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Research Article

Mitigation of Drought Stress and Suppression of Tomato Yellow Leaf Curl Virus (TYLCV) in Tomato (*Solanum lycopersicum*) through Fungal Endophyte Inoculation

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ABSTRACT

Tomato (*Solanum lycopersicum* L.) productivity is severely constrained by drought stress, which also intensifies susceptibility to insect pests and viral diseases. Endophytic fungi have emerged as potential bio-stimulants that enhance plant resilience under such combined stresses. The present study evaluated the effect of five fungal endophytes viz., *Colletotrichum lindemuthianum*, *Gigaspora rosea*, *Glomus mosseae*, *Piriformospora indica*, and *Trichoderma viride* on growth, yield, and stress-related parameters of two tomato varieties (Nadir and Naqeeb) under drought conditions. Results revealed that all endophyte treatments significantly improved plant performance compared with the untreated control. Among them, *C. lindemuthianum* consistently showed the strongest effects across all measured traits. It markedly reduced disease severity and whitefly infestation while simultaneously enhancing vegetative growth, including root length (8.76 cm in Nadir and 5.23 cm in Naqeeb), shoot length (up to 63.40 cm), number of leaves (up to 50.11 per plant), and number of branches (up to 12.20 per plant). Similarly, reproductive performance improved substantially, with the highest fruit yield recorded in *C. lindemuthianum*-treated plants (10.07 fruits per plant in Nadir and 8.22 in Naqeeb), whereas control plants showed the lowest values. Comparatively, *G. rosea*, *G. mosseae*, *P. indica*, and *T. viride* also contributed positively but to a lesser extent. Overall, the Nadir variety exhibited superior performance across all parameters, indicating higher responsiveness to endophytic associations under drought stress. It is concluded that, fungal endophytes, especially *C. lindemuthianum*, enhance drought tolerance, reduce pest infestation, and improve tomato growth and yield, highlighting their potential as sustainable bioinoculants for crop management under water-limited conditions.

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Introduction

Solanum lycopersicum, commonly known as tomato, is one of the most widely cultivated vegetable crops worldwide. The global area under tomato cultivation is approximately 4.582 million hectares, with a total production of about 174 million tons (FAOSTAT, 2020). In Pakistan, tomato is cultivated on an area of about 9,674 hectares, with a total production of 232,098 tons, whereas in Punjab, the

cultivated area is 6,487 hectares with a production of 130,839 tons (MNFSR, 2021-22). Tomato export from Pakistan remained negligible until 2000; however, it has expanded significantly since 2007. The main objective of Pakistani exporters is to supply tomatoes to markets in the Middle East and Afghanistan (Tahir et al., 2012).

Despite the large area under cultivation, tomato productivity remains relatively low. This reduced yield is primarily due to production losses caused by numerous abiotic and biotic factors (Gondal et al., 2024; Azeem et al., 2025). Abiotic stresses include salinity, heat, chilling, drought, irregular rainfall, high temperature, wind velocity, and humidity (Yaseen et al., 2024), whereas biotic factors comprise various disease-causing agents such as viruses, bacteria, fungi, and nematodes (Tariq-Khan et al., 2025; Yaseen et al., 2005; Mehak et al., 2026). Both categories of stresses significantly reduce the yield and quality of the tomato crop (Aslam et al., 2017). Biotic factors such as bacterial, viral, and fungal pathogens are responsible for a wide range of diseases, while abiotic stresses arise from adverse environmental conditions such as heat, drought, and salinity.

Among viral diseases, Tomato Yellow Leaf Curl Virus (TYLCV), a member of the genus *Begomovirus* (family *Geminiviridae*), is one of the most destructive viruses affecting S. lycopersicum, causing symptoms such as leaf curling, chlorosis, stunted growth, and significant yield losses that may reach up to 100% under severe infestations. The virus is persistently transmitted by the whitefly Bemisia tabaci, which has a wide host range and high reproductive capacity, facilitating rapid virus spread across regions (Hanssen et al., 2010; Navas-Castillo et al., 2011). The TYLCV-whitefly complex is particularly problematic in tropical and subtropical regions, including Pakistan, where favorable climatic conditions enhance vector population dynamics and virus transmission efficiency. Furthermore, the emergence of new biotypes of *B. tabaci* with increased insecticide resistance has complicated management strategies, making TYLCV a persistent constraint to sustainable tomato production (Lapidot and Friedmann, 2002; Perring, 2001).

Among these factors, drought stress is one of the most critical constraints affecting tomato production. Under drought conditions, stomata remain closed, which significantly disrupts CO_2 balance within the plant. Stomatal closure is the primary physiological response to water deficit conditions (Hommel et al., 2014; Xie et al., 2014). Stomata close when the plant water status declines or when leaf turgor pressure is reduced. This response decreases CO_2 exchange in the leaves (Chaves et al., 2009), leading to a reduction in the net photosynthetic rate. The process of photosynthesis in plants largely depends on the availability of CO_2, particularly in photosystem II (PSII). Under drought conditions, the initial limitation in photosynthesis is primarily due to CO_2 deficiency.

The closure of stomata during drought stress reduces internal CO_2 concentration (Ci), which leads to over-reduction of components in the photosynthetic electron transport chain. As a consequence, electrons are transferred to oxygen at photosystem I (PSI), resulting in the production of reactive oxygen species (ROS) (Mahajan and Tuteja, 2005). Water deficit conditions also reduce the activity of key photosynthetic enzymes, including ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), phosphoenolpyruvate carboxylase (PEPCase), NADP-malic enzyme (NADP-ME), fructose-1,6-bisphosphatase (FBPase), and pyruvate orthophosphate dikinase (PPDK) (Bota et al., 2004). Moreover, the water potential of plant tissues decreases under drought stress.

The increased production of ROS, along with reduced enzymatic activity, leads to decreased carboxylation efficiency. Moreover, drought stress impairs non-cyclic electron transport, which adversely affects ATP synthesis. As a result of reduced carboxylation efficiency and lower ATP production, the overall process of photosynthesis is significantly inhibited under drought conditions (Farooq et al., 2009). These physiological and biochemical disruptions ultimately lead to reduced plant growth and productivity.

The study, therefore, aimed to evaluate the efficacy of five fungal endophytes (*Piriformospora indica, Gigaspora rosea, Colletotrichum lindemuthianum, Trichoderma viride, and Glomus mosseae*) in suppressing Tomato Yellow Leaf Curl Virus (TYLCV) disease severity and whitefly populations, assess their effects on growth parameters, quantify their impact on fruit yield in two tomato varieties (Nadir and Naqeeb), and identify the most effective fungal endophyte for integrated management of combined drought and viral stress in tomato under drought stress.

Materials and Methods

Experimental design and plant material

A pot experiment was conducted under controlled environmental conditions to evaluate the role of fungal endophytes in alleviating drought stress in tomato (*Solanum lycopersicum* L.). Two commercially cultivated

tomato varieties, Nadir and Naqeeb, were selected based on their differential responses to environmental stress. The experiment was arranged in a completely randomized design (CRD) with a factorial structure involving two factors: endophytic treatments and tomato varieties, assessed at three sampling intervals. Each treatment was replicated three times to ensure statistical robustness. Such factorial experimental designs are widely employed to quantify main and interaction effects of multiple factors in plant stress physiology studies (Gomez and Gomez, 1984).

Fungal endophytes and inoculation procedure

Five fungal endophytes, namely *Piriformospora indica*, *Gigaspora rosea*, *Colletotrichum lindemuthianum*, *Trichoderma viride*, and *Glomus mosseae*, were included in the study based on their prior *in vitro* screening and superior performance. Spore suspensions were prepared using standard microbiological techniques at a concentration of 1×10^6 spores ml^{-1}. Healthy tomato seedlings at the 3-4 leaf stage were transplanted into sterilized soil-filled plastic pots (5 kg capacity) and inoculated by applying 50 ml of the respective spore suspension directly into the rhizosphere zone to ensure effective colonization. Control plants received an equal volume of sterile distilled water without endophytes.

Growth conditions and imposition of drought stress

After establishment, plants were maintained under uniform agronomic and controlled environmental conditions in sterilized soil. Drought stress was imposed by withholding irrigation at a defined vegetative stage. Soil moisture content in drought-stressed treatments was maintained at approximately 40-50% field capacity, whereas control plants were kept under well-watered conditions. All other environmental factors, including temperature and photoperiod, were kept as constant as possible throughout the experiment to minimize experimental variability and ensure treatment-specific effects.

Data collection and measurements

Observations were recorded at three time intervals after the imposition of drought stress.

Disease severity (%)

Disease severity of Tomato Yellow Leaf Curl Virus (TYLCV) was assessed using a standard rating scale and expressed as percentage using the following formula:

$$\text{Disease Severity (\%)} = \frac{\sum(\text{Rating} \times \text{Number of infected leaves})}{\text{Total number of leaves} \times \text{Maximum rating}} \times 100$$

Whitefly population

The number of whiteflies per leaf was recorded by counting insects on three randomly selected leaves per plant and calculating the average.

Growth and yield parameters

Plant growth and yield-related attributes were recorded to evaluate the influence of fungal endophytes on tomato performance under drought stress conditions. Measurements were taken at three predefined observation intervals after stress imposition, except for root length and fruit yield, which were recorded at final harvest.

Number of leaves per plant

The total number of fully expanded leaves per plant was counted manually at each observation interval. Only healthy, photosynthetically active leaves were included, while senescent or damaged leaves were excluded from the count. Leaf number was used as an indicator of vegetative growth and plant vigor under stress conditions.

Number of branches per plant

Primary branches arising from the main stem were counted for each plant at each observation interval. Branching was considered an important parameter reflecting plant architecture and its capacity to support reproductive structures under drought stress.

Shoot length (cm)

Shoot length was measured from the soil surface to the apical meristem using a calibrated measuring scale. Measurements were taken carefully to avoid damage to the plant. This parameter was used to assess the overall vegetative growth and elongation response of plants subjected to different endophytic treatments under limited water availability.

Root length (cm)

Root length was recorded at the final harvest stage. Plants were carefully uprooted, and roots were washed gently under running tap water to remove adhering soil particles without damaging fine root structures. The length of the primary root was measured from the collar region to the root tip using a ruler. Root length served as an important indicator of below-ground adaptation to drought stress.

Number of fruits per plant

The total number of fruits per plant was recorded at physiological maturity. Only fully developed and marketable fruits were counted, while malformed or aborted fruits were excluded. This parameter was used as a direct measure of reproductive success and yield performance under drought conditions. For each parameter, observations were recorded from all plants

within each treatment replicate, and mean values were calculated. Care was taken to maintain uniformity in measurement procedures across all treatments and replications to minimize experimental error.

Statistical Analysis

All collected data were subjected to analysis of variance (ANOVA) appropriate for a factorial CRD to evaluate the significance of main and interaction effects of endophytes, varieties, and observation intervals. The statistical model included main effects (Endophytes, Variety, and Date) and their interactions (E×V, E×D, V×D, and E×D×V).

Treatment means were compared using the Least Significant Difference (LSD) test at a 5% probability level (Steel et al., 1997). The coefficient of variation (CV%) was calculated to assess experimental precision, while F-values and corresponding P-values were used to determine the significance of treatment effects. All statistical analyses were performed using Statistix 8.1 statistical software package.

Results

Effect of fungal endophytes on disease severity under drought stress

ANOVA for the effects of fungal endophytes, tomato varieties, and sampling dates and their interactions on disease severity under drought stress conditions showed significant effects (Table 1). Among the two tomato varieties tested, the Nadir variety exhibited comparatively better performance in terms of reduced disease severity. All tested endophytes significantly contributed to disease suppression in this variety under drought conditions (Figure 1).

Among the evaluated endophytes, *Colletotrichum lindemuthianum* proved to be the most effective, resulting in the lowest disease severity across all observation intervals. The recorded disease severity values were 6.22%, 17.22%, and 28.22%, respectively. Other endophytes also demonstrated notable efficacy in reducing disease severity. *Gigaspora rosea* showed relatively low disease severity values of 7.00%, 19.22%, and 32.50%, followed by *Glomus mosseae* (8.22%, 20.40%, and 36.76%), *Piriformospora indica* (8.96%, 21.00%, and 41.54%), and *Trichoderma viride* (11.30%, 22.50%, and 45.22%) across the respective intervals.

In contrast, the untreated control plants exhibited the highest disease severity, with values of 14.56%, 28.30%, and 51.25% at the corresponding observation intervals.

A similar trend was observed in the Naqeeb variety, where all endophytes significantly reduced disease severity compared to the control. *C. lindemuthianum* again showed superior performance, with disease severity values of 8.33%, 10.46%, and 30.22%, respectively. *G. rosea* also demonstrated effective disease suppression, with values of 10.10%, 21.50%, and 28.50%, followed by *G. mosseae* (12.00%, 23.90%, and 38.50%), *P. indica* (14.22%, 26.50%, and 43.55%), and *T. viride* (16.60%, 31.50%, and 47.55%).

The untreated control plants of the Naqeeb variety showed the highest disease severity, with values of 18.50%, 35.44%, and 55.60% across the respective intervals (Figure 1).

Table 1. Analysis of variance (ANOVA) for the effects of fungal endophytes, tomato varieties, and sampling dates and their interactions on disease severity under drought stress conditions.

SOV	DF	SS	MS	F.ratio	P
Replication	2	0.00191			
Endophytes	5	4133.32	826.665	207585	0.0000
Date	2	13845.7	6922.85	1738405	0.0000
Variety	1	138.811	138.811	34856.9	0.0000
Endophytes*Date	10	907.807	90.7807	22796.0	0.0000
Endophytes*Variety	5	344.478	68.8955	17300.4	0.0000
Date*Variety	2	108.225	54.1123	13588.2	0.0000
Endophytes*Date*Variety	10	108.236	10.8236	2717.94	0.0000
Error	70	0.27876	0.00398		
Total	107	19586.9			

Grand Mean = 24.492, CV = 0.26.

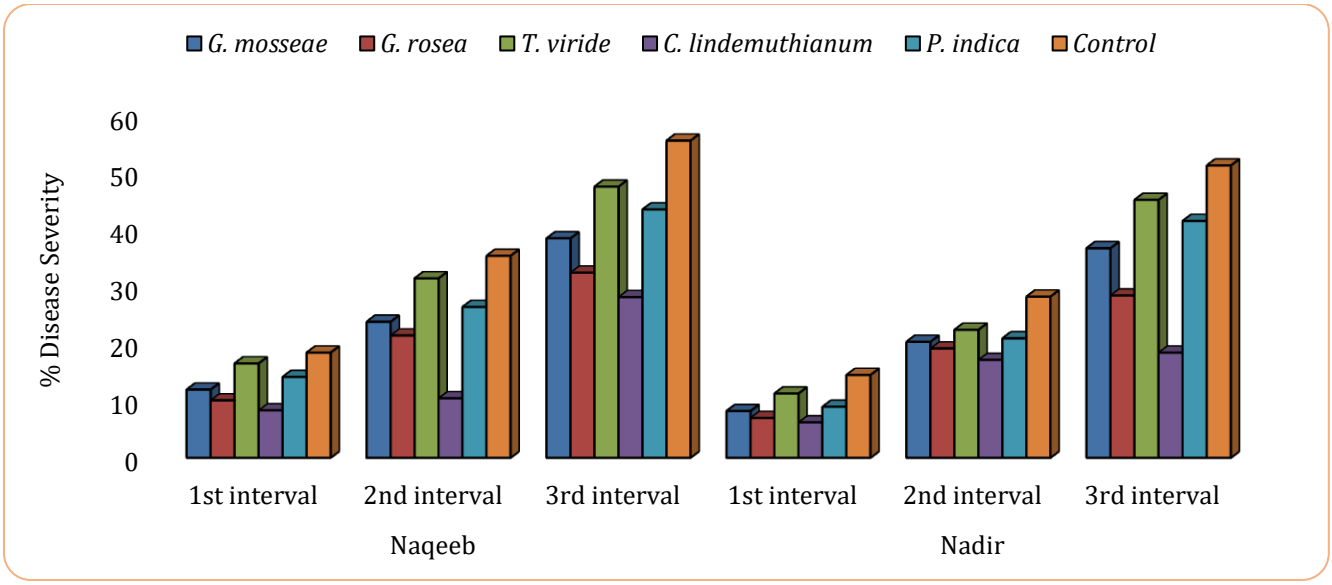


Figure 1. Effect of different fungal endophytes on disease severity in plants under drought stress conditions.

Effect of fungal endophytes on whitefly population under drought stress

Analysis of variance (ANOVA) for the effects of fungal endophytes, tomato varieties, and sampling dates and their interactions on whitefly population under drought stress conditions showed significant effects (Table 2).

The tomato variety Nadir exhibited comparatively lower whitefly infestation across all treatments. The data presented in Figure 2 indicate that among the tested endophytes, *C. lindemuthianum* was the most effective in reducing the number of whiteflies per leaf. The mean whitefly counts recorded for *C. lindemuthianum* at different observation intervals were 0.67, 1.36, and 1.98, respectively. Other endophytes also contributed to a reduction in whitefly populations, although to a lesser extent. *G. rosea* resulted in mean counts of 0.83, 1.66, and 2.56, while *G. mosseae* showed 1.19, 1.88, and 2.94 whiteflies per leaf. Similarly, *P. indica* recorded 1.54, 2.46, and 3.25, and *T. viride* showed comparatively higher values of 1.74, 3.16, and 4.27 whiteflies per leaf across the respective time intervals. In contrast, the control plants exhibited the highest infestation levels, with 2.18, 4.20, and 5.36 whiteflies per leaf, respectively.

A similar trend was observed in the tomato variety Naqeeb, where *C. lindemuthianum* again proved to be the most effective treatment. The mean number of whiteflies per leaf under this treatment was 1.50, 2.50, and 3.22 at successive observation intervals. *G. rosea* resulted in 2.03, 2.96, and 4.00 whiteflies per leaf, while *G. mosseae* showed 2.50, 3.46, and 4.44. *Piriformospora indica* recorded 2.90, 4.22, and 4.70, and *T. viride* showed 3.33, 4.50, and 5.50 whiteflies per leaf. The control treatment again exhibited the highest infestation, with mean values of 3.96, 6.10, and 8.00 whiteflies per leaf across the respective time intervals (Figure 2).

Overall, the results demonstrate that fungal endophytes, particularly *C. lindemuthianum*, significantly reduced whitefly populations under drought stress conditions, with varietal differences observed between Nadir and Naqeeb.

Effect of fungal endophytes on the number of leaves per plant under drought stress

ANOVA revealed that fungal endophytes, tomato varieties, sampling dates, and their interactions had significant effects on the number of leaves per plant under drought stress showed significant effects (Table 3).

In tomato variety Nadir, *C. lindemuthianum* proved to be the most effective endophyte, producing 29.5, 40.30, and 50.11 leaves per plant at successive sampling intervals (Figure 3). Other endophytes also enhanced leaf production compared to the control. *G. rosea* resulted in 25.41, 37.41, and 47.22 leaves per plant, followed by *G. mosseae* (23.25, 35.11, and 44.86), *P. indica* (21.24, 33.25, and 42.20), and *T. viride* (19.25, 30.24, and 39.83). The untreated control plants recorded the lowest leaf numbers, with 15.07, 20.59, and 24.73 leaves per plant across the respective intervals.

Similarly, in tomato variety Naqeeb, *C. lindemuthianum* exhibited the highest efficacy, producing 27.8, 44.5, and

46.22 leaves per plant at the corresponding time points. Other endophytes also significantly improved leaf numbers, with *G. rosea* (23.50, 37.41, and 43.33), *G. mosseae* (21.34, 33.06, and 41.09), *P. indica* (19.30, 31.50, and 40.00), and *T. viride* (16.95, 30.24, and 36.23). In contrast, the untreated control plants exhibited the lowest leaf counts, with 13.53, 19.74, and 21.50 leaves per plant, respectively (Figure 3).

Table 2. Analysis of variance (ANOVA) for the effects of fungal endophytes, tomato varieties, and sampling dates and their interactions on whitefly population under drought stress conditions.

SOV	DF	SS	MS	F. ratio	P
Replication	2	0.008	0.0042		
Endophytes	5	110.986	22.1973	7431.13	0.0000
Date	2	85.476	42.7382	14307.8	0.0000
Variety	1	60.181	60.1813	20147.3	0.0000
Endophytes*Date	10	8.845	0.8845	296.12	0.0000
Endophytes*Variety	5	2.723	0.5446	182.33	0.0000
Date*Variety	2	0.166	0.0832	27.87	0.0000
Endophytes*Date*Variety	10	0.895	0.0895	29.98	0.0000
Error	70	0.209	0.0030		
Total	107	269.492			

Grand Mean = 3.1339, CV = 1.74.

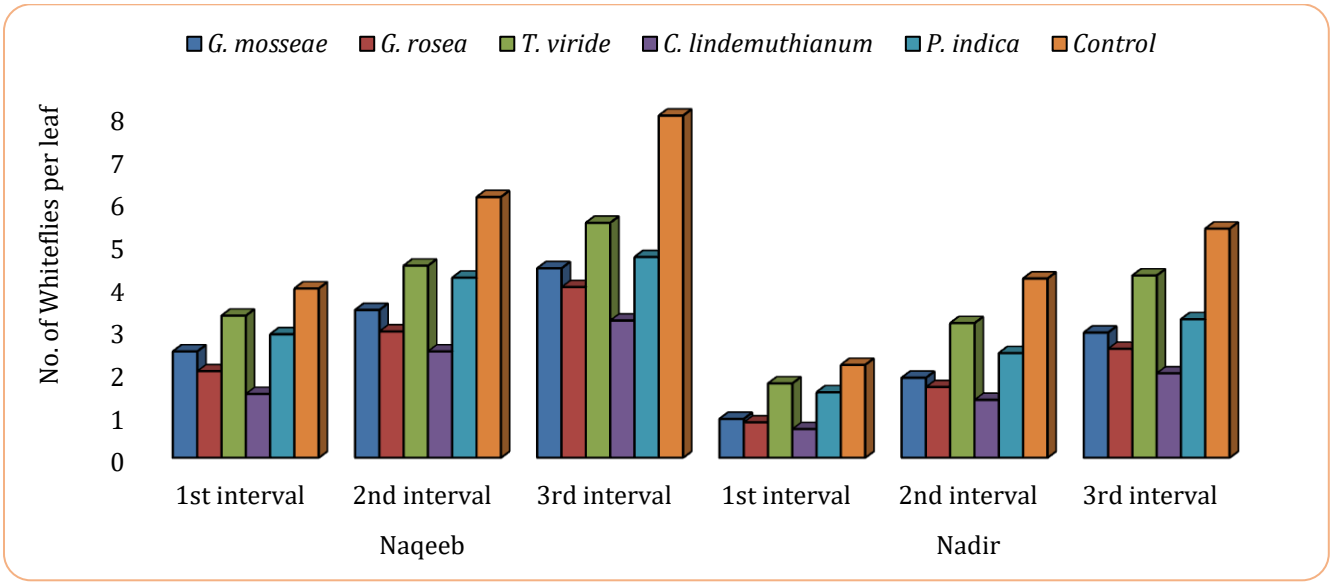


Figure 2. Effect of different fungal endophytes on whitefly population on plants under drought stress conditions.

Effect of fungal endophytes on the number of leaves per plant under drought stress

ANOVA revealed that fungal endophytes, tomato varieties, sampling dates, and their interactions had significant effects on the number of leaves per plant under drought stress showed significant effects (Table 3).

In tomato variety Nadir, *C. lindemuthianum* proved to be the most effective endophyte, producing 29.5, 40.30, and 50.11 leaves per plant at successive sampling intervals (Figure 3). Other endophytes also enhanced leaf production compared to the control. *G. rosea* resulted in 25.41, 37.41, and 47.22 leaves per plant, followed by *G. mosseae* (23.25, 35.11, and 44.86), *P. indica* (21.24, 33.25, and 42.20), and *T. viride* (19.25, 30.24, and 39.83). The untreated control plants recorded the lowest leaf numbers, with 15.07, 20.59, and 24.73 leaves per plant across the respective intervals.

Similarly, in tomato variety Naqeeb, *C. lindemuthianum* exhibited the highest efficacy, producing 27.8, 44.5, and 46.22 leaves per plant at the corresponding time points. Other endophytes also significantly improved leaf numbers, with *G. rosea* (23.50, 37.41, and 43.33), *G. mosseae* (21.34, 33.06, and 41.09), *P. indica* (19.30, 31.50, and 40.00), and *T. viride* (16.95, 30.24, and 36.23). In contrast, the untreated control plants exhibited the lowest leaf counts, with 13.53, 19.74, and 21.50 leaves per plant, respectively (Figure 3).

Table 3. Analysis of variance (ANOVA) for the effects of fungal endophytes, tomato varieties, and sampling dates and their interactions on No. of leaves per plant under drought stress conditions.

SOV	DF	SS	MS	F.ratio	P
Replication	2	0.1	0.03		
Endophytes	5	4452.8	890.55	25021.3	0.0000
Date	2	6274.3	3137.14	88142.5	0.0000
Variety	1	82.9	82.86	2328.14	0.0000
Endophytes*Date	10	363.4	36.34	1021.02	0.0000
Endophytes*Variety	5	9.4	1.89	53.03	0.0000
Date*Variety	2	47.1	23.53	661.00	0.0000
Endophytes*Date*Variety	10	32.5	3.25	91.43	0.0000
Error	70	2.5	0.04		
Total	107	11264.9			

Grand Mean = 31.325, CV = 0.60.

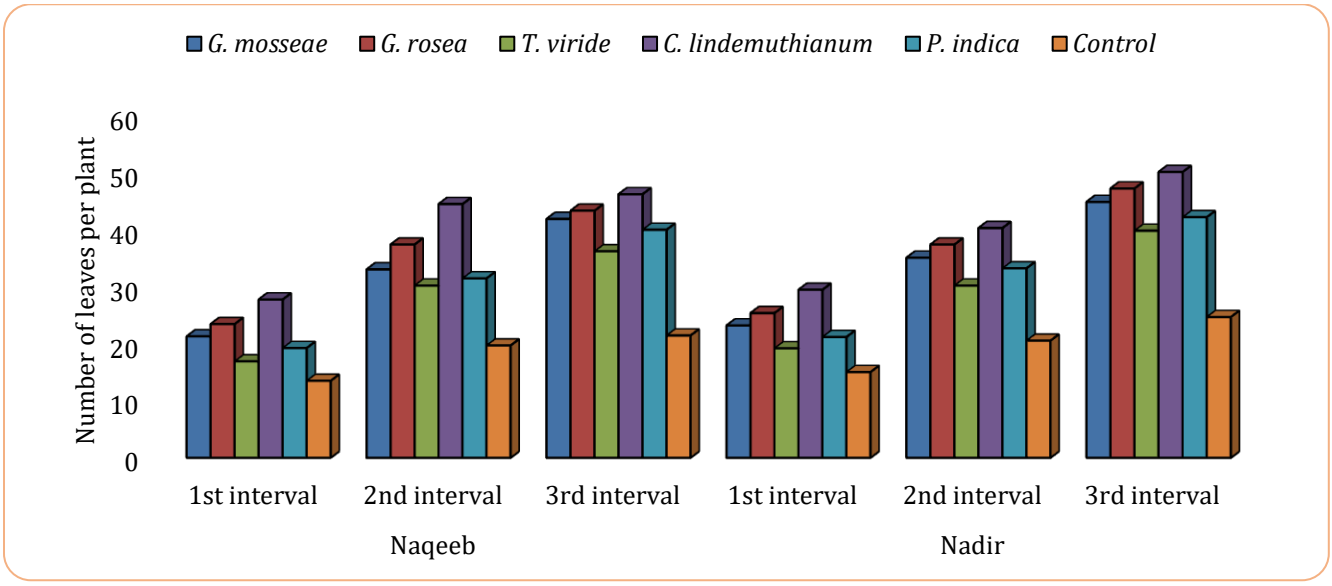


Figure 3. Effect of different fungal endophytes on No. of leaves per plant under drought stress conditions.

Effect of fungal endophytes on the number of branches per plant under drought stress

ANOVA indicated that fungal endophytes, tomato varieties, sampling dates, and their interactions significantly influenced the number of branches per plant under drought stress (Table 4). All endophyte treatments improved branching compared with the untreated control (Figure 4).

In tomato variety Nadir, *C. lindemuthianum* was the most effective endophyte, producing 5.07, 8.20, and 12.20 branches per plant across successive sampling intervals. This was followed by *G. rosea* (4.11, 6.11, and 10.22), *G. mosseae* (3.51, 4.90, and 8.33), *P.a indica* (2.22, 4.45, and 7.90), and *T. viride* (1.51, 4.00, and 6.03). The lowest number of branches was recorded in untreated control plants (1.00, 3.10, and 5.53).

A similar trend was observed in tomato variety Naqeeb. Plants inoculated with *C. lindemuthianum* showed the highest number of branches (4.07, 6.94, and 10.33), followed by *G. rosea* (3.11, 5.11, and 8.23), *G. mosseae* (2.06, 3.50, and 6.58), *P. indica* (1.22, 3.11, and 6.80), and *T. viride* (0.96, 3.00, and 4.56). The control treatment consistently produced the fewest branches (1.00, 1.98, and 4.00) as shown in Figure 4. Generally, inoculation with fungal endophytes, particularly *C. lindemuthianum* and *G. rosea*, markedly enhanced branching in tomato plants under drought stress.

Table 4. Analysis of variance (ANOVA) for the effects of fungal endophytes, tomato varieties, and sampling dates and their interactions on the number of branches per plant under drought stress conditions.

SOV	DF	SS	MS	F.ratio	P
Replications	2	0.003	0.002		
Endophytes	5	314.123	62.825	14676.2	0.0000
Date	2	470.842	235.421	54995.7	0.0000
Variety	1	40.824	40.824	9536.66	0.0000
Endophytes*Date	10	21.346	2.135	498.66	0.0000
Endophytes*Variety	5	1.171	0.234	54.69	0.0000
Date*Variety	2	2.609	1.305	304.75	0.0000
Endophytes*Date*Variety	10	1.370	0.137	31.99	0.0000
Error	70	0.300	0.004		
Total	107	852.587			

Grand Mean = 4.8611, CV = 1.35.

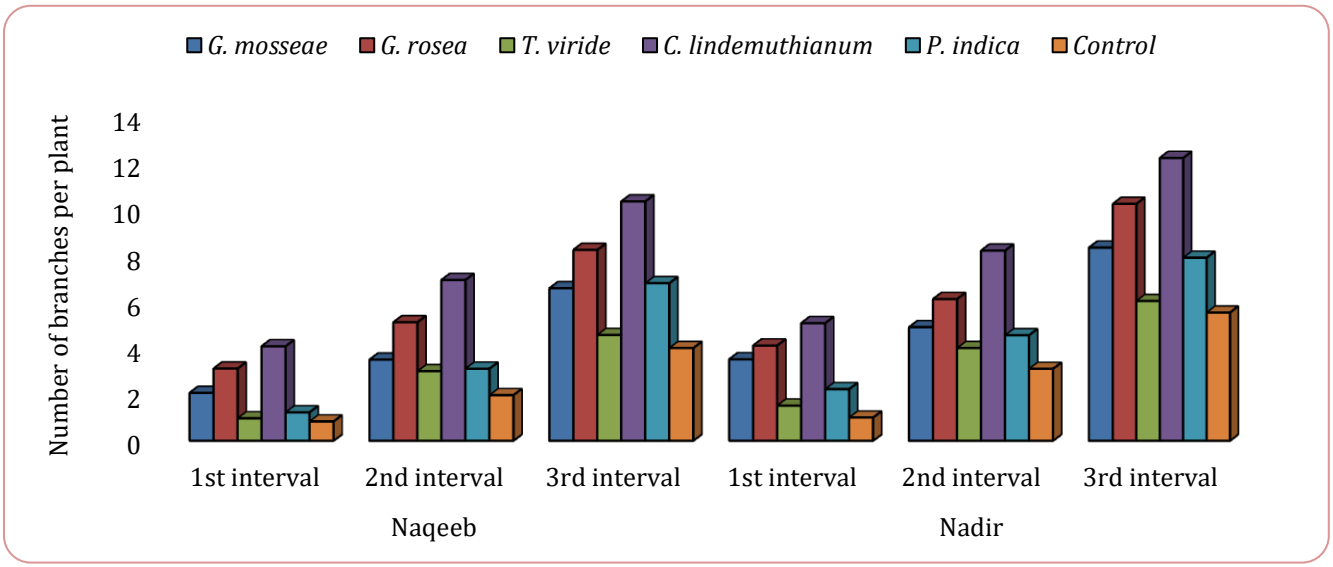


Figure 4. Effect of different fungal endophytes on the number of branches per plant under drought stress conditions.

Effect of fungal endophytes on shoot length under drought stress

ANOVA revealed that fungal endophytes, tomato varieties, sampling dates, and their interactions had significant effects on plant shoot length under drought stress (Table 5). As shown in Figure 5, *C. lindemuthianum* consistently produced the greatest shoot length across sampling intervals (23.03, 35.40, and 63.40 cm). This was followed by *G. rosea* (22.06, 33.22, and 60.83 cm), *G. mosseae* (19.41, 31.50, and 58.10 cm), *P. indica* (18.22, 29.23, and 56.21 cm), and *T. viride* (16.96, 27.66, and 51.76 cm). In contrast, the untreated control exhibited the lowest shoot length (14.50, 25.33, and 44.46 cm) across all sampling intervals (Figure 5).

For the Naqeeb variety, *C. lindemuthianum* again proved most effective, recording shoot lengths of 21.22, 33.53, and 61.93 cm at successive sampling intervals. *G. rosea* showed moderate improvement (19.53, 20.80, and 58.23

cm), followed by *G. mosseae* (17.03, 28.50, and 56.00 cm), *P. indica* (16.22, 27.20, and 53.90 cm), and *T. viride* (15.50, 25.10, and 48.33 cm). The untreated control plants exhibited the lowest shoot length (12.50, 22.97, and 41.24 cm), confirming the beneficial role of endophytes in enhancing plant growth under drought stress (Figure 5).

Table 5. Analysis of variance (ANOVA) for the effects of fungal endophytes, tomato varieties, and sampling dates and their interactions on shoot length under drought stress conditions.

SOV	DF	SS	MS	F.ratio	P
Replication	2	1375.4	687.7		
Endophytes	5	7214.2	1442.8	2.11	0.0744
Date	2	24006.8	12003.4	17.55	0.0000
Variety	1	195.2	195.2	0.29	0.5949
Endophytes*Date	10	6670.4	667.0	0.98	0.4726
Endophytes*Variety	5	3321.1	664.2	0.97	0.4415
Date*Variety	2	1334.0	667.0	0.98	0.3822
Endophytes*Date*Variety	10	6797.1	679.7	0.99	0.4572
Error	70	47875.6	683.9		
Total	107	98789.8			

Grand Mean = 36.419, CV = 71.81.

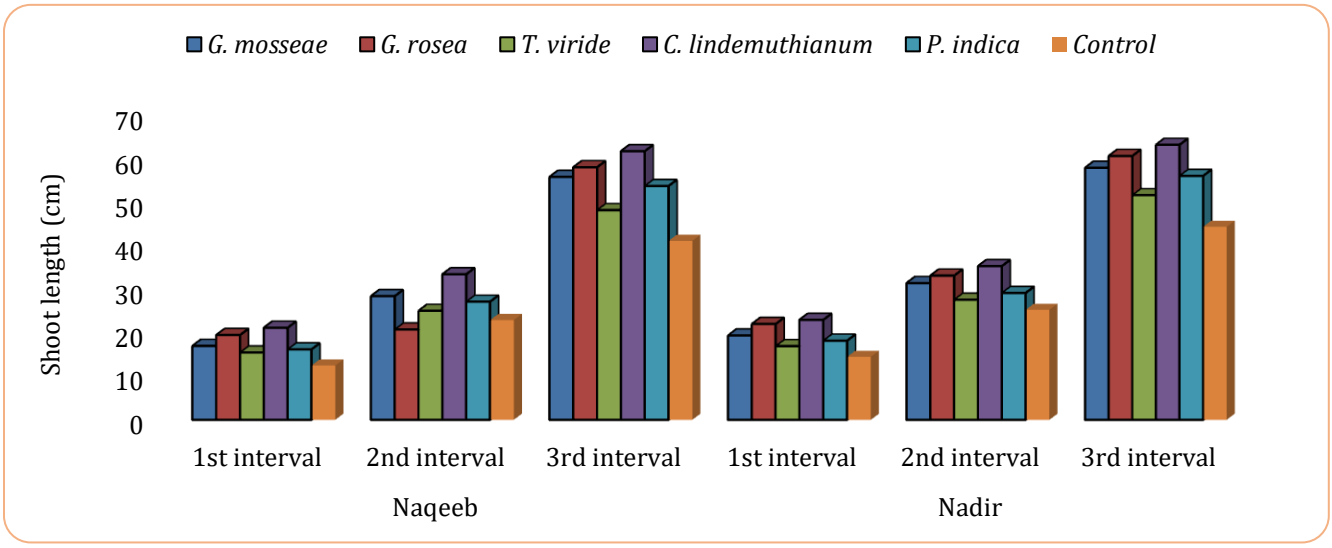


Figure 5. Effect of different fungal endophytes on shoot length under drought stress conditions.

Effect of fungal endophytes on root length of tomato under drought stress

ANOVA indicated that fungal endophytes, tomato varieties, and their interactions significantly influenced root length under drought stress (Table 6). Overall, the variety Nadir exhibited superior root development. As shown in Figure 6, *C. lindemuthianum* was the most effective endophyte in Nadir, producing the greatest root length (8.76 cm), followed by *G. rosea* (7.20 cm), *G. mosseae* (6.11 cm), *P. indica* (5.53 cm), and *T. viride* (4.96 cm). The control plants exhibited the shortest root length (3.06 cm).

A similar trend was observed in the variety Naqeeb, where *C. lindemuthianum* again resulted in the highest root length (5.23 cm). *G. rosea* and *G. mosseae* showed comparable effects (4.50 cm each), followed by *P. indica* (3.53 cm) and *T. viride* (3.46 cm). The minimum root length was recorded in the control (2.00 cm) as shown in Figure 6.

Effect of fungal endophytes on the number of fruits per plant under drought stress

Analysis of variance (ANOVA) revealed that fungal endophytes, tomato varieties, and their interaction had a significant effect on the number of fruits per plant under drought stress (Table 7). The results presented in Figure

7 indicate that all endophyte treatments significantly increased fruit number in the tomato variety Nadir compared to the control. Among the tested endophytes, *C. lindemuthianum* was the most effective, producing the highest number of fruits per plant (10.07) under drought conditions. This was followed by *G. rosea* (8.22), *G. mosseae* (6.66), *P. indica* (5.24), and *T. viride* (4.66). In contrast, the control plants exhibited a markedly lower fruit number (3.45 fruits per plant).

A similar trend was observed in the variety Naqeeb, where *C. lindemuthianum* again resulted in the highest fruit number per plant (8.22). *G. rosea* produced 6.23 fruits per plant, followed by *G. mosseae* (5.00), *P. indica* (3.96), and *T. viride* (3.00). The lowest fruit number was recorded in the control treatment, with only 1.55 fruits per plant (Figure 7).

Table 6. Analysis of variance (ANOVA) for the effects of fungal endophytes, tomato varieties, and their interactions on root length under drought stress conditions.

SOV	DF	SS	MS	F.ratio	P
Replication	2	0.029	0.0146		
Endophytes	5	53.613	10.7226	1497.82	0.0000
Variety	1	44.979	44.9794	6283.06	0.0000
Endophytes* Variety	5	7.818	1.5637	218.43	0.0000
Error	22	0.157	0.0072		
Total	35	106.598			

Grand Mean = 4.9894, CV = 1.70.

Table 7. Analysis of variance (ANOVA) for the effects of fungal endophytes, tomato varieties, and their interactions on the number of fruits per plant under drought stress conditions.

SOV	DF	SS	MS	F. ratio	P
Replication	2	0.043	0.0216		
Endophytes	5	173.848	34.7697	2399.29	0.0000
Variety	1	26.884	26.8842	1855.15	0.0000
Endophytes* Variety	5	0.480	0.0959	6.62	0.0000
Error	22	0.319	0.0145		
Total	35	201.574			

Grand Mean = 5.5242, CV = 2.18.

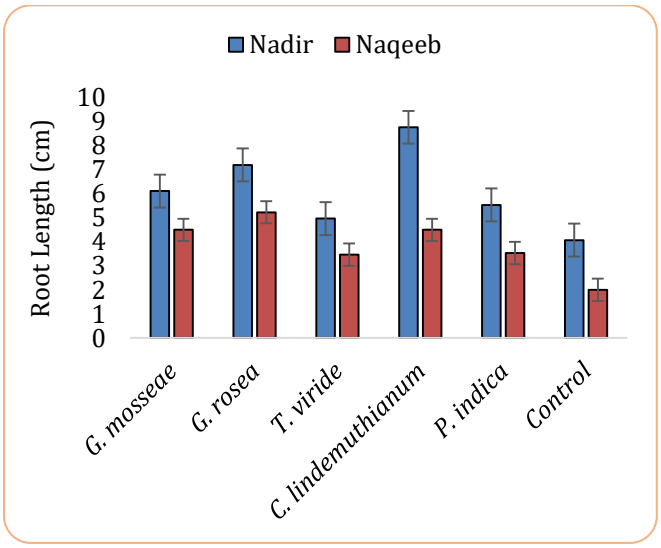


Figure 6. Effect of different fungal endophytes on root length under drought stress conditions.

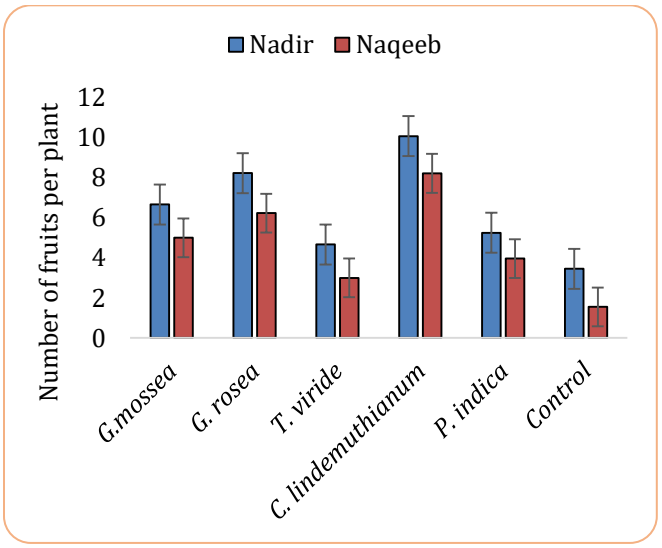


Figure 7. Effect of different fungal endophytes on the number of fruits per plant under drought stress conditions.

Discussion

The present study demonstrates that inoculation of tomato seedlings with different fungal endophytes, including *Colletotrichum lindemuthianum*, *Gigaspora rosea*, *Glomus mosseae*, *Piriformospora indica*, and *Trichoderma viride*, significantly enhanced plant tolerance to drought stress. Overall, these endophytic associations not only improved drought resilience but also contributed to a reduction in Tomato Yellow Leaf Curl Virus (TYLCV) disease severity and whitefly infestation. In addition, endophyte-treated plants exhibited marked improvements in both vegetative and reproductive growth parameters; including root length, shoot length, number of leaves per plant, number of branches per plant, and number of fruits per plant. These findings collectively indicate that fungal endophytes play a multifaceted role in strengthening plant performance under combined abiotic and biotic stress conditions.

Among all tested endophytes, *C. lindemuthianum* showed the most pronounced effects in mitigating drought stress and reducing disease severity across both tomato varieties (Nadir and Naqeeb). In the Nadir variety, disease severity under TYLCV infection was reduced to 6.22%, 17.22%, and 28.22% across successive observation intervals, whereas in the Naqeeb variety, corresponding values were 8.33%, 10.46%, and 18.5%, respectively. These results indicate a consistently lower disease progression in the Nadir variety, suggesting a stronger inherent or induced resistance compared to Naqeeb. Overall, Nadir exhibited superior performance in terms of disease suppression and growth enhancement under endophyte inoculation.

Growth parameter analysis further confirmed the beneficial role of *C. lindemuthianum* under drought stress. In the Nadir variety, root length reached 8.76 cm compared to only 4.5 cm in Naqeeb. Similarly, the number of branches per plant in Nadir increased to 12.20, whereas Naqeeb produced 10.33 branches at the third observation interval. Leaf production also followed a similar trend, with Nadir showing 50.11 leaves per plant compared to 46.22 in Naqeeb. Shoot length was recorded as 63.4 cm in Nadir and 61.93 cm in Naqeeb, indicating overall improved vegetative growth in the former. These enhancements suggest that endophyte inoculation improves nutrient acquisition, water uptake efficiency, and overall plant vigor under drought conditions.

In terms of pest suppression, endophyte-treated plants also showed reduced whitefly populations. The mean number of whiteflies per leaf was significantly lower in Nadir (1.98) compared to Naqeeb (3.22), indicating that fungal endophytes may indirectly contribute to reducing vector abundance and thereby lowering TYLCV transmission pressure. Additionally, fruit production was significantly improved, with Nadir producing 10.07 fruits per plant compared to 8.22 fruits in Naqeeb at the final observation stage. This increase in reproductive output further highlights the agronomic benefits of endophytic associations.

These findings are consistent with previous reports emphasizing the role of microbial endophytes in enhancing plant tolerance to abiotic stress. For instance, Nadeem et al. (2019) reported that drought stress severely reduced crop productivity by inhibiting germination and growth processes, particularly in legumes cultivated in arid environments. They further demonstrated that inoculation with beneficial fungal endophytes and plant growth-promoting rhizobacteria enhances drought tolerance by improving water use efficiency and maintaining physiological stability, thereby increasing yield potential under water-limited conditions.

Similarly, *P. indica* has been widely reported to colonize plant roots and enhance drought tolerance through improved chlorophyll content, nutrient uptake, and biomass accumulation. Ripa et al. (2019) documented that various fungal endophytes, including *Fusarium*, *Trichoderma*, *Penicillium*, *Aspergillus*, and *Alternaria* spp., contribute significantly to drought stress mitigation in wheat across different temperature regimes by improving physiological and biochemical resilience (Iqbal and Mukhtar, 2020; Mukhtar et al., 2021).

Furthermore, endophyte-associated plants such as rice, tomato, and dune grasses have been reported to exhibit lower water consumption compared to non-inoculated plants (Khan et al., 2017; Azeem et al., 2025). This improved water economy is attributed to enhanced solute accumulation, reduced leaf conductance, decreased transpiration rates, and increased cuticular thickness (Ripa et al., 2019). These physiological adaptations collectively contribute to improved drought tolerance and survival under water-deficit conditions.

In conclusion, the present study confirms that fungal endophytes, particularly *C. lindemuthianum*, play a significant role in enhancing drought tolerance, suppressing TYLCV disease severity, reducing whitefly populations, and improving overall plant growth and yield. These findings support the potential application of

endophytic fungi as sustainable biocontrol and bio-stimulant agents in integrated crop management systems under changing climatic conditions.

Author's contributions

MA performed the experiment. SA supervised the study. AH verified the statistical analysis. MK reviewed the manuscript. IK assisted in manuscript writing.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 12: Responsible Consumption and Production
SDG 13: Climate Action

Policy Addressed

1. National Climate Change Policy of Pakistan (2021)
2. National Food Security Policy of Pakistan (2018)

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