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EFFICACY OF LEMON GRASS OIL ON THE MANAGEMENT OF ROOT ROT OF OKRA [FUSARIUM SOLANI (MART.) SACC]

Original Article

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ABSTRACT

Background: Okra (*Abelmoschus esculentus* L.) is an important vegetable crop cultivated in tropical and subtropical regions. Its production is threatened by root rot caused by *Fusarium solani*, leading to severe yield losses. Conventional management relies on synthetic fungicides, which are effective but associated with adverse effects on human health, soil microbiota, and environmental safety. Botanical alternatives such as lemongrass oil, containing bioactive antifungal compounds, have emerged as safer, eco-friendly strategies for sustainable crop protection.

Objective: This study aimed to determine the incidence of okra root rot in District Charsadda and to evaluate the antifungal efficacy of lemongrass oil against *F. solani* under both in vitro and in vivo conditions.

Methods: A field survey was conducted across fifteen okra-growing localities in Charsadda during April–May 2021 at the seedling stage. Seedling mortality percentage was calculated from five representative fields at each site. Infected seedlings were collected, and *F. solani* was isolated and confirmed morphologically. In vitro bioassays employed lemongrass oil at concentrations of 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% using the food poisoning technique, with Mancozeb as a positive control. In vivo experiments were performed in a screen house, where okra seeds were sown in sterilized soil and artificially inoculated with *F. solani*. Treatments were arranged in a Completely Randomized Design (CRD) with five replications, and data were statistically analyzed using ANOVA and LSD tests.

Results: Root rot prevalence in Charsadda ranged from 9.00% in Rahim Abad to 20.14% in Bad Shah Kali, with a mean mortality of 13.27%. In vitro, lemongrass oil at 3% reduced colony diameter by 76.10%, biomass by 76.60%, and spore concentration by 97.29% compared to control. In vivo, seedling mortality decreased to 16.00% and germination increased to 84.00% at 3% concentration, while untreated controls showed 84.00% mortality and 16.00% germination. Lower concentrations (0.5% and 1%) were less effective.

Conclusion: Lemongrass oil significantly suppressed *F. solani* and improved seed germination in both laboratory and screen house conditions. At 3% concentration, it proved highly effective, supporting its potential as a sustainable botanical alternative to chemical fungicides for okra root rot management.

Keywords: Abelmoschus esculentus, Biocontrol, Fusarium solani, Lemongrass oil, Phytoextracts, Root rot, Sustainable agriculture.

INTRODUCTION

Okra (Abelmoschus esculentus L.), commonly referred to as ochro or ladies' fingers, is a widely consumed vegetable valued for its tender green pods. Its origins trace back to West Africa, Ethiopia, and South Asia, from where it spread to warm temperate, tropical, and subtropical regions of the world (1). Rich in dietary fiber and essential vitamins such as K and C, okra also contains moderate amounts of protein, carbohydrates, and micronutrients, alongside mucilage with notable flocculent properties that have been explored for water purification (2). In Pakistan, okra cultivation covers 15,923 hectares with a production of 122,157 tons, while in Khyber Pakhtunkhwa (KPK) alone it is cultivated on 2,138 hectares yielding 17,274 tons annually (3). Despite its nutritional and economic significance, okra cultivation is severely constrained by plant diseases. The crop, a member of the Malvaceae family, is vulnerable to attacks from fungi, viruses, and nematodes, resulting in considerable yield losses. Major diseases include Cercospora blight, wilt, powdery mildew, damping-off, yellow vein mosaic virus, and root rot (4). Among these, Fusarium solani is particularly destructive, causing root rot that leads to wilting, leaf shrinkage, seedling death, and severe root degradation (5,6). The pathogen not only diminishes yield and quality in okra but also affects other vegetables such as beans, with disease prevalence reported between 10–80%, reaching up to 88% in kitchen gardens (7–9).

The persistence of this fungus in infected seeds and soil further complicates its management (10). Conventional disease management strategies rely on chemical pesticides, crop rotation, and cultural practices. While chemical control provides rapid results, it poses significant risks to human health, beneficial soil microorganisms, and environmental integrity, raising long-term sustainability concerns. In contrast, eco-friendly alternatives such as plant-derived extracts, including essential oils from lemongrass and other medicinal plants, have demonstrated promising antifungal properties without adverse ecological effects (11,12). Given the increasing demand for safe, sustainable, and effective approaches to disease management, this study was undertaken to evaluate the efficacy of lemongrass oil in the control of Fusarium solani–induced root rot in okra. The objective was to provide a viable botanical alternative to synthetic agrochemicals, ensuring both crop protection and environmental safety.

METHODS

Okra root rot distribution in District Charsadda: A field survey was conducted in fifteen major okra-growing areas of District Charsadda to assess the distribution and severity of root rot. In each area, five representative fields were selected, and within each field, observations were made at five random spots. Data were collected on seedling mortality by counting the total number of seedlings and the number of rotted seedlings per square meter. Seedling mortality percentage was calculated using the following formula:

Seedling mortality (%) = (Total number of rotted seedlings/m² ÷ Total number of seedlings/m²) × 100

The survey ensured that representative samples were obtained from different localities, although no clear mention was made of seasonal variation or crop stage, which could influence disease distribution.

Isolation of Fusarium solani: Infected okra seedlings showing characteristic root rot symptoms were collected from different locations in District Charsadda. The roots were cut into small pieces and surface sterilized by immersion in 0.1% mercuric chloride ($HgCl_2$) solution for 15–30 seconds, followed by rinsing three times with sterile distilled water to eliminate residual disinfectant. The sterilized tissues were plated on Potato Dextrose Agar (PDA) medium and incubated at 25 °C. Fungal growth was observed daily, and pure colonies were obtained by sub-culturing. Identification of Fusarium solani was carried out using established morphological keys described by earlier scientists (10). It must be noted that the use of mercuric chloride is discouraged globally due to its toxicity and environmental hazards, and safer alternatives such as sodium hypochlorite are usually recommended.

In vitro study: The antifungal efficacy of lemongrass oil against Fusarium solani was evaluated using the food poisoning technique (11). PDA medium was amended with lemongrass oil at concentrations of 0.5%, 1%, 1.5%, 2%, 2.5%, and 3%. Petri dishes were inoculated with a disc of actively growing Fusarium solani culture, sealed, and incubated at 25 °C. Mancozeb at 500 ppm served as the positive control, while PDA without any antifungal agent served as the negative control. Treatments were arranged in a Completely Randomized Design (CRD) with five replications. The following treatments were included:

- T1: Fusarium solani only (negative control)
- T2: Fusarium solani + Mancozeb @ 500 ppm (positive control)
- T3: Fusarium solani + lemongrass oil @ 0.5%
- T4: Fusarium solani + lemongrass oil @ 1%
- T5: Fusarium solani + lemongrass oil @ 1.5%
- T6: Fusarium solani + lemongrass oil @ 2%
- T7: Fusarium solani + lemongrass oil @ 2.5%
- T8: Fusarium solani + lemongrass oil @ 3%

Colony diameter and fresh biomass were recorded at 4-, 8-, and 12-days post-inoculation, whereas spore concentration per milliliter was assessed after 12 days.

Screen house study: To evaluate the in vivo efficacy of lemongrass oil, experiments were conducted under controlled screen house conditions.

Arrangement of pots: Earthen pots (6.5 cm diameter, 8 cm depth) were filled with a sterilized mixture of clay, silt, and farmyard manure (FYM) in a 1:1:1 ratio. A total of 40 pots were arranged in a CRD with five replications. Ten okra seeds (variety Shaheen) were sown per pot. Fusarium solani spore suspension (2.0×10^5 spores/ml) was artificially inoculated near the root zone of seedlings to ensure uniform infection pressure (13). Different concentrations of lemongrass oil were applied as treatments, while Mancozeb served as the positive control and untreated Fusarium-infested soil served as the negative control. Germination percentage and seedling mortality were assessed 22 days after sowing using the following formulas:

Germination (%) = (Number of seeds germinated ÷ Total number of seeds per pot) × 100

Mortality (%) = (Number of rotted seedlings ÷ Total number of seeds per pot) × 100

Experimental layout: The experiment followed a CRD with five replications per treatment. Each treatment consisted of oil concentrations ranging from 0.5% to 3%, alongside positive and negative controls. The layout ensured randomization to minimize environmental bias.

Data recording and statistical analysis: All recorded data were subjected to statistical analysis using Analysis of Variance (ANOVA) appropriate for a CRD. Treatment means were separated using the Least Significant Difference (LSD) test at 5% probability level (12). Data included colony diameter, biomass, spore count, germination rate, and seedling mortality.

Re-isolation of F. solani from contaminated seedlings: Seedlings exhibiting symptoms of root rot were re-isolated to confirm the pathogenicity of Fusarium solani. Infected tissues were surface sterilized in 0.1% $HgCl_2$ and cultured on PDA medium. Morphological characteristics were compared with the original culture to validate Koch's postulates (10).

Effect of lemongrass oil on inoculum of F. solani in soil: A separate soil experiment was performed to assess the reduction of Fusarium inoculum in the soil following lemongrass oil application. Pots were filled with sterilized clay, silt, and FYM in equal ratios and inoculated with Fusarium solani suspension at 2.0×10^5 spores/ml (13). Okra seeds were sown, and different concentrations of lemongrass oil were applied. After 14 days, soil samples were collected and serially diluted using the dilution plating method. One gram of soil was mixed in 0.05% water agar, serially diluted, and plated on Peptone PCNB Agar (PPA), a selective medium for Fusarium solani isolation (14,15). Colonies were counted to determine inoculum density per gram of soil.

Ethical considerations: The study involved no human or animal participants. However, laboratory and screen house experiments were conducted under the approval and biosafety guidelines of the Department of Plant Pathology, University of Agriculture Peshawar.

RESULTS

Incidence and Severity of root rot of okra in district Charsadda: The survey revealed that root rot was prevalent across all surveyed locations of District Charsadda, with seedling mortality ranging between 9.00% and 20.14%. The highest incidence was recorded in Bad Shah Kali (20.14%), followed by Zahid Abad (18.70%) and Azim Khan Pull (17.30%). In contrast, the lowest incidence was noted in Rahim Abad (9.00%), whereas Gulabad and Bahlola recorded values of 10.62% each. Mortality levels in other localities, including Musa Kali (12.00%), Swatu Kali (12.20%), Mufti Abad (12.60%), Manga (12.80%), and Chitral Kali (13.60%), ranged from moderate to high. The mean incidence across all sites was 13.27%, indicating widespread but variable disease intensity.

Isolation and identification of pathogen: Fusarium solani was consistently isolated from infected seedlings collected from all surveyed locations. The pathogen produced characteristic white, flat colonies with boat-shaped macroconidia having distinct septa, confirming its identity.

Effect of lemon grass oil on colony diameter of Fusarium solani: Lemongrass oil significantly inhibited the mycelial growth of Fusarium solani at all tested concentrations. After 4 days of incubation at 25 °C, colony diameter was reduced to 0.92 cm at 3% concentration, corresponding to a 78.09% reduction compared to control. By contrast, the lowest inhibitory effect was seen at 0.5% concentration, where colony diameter reached 3.96 cm. At 8 days, lemongrass oil at 3% reduced colony growth to 1.26 cm (83.84% reduction), while at 12 days, the same concentration further suppressed growth to 1.94 cm, representing a 76.10% reduction relative to untreated control.

Effect of lemon grass oil on fresh biomass of Fusarium solani: Fresh biomass of Fusarium solani was significantly reduced by lemongrass oil application. After 4 days, biomass was lowest (0.12 g) at 3% concentration, representing an 88.57% reduction compared to control (1.05 g), while the maximum biomass (0.78 g) was observed at 0.5% concentration. After 8 days, biomass was 0.65 g at 3% concentration, corresponding to a 68.29% reduction, whereas 1.88 g was recorded at 0.5% concentration. After 12 days, biomass at 3% concentration was 0.73 g, showing a 76.60% reduction compared to control (3.12 g).

Effect of lemon grass oil on spore concentration (10^5) of Fusarium solani after 12 days of incubation at 25 °C: Spore production was drastically suppressed by lemongrass oil. The control recorded 7.40×10^5 spores/ml, whereas the application of 3% lemongrass oil reduced spore concentration to 0.20×10^5 spores/ml, a 97.29% reduction. The lowest concentration (0.5%) showed limited effect, with 6.20×10^5 spores/ml, corresponding to only a 16.21% reduction. Intermediate concentrations (1%, 1.5%, and 2%) showed stepwise reductions to 5.00×10^5, 3.80×10^5, and 2.60×10^5 spores/ml, respectively.

Screen house study

Effect of Fusarium solani on seedling mortality: Seedling mortality in the untreated control reached 84%. Lemongrass oil significantly reduced mortality in a concentration-dependent manner. At 3% application, seedling mortality was minimized to 16%, reflecting an 80.95% reduction compared to control. The lowest efficacy was observed at 0.5% concentration, where mortality remained high at 72%. Intermediate concentrations achieved reductions ranging from 26.19% to 69.04%.

Seed germination: Seed germination was significantly improved by lemongrass oil treatment. The highest germination percentage was observed at 3% concentration (84.00%), representing a 425% improvement over the control (16%). Conversely, the lowest effect was noted at 0.5% concentration, where germination was 28%. Other treatments demonstrated progressive increases, with 1% yielding 38%, 1.5% yielding 58%, and 2.5% yielding 74%.

Effect of lemon grass oil on density of Fusarium solani inoculum in the soil: Application of lemongrass oil reduced soil inoculum density in a concentration-dependent manner. The untreated control exhibited 40.20 colonies/g of soil. At 3% concentration, colony count was minimized to 12.00, corresponding to a 70.14% reduction. In contrast, the lowest concentration (0.5%) recorded 33.60 colonies/g, reflecting only a 16.41% reduction. Intermediate treatments showed moderate suppression ranging from 22.88% at 1% to 55.22% at 2.5%.

Table 1: Experimental Layout for In Vivo and Small Pot Studies

Row 1	Row 2	Row 3	Row 4	Row 5	Row 6	Row 7	Row 8
T1R1	T6R2	T2R1	T8R3	T8R5	T5R1	T6R4	T7R2
T3R1	T1R2	T8R1	T3R2	T2R4	T6R3	T4R1	T4R3
T2R2	T7R3	T1R3	T7R5	T4R5	T3R3	T8R4	T6R1
T4R2	T4R4	T5R4	T1R4	T8R2	T5R2	T3R4	T6R5
T5R5	T7R4	T2R3	T5R3	T1R5	T2R5	T7R1	T3R5

Table 2: Mortality of root rot of okra in different areas of district Charsadda during 2021 growing season

Locations	Seedling Mortality (%)
1. Rahim Abad	09.00 g
2. Khan Mahi	11.00 ef
3. Mufti Abad	12.60 cde
4. Manga	12.80 cd
5. Mera Ahmad Gull	14.10 c
6. Bahlola	10.62 fg
7. Swatu Kali	12.20 def
8. Azim Khan Pull	17.30 b
9. Dargai	13.40 cd
10. Musa Kali	12.00 def
11. Chitral Kali	13.60 cd
12. Badraga Kali	11.00 ef
13. Gulabad	10.62 fg
14. Zahid Abad	18.70 ab
15. Bad Shah Kali	20.14 a
Mean	13.27
CV (%)	10.40
LSD value	1.74

Table 3: Effect of Lemongrass Oil on Colony Diameter of *Fusarium solani* at Different Incubation Periods (4, 8, and 12 Days at 25 °C)

Treatments	Colony Diameter (cm) – 4 Days	% Reduction vs Control – 4 Days	Colony Diameter (cm) – 8 Days	% Reduction vs Control – 8 Days	Colony Diameter (cm) – 12 Days	% Reduction vs Control – 12 Days
T1 (Fusarium solani)	4.20 a	-	7.80 a	-	8.12 a	-
T2 (F. solani + Mancozeb @ 500 ppm)	1.39 f	66.90	2.08 g	73.33	3.02 g	62.80
T3 (F. solani + Lemongrass oil @ 0.5%)	3.96 b	5.71	7.20 b	7.69	7.62 b	6.15
T4 (F. solani + Lemongrass oil @ 1%)	3.36 c	20.00	5.78 c	25.89	7.10 c	12.56
T5 (F. solani + Lemongrass oil @ 1.5%)	2.46 d	41.42	4.44 d	43.07	6.62 d	18.47
T6 (F. solani + Lemongrass oil @ 2%)	1.92 e	54.28	3.92 e	49.74	5.72 e	29.55
T7 (F. solani + Lemongrass oil @ 2.5%)	1.42 f	66.19	3.08 f	60.51	3.86 f	52.46
T8 (F. solani + Lemongrass oil @ 3%)	0.92 g	78.09	1.26 g	83.84	1.94 h	76.10

Mean: 2.45 (4 days), 4.44 (8 days), 5.50 (12 days)
CV (%): 4.78 (4 days), 7.41 (8 days), 6.44 (12 days)
LSD value: 0.15 (4 days), 0.42 (8 days), 0.45 (12 days)

Table 4: Effect of Lemongrass Oil on Biomass of *Fusarium solani* at Different Incubation Periods (4, 8, and 12 Days at 25 °C)

Treatments	Biomass (g) – 4 Days	% Reduction vs Control – 4 Days	Biomass (g) – 8 Days	% Reduction vs Control – 8 Days	Biomass (g) – 12 Days	% Reduction vs Control – 12 Days
T1 (Fusarium solani)	1.05 a	-	2.05 a	-	3.12 a	-
T2 (F. solani + Mancozeb @ 500 ppm)	0.15 g	85.71	0.79 g	61.46	1.12 g	64.10
T3 (F. solani + Lemongrass oil @ 0.5%)	0.78 b	25.71	1.88 b	8.29	2.87 b	8.01
T4 (F. solani + Lemongrass oil @ 1%)	0.72 c	31.42	1.82 c	11.21	2.31 c	25.96
T5 (F. solani + Lemongrass oil @ 1.5%)	0.57 d	45.71	1.55 d	24.39	2.08 d	33.33
T6 (F. solani + Lemongrass oil @ 2%)	0.38 e	63.80	1.25 e	39.02	1.86 e	40.38
T7 (F. solani + Lemongrass oil @ 2.5%)	0.22 f	79.04	0.97 f	52.68	1.25 f	59.93
T8 (F. solani + Lemongrass oil @ 3%)	0.12 h	88.57	0.65 h	68.29	0.73 h	76.60

Mean: 0.49 (4 days), 1.37 (8 days), 1.91 (12 days)
CV (%): 2.84 (4 days), 1.04 (8 days), 4.38 (12 days)
LSD value: 0.01 (4 days), 0.01 (8 days), 0.10 (12 days)

Table 5: Effect of Lemongrass Oil on Spore Concentration, Seedling Mortality, and Germination of Okra under *Fusarium solani* Infection

Treatments	Spore Concentration ($\times 10^5$/ml) – 12 Days	% Reduction vs Control (Spore)	Mortality (%) – 22 Days	% Reduction vs Control (Mortality)	Germination (%) – 22 Days	% Increase vs Control (Germination)
T1 (Fusarium solani)	7.40 a	-	84.00 a	-	16.00 f	-
T2 (F. solani + Mancozeb @ 500 ppm)	1.20 f	83.78	22.00 ef	73.80	78.00 ab	387.5
T3 (F. solani + Lemongrass oil @ 0.5%)	6.20 b	16.21	72.00 b	14.28	28.00 e	75.00
T4 (F. solani + Lemongrass oil @ 1%)	5.00 c	32.43	62.00 c	26.19	38.00 d	137.5
T5 (F. solani + Lemongrass oil @ 1.5%)	3.80 d	48.64	42.00 d	50.00	58.00 c	262.5
T6 (F. solani + Lemongrass oil @ 2%)	2.60 e	64.86	30.00 e	64.28	70.00 b	337.5
T7 (F. solani + Lemongrass oil @ 2.5%)	1.40 f	81.08	26.00 e	69.04	74.00 b	362.5
T8 (F. solani + Lemongrass oil @ 3%)	0.20 g	97.29	16.00 f	80.95	84.00 a	425.00

Mean: Spore conc. 3.47; Mortality 44.25; Germination 55.7
CV (%): Spore conc. 19.03; Mortality 14.29; Germination 11.34
LSD value: Spore conc. 0.85; Mortality 8.14; Germination 8.14

Table 6: Number of Fusarium solani colonies as affected by different concentrations of lemon grass oil in soil

Treatments	No. of Colonies	Percent reduction in colonies percentage compared to control
T1 (Fusarium solani)	40.20 a	-
T2 (F.solani + Mancozeb @ 500 ppm)	14.00 g	65.17
T3 (F.solani + lemon grass oil @ 0.5%)	33.60 b	16.41
T4 (F. solani + lemon grass oil @ 1%)	31.00 c	22.88
T5 (F. solani + lemon grass oil @ 1.5%)	28.00 d	30.34
T6 (F. solani + lemon grass oil @ 2%)	23.00 e	42.78
T7 (F. solani + lemon grass oil @ 2.5%)	18.00 f	55.22
T8 (F. solani + lemon grass oil @ 3%)	12.00 g	70.14
Mean	24.97	-
CV (%)	6.64	-
LSD value	2.13	-

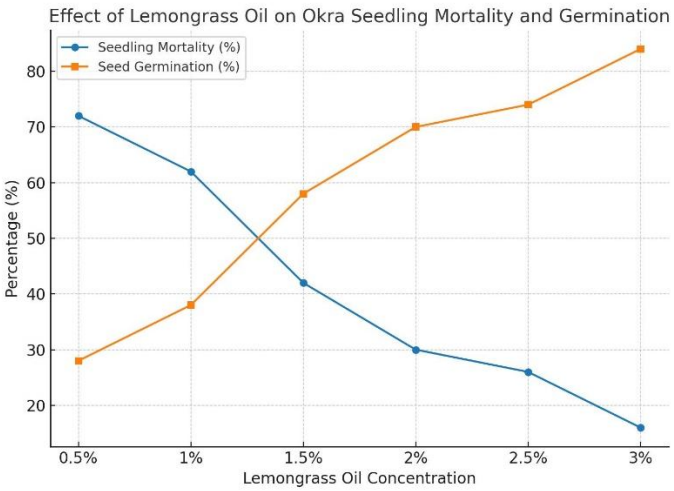

Figure 1 Effect of Lemongrass Oil on Okra Seedling Mortality and Germination

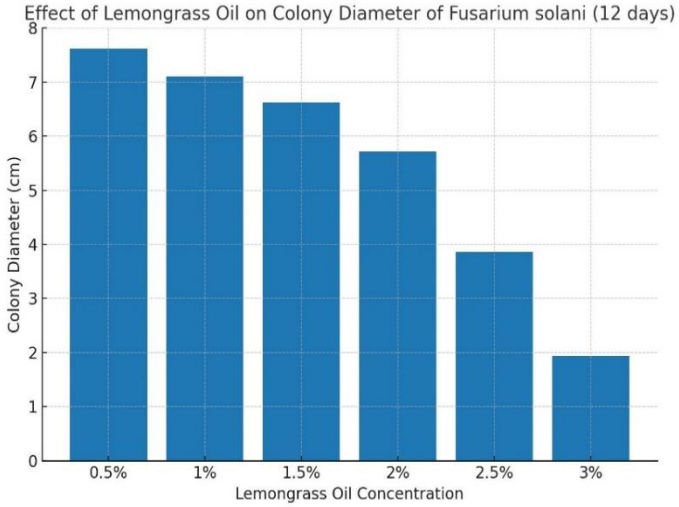

Figure 2 Effect of Lemongrass Oil on Colony Diameter of Fusarium Solani (12 days)

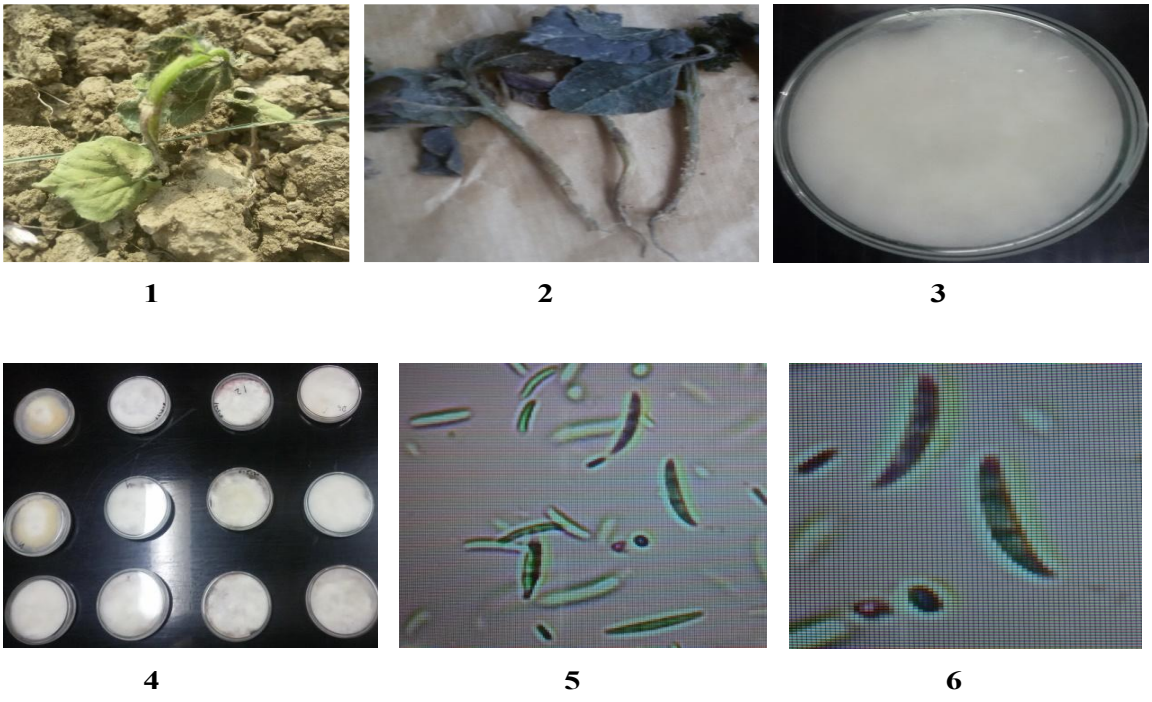

Figure 3 Okra plant, fungal spores and culture of F. solani infecting okra, (1): Okra plant infected by F. solani, (2): Samples of okra root rot, (3): Pure culture of F. solani, (4): Sub culture of F. solani, (5): Boat shaped spores (macroconidia), (6): Spores having septa (macroconidia).

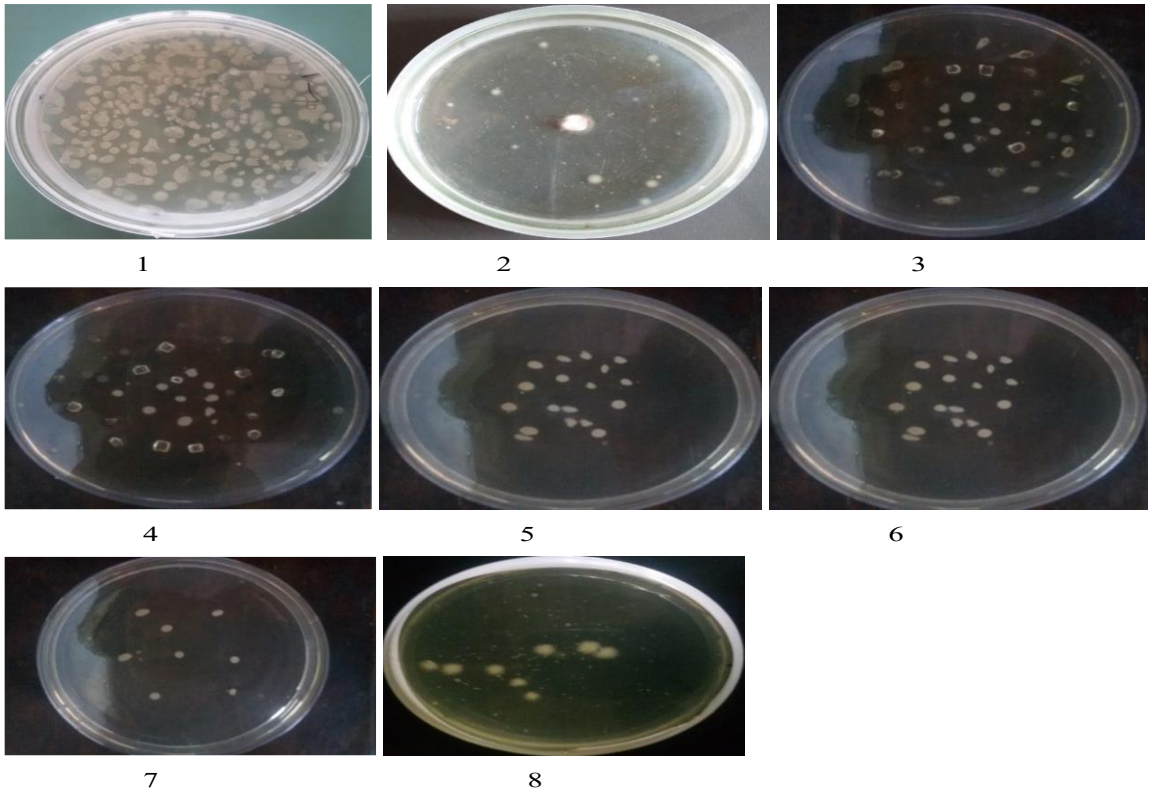

Figure 4 Effect of lemon grass oil concentration on F.solani inoculum in soil. (1): Negative control (SDW), (2): Positive control (F. solani + Mancozeb), (3): Lemon grass oil @ 0.5%, (4): Lemon grass oil @ 1%, (5): Lemon grass oil @ 1.5%, (6): Lemon grass oil @ 2%, (7): Lemon grass oil @ 2.5%, (8): Lemon grass oil @ 3%.

DISCUSSION

The present study demonstrated that *Fusarium solani* remains a highly destructive pathogen of okra, particularly in warm soil conditions where its prevalence can reach up to 80%. This aligns with reports from previous investigations where the disease was shown to cause significant reductions in both quality and yield of okra, particularly under field conditions where losses may range from 10% to 45% (16). The findings confirm that *F. solani* is a major constraint to okra production and necessitates effective and sustainable management strategies. The results of the survey conducted across fifteen locations in District Charsadda highlighted a widespread incidence of root rot, with mortality rates varying between 9% and 20.14%. Such variability in field prevalence reflects differences in soil type, climatic conditions, and agronomic practices across localities (17,18). The consistent recovery of *F. solani* from symptomatic seedlings further strengthened its role as the primary pathogen associated with root rot in the region. The in vitro assays provided compelling evidence of the antifungal potential of lemongrass oil. Concentration-dependent inhibition of colony growth, biomass accumulation, and spore production was observed, with 3% application proving most effective. This reduction, ranging from 6.15–76.10% for colony diameter, 8.01–76.60% for biomass, and 16.21–97.29% for spore count, compares favorably with previous reports where essential oils reduced *F. solani* growth by 42–62% (19,20). The fungicidal action of lemongrass oil is attributed to its phytochemical constituents, including ethyl acetate and ethanolic compounds, which interfere with fungal cell wall integrity, enzyme activity, and respiration, ultimately disrupting metabolic functions (21–23). The results substantiate that lemongrass oil possesses broad antifungal properties and can serve as an alternative to synthetic fungicides.

The in vivo experiments further validated these findings. Application of lemongrass oil reduced seedling mortality by 14.28–80.95% and enhanced germination by 75–425% compared to untreated control pots. The superior performance at 3% concentration suggests that lemongrass oil not only suppresses pathogen development but also promotes seedling vigor. These findings are consistent with earlier observations where phytoextracts improved germination and reduced seedling mortality under pathogen pressure (24,25). Importantly, soil inoculum density was also suppressed by 16.41–70.14%, indicating that lemongrass oil has a suppressive effect on soil-borne inocula, thereby contributing to long-term disease management. The strengths of the study lie in its dual approach of combining in vitro and in vivo assessments, as well as its emphasis on eco-friendly disease management. The use of lemongrass oil provides a safer, sustainable, and cost-effective alternative to agrochemicals, which often have adverse effects on the environment and non-target organisms. By demonstrating its efficacy against *F. solani* in controlled conditions, the study lays the groundwork for its adoption as a biocidal agent.

However, limitations must also be acknowledged. The experiments were primarily conducted under laboratory and screen house conditions, which may not fully replicate the complex interactions in open field environments. Factors such as soil microbiota, environmental fluctuations, and pathogen diversity could influence efficacy under field conditions. Additionally, the use of small pots may have restricted root development, potentially affecting plant response and pathogen behavior. Another limitation is the reliance on mercuric chloride for sterilization during pathogen isolation, which is both toxic and environmentally hazardous. Safer sterilizing agents should be considered in future studies. Future research should focus on field trials across diverse agro-ecological zones to validate these findings under natural conditions (26). Investigations into the synergistic effects of lemongrass oil with other plant extracts or biological control agents may enhance its effectiveness and sustainability. Further, efforts should be directed towards the formulation and commercialization of lemongrass oil-based products to ensure consistency in efficacy and cost-effectiveness for farmers. Advanced studies at the biochemical and molecular level are also warranted to elucidate the precise mechanisms by which lemongrass oil inhibits fungal metabolism. Overall, the findings confirm that lemongrass oil has considerable potential as a botanical biocide for the management of okra root rot caused by *Fusarium solani*. While additional validation is required, its environmentally friendly profile, coupled with significant antifungal efficacy, suggests that it could contribute meaningfully to integrated disease management programs for okra cultivation.

CONCLUSION

The study concluded that root rot of okra was widespread in the Charsadda district, with *Fusarium solani* identified as the principal causal pathogen. Lemongrass oil demonstrated strong antifungal potential, particularly at higher concentrations, effectively suppressing pathogen growth both in vitro and in vivo. Lower concentrations showed limited effectiveness, highlighting the importance of optimizing dosage for practical application. Overall, the findings emphasize the promise of lemongrass oil as an eco-friendly, sustainable, and cost-effective alternative to chemical fungicides for managing okra root rot, offering a safer strategy for improving crop health and productivity.

AUTHOR CONTRIBUTION

Author	Contribution
Muhammad Aftab Alam	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Hakim Khan	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
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