited range of concentrations were evaluated, while plant responses were assessed primarily through disease incidence and plant height. Therefore, future research should validate the effectiveness of Lemongrass under open-field conditions across different environmental and soil characteristics. Further studies are also recommended to optimize formulation and application techniques, evaluate the persistence and stability of the essential oil under field conditions, investigate its effects on tomato yield, fruit quality, and economic feasibility, and assess its compatibility with biological control agents or other integrated disease management practices. Such investigations will provide a more comprehensive understanding of the practical application of Lemongrass and support its wider adoption as a sustainable botanical pesticide in tomato production systems.

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Acknowledgment
We gratefully acknowledge the contributions of individuals who supported the completion of this article.

Funding Information
This research did not receive any funding.

Conflict of Interest Statement
The authors declare that there is no conflict of interest.

Ethical Approval and Originality Statement
Ethical approval was obtained for this study. The manuscript represents original work and has not been previously published, nor is it under consideration by another journal.

Data Disclosure Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.