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The effect of biofertilizers on selected physiological and biochemical traits of *Pelargonium graveolens* plants infected with *Fusarium Oxysporum*

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Abstract

The present study was conducted under the wooden shade house of the Department of Forestry, College of Agriculture and Forestry, University of Mosul, during the 2025–2026 growing season, to evaluate the effect of biofertilizers on certain physiological and biochemical processes in two cultivars of Pelargonium grown in loamy clay soil.

The results showed that treating Pelargonium plants with biofertilizers led to significant increases in plant height, leaf area, soluble sugar content, chlorophyll A content, chlorophyll B content, and essential oil percentage. The percentages of increase were 68.00%, 26.60%, 3.88%, 8.59%, 5.72%, and 3.96%, respectively.

Furthermore, biofertilizer application played an important role in alleviating the negative effects associated with the activity of antioxidant enzymes (SOD and CAT) in both cultivars of Pelargonium. The reduction percentages were 0.64% for superoxide dismutase (SOD) activity and 1.59% for catalase (CAT) activity.

In addition, plants grown in loamy clay soil exhibited superior performance in most physiological and biochemical traits. The results also demonstrated a clear superiority of the Tea cultivar over the Stab cultivar in most of the studied characteristics.

Keywords: Pelargonium, biofertilizers, physiological traits, biochemical traits, loamy clay soil, plant height, leaf area, soluble sugars

Introduction

Biofertilizers, comprising favorable microbes like bacteria, fungi, and algae, constitute a key advancement in soil science. These microbes colonize the seed or soil and help enhance soil fertility and plant growth by aiding in the acquisition and uptake of necessary nutrients, especially N and P (Giri *et al*., 2019) [7]. Moreover, biofertilizers, unlike their chemical counterparts, help preserve soil fertility and pollution-free environment (Areej *et al*., 2024) [14].

An imbalance of nature occurred, especially on human health, by an increased reliance on producing food through the application of chemical fertilizers. On the economic side, this method of food production was not sustainable to several farmers (Fasusi *et al*., 2021) [5]. Chemical fertilizers provide nutrients to plants in an extremely inefficient way, as most of the nutrients get fixed in the soil due to several reactions and interactions with mineral cations. The disproportionate application of chemical fertilizers results in a variety of environmental predicaments that ultimately call for the adoption of efficient agricultural methods (Babalola, 2010) [6]. The chemical fertilizers, in addition to their contribution to the environmental catastrophes, cause an excessive use of fossil fuels, and as a result, an abundant release of nitrogen and CO2 in the terrestrial ecosystems (Giri *et al*., 2019) [7].

Salinity and drought stress present significant challenges for agriculture and sustaining global food production. Bio-fertilizers can ameliorate some of these challenges through their growth-promoting substances that are rich in auxins. Auxins stimulate root growth, and in addition, improve resistance to various environmental stressors (Abdallah *et al*., 2009) [8]. Contrary to the fertilizer industry, which promotes the use of chemical fertilizers, bio-fertilizers improve soil quality and reduce the reliance on chemical fertilizers (Woźniak & Siebielec, 2025) [9]. Bio-fertilizers stimulate soil microbial activity, enhance soil structure and improve the physical and biological properties of the soil, and increase soil resilience to environmental stressors (Mahanty *et al*., 2017) [10].

Mycorrhizal bio-fertilizers contain beneficial microorganisms that help in the formation of mycorrhizal associations in roots. Mycorrhizal fungi have extensive hyphae that allow for the absorption of water, nutrients (including Phosphorus), and even soil Carbon from the plant (Pooja *et al*., 2025) [11]. Bio-fertilizers also enhance the ability of the soil to support plant growth by including microorganisms that promote Nitrogen fixation. These microorganisms, which include several species of Rhizobium and Azotobacter, transform Nitrogen in the atmosphere to a less complex and more readily absorbable form of Nutrient (Aasfar *et al*., 2024) [13].

Microorganisms that solubilize phosphates represent a significant category of biofertilizers. Microorganisms of this category transform insoluble inorganic phosphorous compounds of soil into phosphates that can be absorbed by plants. An example of such microorganisms is Pseudomonas, Bacillus, Penicillium, and Aspergillus (Alori *et al*., 2017) [12]. Biofertilizers of this category are identified by their capability to transform potassium from soil minerals into forms that are easily accessible to plants. Such microorganisms include some species of Frateuria and Bacillus (Dobhal *et al*., 2019) [15].

Recent studies show that biofertilizers have a positive effect on the physiology and biochemistry of geranium (Pelargonium). This includes improvement in growth and nurturing, as well as an increase in the ability to adapt to different environmental conditions. The use of arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria

is reported to result in the improvement of growth and productivity of the plants due to an increase in the chlorophyll content, improvement of the water status of the plant, and enhancement of the antioxidant defense system (Deepa *et al*., 2024; Okla *et al*., 2022) [1, 2].

These microorganisms positively affect the uptake of macronutrients such as nitrogen, phosphorous, and potassium and actively participate in the metabolism that leads to the production of secondary metabolites and essential oils that have great economic importance to geranium (Deepa *et al*., 2024) [1].

Mycorrhizal inoculation modifies root development and enhances the zone from which plants can scavenge water and nutrients, ultimately improving the yield and quality of the produced essential oil. Mycorrhizal fungi and bacterial dual inoculation induce synergistic effects resulting in greater branching and increased plant biomass and essential oil yield, when compared to their uninoculated control counterparts (Negi *et al*., 2022) [2]. Moreover, bacterial inoculation enhances the expression of genes and the activity of plant enzymes involved in the biosynthetic pathway of secondary metabolites. These bacteria also synthesize and secrete plant growth regulators such as auxins and gibberellins that stimulate vegetative growth and result in increased biosynthesis of active compounds in essential oils (Deepa *et al*., 2024) [1].

In terms of soil texture, geranium thrives in well-drained and well-aerated sandy loam soils. These minimize waterlogging and hypoxic root conditions, both of which stymie root development. While very heavy clay soils negatively influence the capacity of a plant to uptake nutrients, due to high moisture retention and poor aeration, very coarse sandy soils negatively impact essential oil yield due to their propensity for leaching essential nutrients and moisture (Okla *et al*., 2022; Jadidi *et al*., 2023) [2, 3]. For geranium cultivation, a well-structured soil with adequate organic matter would yield the highest productivity and growth (Okla *et al*., 2022; Jadidi *et al*., 2023) [2, 3].

The physical properties of soil, including porosity and bulk density, also play a crucial role in promoting root proliferation and improving nutrient uptake efficiency, particularly nitrogen, which is essential for protein and chlorophyll synthesis. Studies have confirmed that the application of biofertilizers improves both the physical and biological properties of soil and increases microbial activity in the rhizosphere. These improvements contribute to greater plant height, increased branching, higher biomass accumulation, and enhanced essential oil content compared with soils that do not receive biofertilizer treatments (Negi *et al*., 2022; Savastano & Bais, 2024) [2, 4].

Materials and working methods

First: Traits Evaluated in the Shade House Experiment

Plant Height (cm)

Plant height of geranium (Pelargonium) was measured from the point of attachment to the soil surface up to the apex of the main stem using a graduated ruler.

Leaf Area (cm² / plant)

Leaf area was determined according to the method described by (Scott *et al*., 1973) [23] which involves calculating the ratio between the dry weight of leaf discs of known area and the total dry weight of the leaves. Leaf area was then estimated using the equation proposed by (Roy *et al*., 1981) [22].

$$\text{Leaf Area (cm}^2\text{/plant)} = \frac{\left(\text{(Disc Area (cm}^2\text{)} \times \text{Dry Weight of Discs (g))} + \text{Dry Weight of Plant Leaves (g)}\right)}{\text{Dry Weight of Discs (g)}}$$

Second: Physiological Parameters

Relative Water Content (RWC)

Relative water content was determined according to the method of (Turner, 1981) [24] which has been widely adopted by researchers, including (Schonfeld *et al*., 1988) [25].

Relative Water Content (%) = [(Fresh Weight - Dry Weight) / (Turgid Weight - Dry Weight)] ×100%

Determination of Soluble Sugars

Total soluble sugars in the leaves were determined following the method described by (Otls, 2011). The intensity of the brown color developed in the test solution was measured using a spectrophotometer at a wavelength of 490 nm.

Third: Biochemical Parameters:

Non-Enzymatic Antioxidant System

Determination of Proline Content

Proline concentration in geranium leaves was determined according to the method of (Bates *et al*., 1973) [26]. Measurements were carried out using a (spectrophotometer) at a wavelength of 520 nm.

Enzymatic Antioxidant System

Determination of Catalase (CAT) Activity

Catalase (CAT) activity was measured according to the method described by (Goth, 1991) [29]. Absorbance was recorded using a spectrophotometer at a wavelength of 405 nm.

Determination of Superoxide Dismutase (SOD) Activity

The activity of superoxide dismutase (SOD) in geranium leaves was determined according to the method of (Calatayud *et al*., 2002) [27], using a spectrophotometer at a wavelength of 560 nm.

Determination of Essential Oil Percentage in Leaves and Stems

The essential oil content was determined using 100 g of chopped leaves and stems of geranium. The plant material was placed in a glass flask containing 2 L of distilled water and heated to boiling at 100°C. The distillation process continued for approximately 12 hours until complete extraction of the essential oil from the plant tissues was achieved. The extracted oil was then collected and stored in dark, airtight glass bottles and kept at 4°C until further use. The extraction was carried out using the hydrodistillation (steam distillation) method with a Clevenger apparatus, following the procedure described by Wagner and (Bladt, 2009) [28].

Result

Plant Height

Results shown in (1) indicated that infection of geranium (Pelargonium) plants with Fusarium fungus drastically decreased plant growth by a value of 3.3% in comparison to non-infected plants.

Regarding treatment effect, results indicated that plant height increased significantly when mycorrhiza was inoculated and when Cendre was applied. The Cendre +

Mycorrhiza treatment resulted in the highest plant height, which is an improvement of 14.9% compared to the control plants that received no treatment.

In terms of cultivar effects, the Stab cultivar resulted in a significantly higher plant height than the Tea cultivar.

Results also showed a significant effect of the cultivar × infection interaction in which the non-infected Stab plants were in a superior class compared to the other treatment combinations.

Lastly, the interaction of cultivar × treatment × infection indicated that there was a significant decrease in plant height of the Fusarium infected Tea plants that were not treated.

Table 1: Effect of biofertilizers on plant height of geranium (Pelargonium) plants infected with Fusarium fungus.

Plant Type	Infection Status	Transactions				Plant Type × Infection	Effect of Plant Type	Effect of Infection
		Control	Mycorrhiza	Fungicide	Combination (Mix)			
Tea	Infected	46.73 j	52.20 gh	50.80 hi	54.70 f	51.11 d		
	Non-infected	49.10 i	53.60 fg	52.70 g	56.90 e	53.08 c		
Stap	Infected	57.80 e	64.20 c	62.00 d	66.20 b	62.55 b		
	Non-infected	60.30 d	65.50 bc	64.50 bc	68.00 a	64.58 a		
Plant Type × Treatments	Tea	47.92 g	52.90 f	51.75 f	55.80 e		52.09 b	
	Stap	59.05 d	64.85 b	63.25 c	67.10 a		63.56 a	
Infection × Treatments	Infected	52.27 g	58.20 d	56.40 e	60.45 b			56.83 b
	Non-infected	54.70 f	59.55 bc	58.60 cd	62.45 a			58.83 a
Effect of Treatments		53.48 d	58.88 b	57.50 c	61.45 a			

Relative Water Content (RWC)

The data in Table (2) indicate that infection of Pelargonium plants with Fusarium fungus reduced their relative water content. In the study, uninfected Pelargonium plants had relative water content values that were 3.1% higher than infected plants.

In mycorrhiza treatments, relative water content was significantly increased in response to the application of Cendre. The combination of Cendre and mycorrhiza also significantly increased relative water content, with an increase of 9.3% compared to the control plants.

In the studied plant cultivars, the Stab cultivar had significantly higher relative water content than the Tea cultivar.

According to the presented data, the combination of cultivars and infection caused relative water content to be significantly reduced in Fusarium infected Tea cultivar plants.

Moreover, the three-way interaction (Cultivar × Infection × Treatment) revealed a significant decrease in relative water content in Fusarium-infected Tea plants that did not receive any biofertilizer treatment.

Table 2: Effect of biofertilizers on the relative water content of geranium (Pelargonium) plants infected with Fusarium fungus.

Plant Type	Infection Status	Transactions				Plant Type × Infection	Effect of Plant Type	Effect of Infection
		Control	Mycorrhiza	Fungicide	Combination (Mix)			
Tea	Infected	58.80 h	62.10 g	61.70 g	64.50 ef	61.78 d		
	Non-infected	61.40 g	64.30 ef	63.20 fg	66.10 de	63.75 c		
Stap	Infected	62.70 fg	67.20 cd	65.50 de	68.60 bc	66.00 b		
	Non-infected	64.40 ef	69.30 b	67.10 cd	71.20 a	68.00 a		
Interaction between Plant Type and Treatments	Tea	60.10 e	63.20 d	62.45 d	65.30 c		62.76 b	
	Stap	63.55 d	68.25 b	66.30 c	69.90 a		67.00 a	
Interaction between Infection and Treatments	Infected	60.75 f	64.65 cd	63.60 de	66.55 b			63.89 b
	Non-infected	62.90 e	66.80 b	65.15 c	68.65 a			65.88 a
Effect of Treatments		61.83 d	65.73 b	64.38 c	67.60 a			

Chlorophyll A

The results presented in Table (3) indicate that infection of geranium (Pelargonium) plants with Fusarium fungus led to a significant increase in chlorophyll A content, with an increase of 8.5% compared with non-infected plants.

Regarding the effect of treatments, the results showed a significant decrease in chlorophyll A content with mycorrhiza inoculation and Cendre application. The control treatment recorded a 33.4% reduction in chlorophyll A content compared with the combined treatment (Cendre + Mycorrhiza), which showed the highest values.

With respect to cultivar effects, the Stab cultivar significantly outperformed the Tea cultivar in chlorophyll A content.

The results also revealed that the interaction between infection and cultivar (Infection × Cultivar) showed a significant superiority in the non-infected Stab cultivar plants.

Furthermore, the three-way interaction (Cultivar × Infection × Treatment) indicated a significant decrease in chlorophyll A content in Fusarium-infected Tea plants that did not receive any treatment.

Table 3: Effect of biofertilizers on chlorophyll A content of geranium (Pelargonium) plants infected with Fusarium fungus.

Plant Type	Infection Status	Transactions				Plant Type × Infection	Effect of Plant Type	Effect of Infection
		Control	Mycorrhiza	Fungicide	Combination (Mix)			
Tea	Infected	3.78 j	5.28 gh	4.62 i	5.67 g	4.84 d		
	Non-infected	4.12 j	6.26 ef	5.37 gh	6.74 d	5.62 c		
Stap	Infected	5.10 h	7.15 c	6.66 de	7.78 b	6.67 b		
	Non-infected	6.17 f	6.62 de	6.10 f	8.59 a	6.87 a		

Plant Type × Treatments	Tea	3.95 f	5.77 d	5.00 e	6.21 c		5.23 b	
	Stap	5.64 d	6.89 b	6.38 c	8.19 a		6.77 a	
Infection × Treatments	Infected	4.44 f	6.22 c	5.64 d	6.73 b			5.76 b
	Non-infected	5.15 e	6.44 c	5.74 d	7.67 a			6.25 a
Effect of Treatments		4.79 d	6.33 b	5.69 c	7.20 a			

Chlorophyll B

The results included in Table 4 indicate that the infection of geranium (Pelargonium) plants with Fusarium fungus caused a significant decrease in the amount of chlorophyll B, having an approximate 12.1% decrease in comparison to the non-infected plants.

As for the treatments, it was observed that the amount of chlorophyll B increased significantly after mycorrhiza inoculation and Cendre application. The combination of Cendre and Mycorrhiza treatments resulted in an increase of chlorophyll B by 45.02% in comparison to the control plants.

As for the cultivars, the Stab cultivar had a significantly higher amount of chlorophyll B, in comparison to the Tea cultivar.

It was also observed that the chlorophyll B content of the Tea cultivar, in comparison to the Stab cultivar, was significantly lower due to the interactons of the cultivar and treatment.

The three-way interaction of the cultivar, infection, and treatment showed that Tea plants infected by Fusarium and given no treatment had a significantly lower amount of chlorophyll B.

Table 4: Effect of biofertilizers on chlorophyll B content of geranium (Pelargonium) plants infected with Fusarium fungus.

Plant Type	Infection Status	Transactions				Plant Type × Infection	Effect of Plant Type	Effect of Infection
		Control	Mycorrhiza	Fungicide	Combination (Mix)			
Tea	Infected	2.86 h	3.88 d-g	3.27 fgh	4.25 cde	3.57 c		
	Non-infected	3.19 gh	5.17 ab	3.58 e-h	4.75 bc	4.17 b		
Stap	Infected	3.63 e-h	4.74 bc	4.00 c-f	5.12 ab	4.37 b		
	Non-infected	4.01 c-f	5.21 ab	4.53 bcd	5.72 a	4.87 a		
Plant Type × Treatments	Tea	3.03 f	4.53 bc	3.43 ef	4.50 bc		3.87 b	
	Stap	3.82 de	4.98 ab	4.27 cd	5.42 a		4.62 a	
Infection × Treatments	Infected	3.25 e	4.31 bc	3.64 de	4.69 b			3.97 b
	Non-infected	3.60 de	5.19 a	4.06 cd	5.24 a			4.52 a
Effect of Treatments		3.42 c	4.75 a	3.85 b	4.96 a			

Carotenoids

The results presented in Table (5) indicate that infection of geranium (Pelargonium) plants with Fusarium fungus led to a significant increase in carotenoid content, with an increase of 8.1% compared with non-infected plants.

Regarding the effect of treatments, the results showed a significant decrease in carotenoid content following mycorrhiza inoculation and Cendre application. The control treatment recorded a 19.7% reduction in carotenoid content compared with the combined treatment (Cendre + Mycorrhiza), which showed the highest values.

With respect to cultivar effects, the Stab cultivar significantly outperformed the Tea cultivar in carotenoid content.

The results also revealed that the interaction between infection and cultivar (Infection × Cultivar) resulted in a significant superiority in non-infected plants of the Stab cultivar.

Furthermore, the three-way interaction (Cultivar × Infection × Treatment) showed a significant reduction in carotenoid content in Fusarium-infected Tea plants that did not receive any treatment.

Table 5: Effect of biofertilizers on carotenoid content of geranium (Pelargonium) plants infected with Fusarium fungus.

Plant Type	Infection	Transactions				Plant Type × Infection	Plant Type Effect	Infection Effect
		Control	Mycorrhiza	Fungicide	Mix			
Tea	Infected	0.48 g	0.58 def	0.53 fg	0.63 cd	0.55 d		
	Non-infected	0.56 ef	0.63 cd	0.61 de	0.68 bc	0.62 c		
Stap	Infected	0.60 de	0.68 bc	0.64 cd	0.72 b	0.66 b		
	Non-infected	0.64 cd	0.72 b	0.68 bc	0.80 a	0.71 a		
Plant Type × Treatments	Tea	0.52 f	0.60 de	0.57 e	0.65 c		0.59 b	
	Stap	0.62 cd	0.70?	0.66 c	0.76 a		0.68 a	
Infection × Treatments	Infected	0.54 f	0.63 cd	0.58 e	0.68 b			0.61 b
	Non-infected	0.60 de	0.67 b	0.64 bc	0.74 a			0.66 a
Effect of Treatments		0.57 d	0.65 b	0.61 c	0.71 a			

Essential Oil Percentage

The data in **Table 6** indicate that geranium plants (Pelargonium) infected by the Fusarium fungal species saw a decline in their essential oil yield by 8.2% as compared to non-infected plants.

Considering treatment effects, the application of mycorrhizae and Cendre resulted in an increase in the yield of essential oils, with the combination of both treatments (Cendre + Mycorrhiza) being the most effective, resulting in a 44.7% increase over the control plants.

In terms of cultivar effects, the Tea cultivar had a lower percentage of essential oils compared to the Stab cultivar.

The interaction between cultivar and treatment also demonstrated a greater precedence of the Stab cultivar over the Tea cultivar.

The three-way interaction of cultivar, infection, and treatment also showed the greatest precedence of non-infected, non-treated Stab plants in respect to their essential oil yield.

Table 6: Effect of biofertilizers on essential oil percentage of geranium (Pelargonium) plants infected with Fusarium fungus

Plant Type	Infection Status	Transactions				Plant Type × Infection	Effect of Plant Type	Effect of Infection
		Control	Mycorrhiza	Fungicide	Combination (Mix)			
Tea	Infected	2.20 k	2.85 ghi	2.56 ij	3.11 d-g	2.68 c		
Tea	Non-infected	2.43 jk	3.22 c-f	2.97 e-h	3.40 cd	3.01 b		
Stap	Infected	2.47 jk	3.30 cde	2.95 fgh	3.77 ab	3.12 b		
	Non-infected	2.75 hij	3.51 bc	3.00 e-h	3.96 a	3.31 a		
Plant Type × Treatments	Tea	2.32 f	3.04 c	2.77 de	3.26 b		2.84 b	
	Stap	2.61 e	3.41 b	2.98 cd	3.87 a		3.21 a	
Infection × Treatments	Infected	2.34 e	3.08 c	2.76 d	3.44 b			2.90 b
	Non-infected	2.59 d	3.37 b	2.99 c	3.68 a			3.16 a
Effect of Treatments		2.46 d	3.22 b	2.87 c	3.56 a			

Catalase Enzyme Activity (CAT)

Infection of geranium (Pelargonium) plants with Fusarium fungus as noted in Table (7) showed that there was a 3.5% increase in catalase (CAT) enzyme activity when compared to non-infected plants.

Among treatments, inoculation with mycorrhiza and application of Cendre resulted in increased activity of the CAT enzyme. A control treatment resulted in an 11.8% increase in catalase activity when compared to the combined treatment of Cendre and Mycorrhiza.

Regarding the cultivars, the activity of the Tea cultivar was higher than that of the Stab cultivar.

Additionally, the CAT activity in the Tea cultivar was significantly higher in infected plants when observing the infection and cultivar interaction.

In the non-infected, non-treated Stab plants, the three-way interaction (Cultivar × Treatment × Infection) resulted in a significant decrease of catalase activity.

Table 7: Effect of biofertilizers on catalase (CAT) activity of geranium (Pelargonium) plants infected with Fusarium fungus.

Plant Type	Infection Status	Transactions				Plant Type × Infection	Effect of Plant Type	Effect of Infection
		Control	Mycorrhiza	Fungicide	Combination (Mix)			
Tea	Infected	1.59 a	1.45 ab	1.50 ab	1.40 ab	1.49 a		
	Non-infected	1.55 ab	1.42 ab	1.50 ab	1.35 ab	1.46 ab		
Stap	Infected	1.48 ab	1.40 ab	1.44 ab	1.35 ab	1.42 ab		
	Non-infected	1.42 ab	1.33 ab	1.35 ab	1.28 b	1.35 b		
Plant Type × Treatments	Tea	1.57 a	1.44 ab	1.50 ab	1.38 b		1.47 a	
	Stap	1.45 ab	1.37 b	1.40 ab	1.32 b		1.38 b	
Infection × Treatments	Infected	1.54 a	1.43 ab	1.47 ab	1.38 ab			1.45 a
	Non-infected	1.49 ab	1.38 ab	1.43 ab	1.32 b			1.40 a
Effect of Treatments		1.51 a	1.40 ab	1.45 ab	1.35 b			

Superoxide Dismutase (SOD)

The data indicated in Table (8) show that the infection of geranium (Pelargonium) plants with the Fusarium fungus results in a 3.5% decrease in the activity of the enzyme superoxide dismutase (SOD) in comparison with uninfected plants.\

Considering the effect of treatments, it can be said that the activities of the enzyme SOD decreased, following the inoculation of mycorrhiza and the application of Cendre. The combined effect (Cendre + Mycorrhiza) resulted in a decrease of SOD activity by 13.3% in comparison with control plants.

Regarding cultivar effects, the activity of the enzyme SOD was higher in the Stab cultivar than in the Tea cultivar.

It was also shown that the effects of the combination of infection and cultivar (Infection × Cultivar) resulted in greater activity of the SOD enzyme in the Tea cultivar, in comparison with the Stab cultivar, under Fusarium infection.

In addition, the combination of the three factors Cultivar, Infection and Treatment resulted in a significant decrease in the activity of the SOD enzyme in the Tea plants that were not infected and not subjected to any treatment.

Table 8: Effect of biofertilizers on superoxide dismutase (SOD) activity of geranium (Pelargonium) plants infected with Fusarium fungus.

Plant Type	Infection Status	Transactions				Plant Type × Infection	Effect of Plant Type	Effect of Infection
		Control	Mycorrhiza	Fungicide	Combination (Mix)			
Tea	Infected	0.64 a	0.58 abc	0.61 abc	0.55 abc	0.60 a		
	Non-infected	0.62 ab	0.56 abc	0.58 abc	0.53 abc	0.57 ab		
Stap	Infected	0.58 abc	0.54 abc	0.56 abc	0.51 bc	0.55 ab		
	Non-infected	0.55 abc	0.53 abc	0.53 abc	0.50 c	0.53 b		
Plant Type × Treatments	Tea	0.63 a	0.57 abc	0.60 ab	0.54 bc		0.58 a	
	Stap	0.57 abc	0.54 bc	0.55 bc	0.51 c		0.54 b	
Infection × Treatments	Infected	0.61 a	0.56 ab	0.59 ab	0.53 b			0.57 a
	Non-infected	0.59 ab	0.55 ab	0.56 ab	0.52 b			0.55 a
Effect of Treatments		0.60 a	0.55 ab	0.57 ab	0.52 b			

Discussion

Table (1) shows how Fusarium fungal infections decreased overall plant height. There is a justifiable expectation in decreased height due to fungal infections resulting in blocked paths for the plant to absorb essential nutrients and water, thus reducing growth.

The application of treatments, especially the combination of mycorrhiza with the fungicidal amendment, resulted in increased plant height with the combination achieving the greatest height. This is likely due to increased plant uptake of nutrients and growth stimulation.

When considering growth and stress tolerance, the Stab cultivar was superior to the Tea cultivar. This was also evident with the interaction effects, especially for the non-infected plants. In the case of the triple interaction, the infected untreated Tea plants suffered the most, showing their high susceptibility when facing the absence of growth-promoting treatments (El-Otmani *et al*., 2024) [17].

From Table (2), it was clear that the Fusarium infection caused an imbalance of the internal water of the plant and decreased the relative water content. However, the application of mycorrhiza and the fungicide treatment boosted relative water content by improving the plant's uptake of water and nutrients.

The Stab cultivar also displayed a greater ability relative to the Tea cultivar to maintain water status. Interaction effects also confirmed that the infected untreated Tea plants were the most affected, and had higher sensitivity to disease stress (Draiaia *et al*., 2025) [21].

Table (3) states that the Fusarium infection increased the content of chlorophyll A. This can be viewed as the stressed plant attempting to balance the demand of the photosynthetic process. For the other treatments, the application of mycorrhiza and fungicide improved the content of chlorophyll A in comparison to the control treatment. This indicated that they enhanced the photosynthetic process, despite the fluctuations in the level of chlorophyll A. The Stab cultivar surpassed the Tea cultivar indicating better stability of the pigments. The interactive results indicated that the unaffected Stab plants were the best and that the affected Tea plants were the most affected.

Table (4) states that the infection of Fusarium reduced the amount of chlorophyll B. This is due to the degradation of the photosynthetic apparatus and stress induced degradation of pigments.

The application of mycorrhiza and fungicide increased the levels of chlorophyll B, with the highest levels in the combined treatment, indicating better photosynthetic processes and better plant growth. The Stab cultivar surpassed the Tea cultivar in pigment stability, whereas the Tea cultivar, especially when infected and untreated, was the most affected (Haikal *et al*., 2025) [16].

Table (5) states that the infection of Fusarium increased the content of carotenoids. This can be interpreted as a response to stress, and due to the increased oxidative and antioxidant systems, it can be viewed as a defensive response.

In general, results regarding mycorrhiza application, alone or combined with fungicide application, tended to be better compared to control treatments. It appears that applied treatments, in general, may affect the accumulation of carotenoids according to the plants' physiological condition. The results showed again the superiority of Stab over Tea, with the untreated infected Tea plants being the worst, showing the greatest susceptibility to stress.

As noted in Table (6), there was a decrease in the percentage of essential oils due to infection with Fusarium, and this was assumed to be due to the disturbance of the metabolic pathways that are responsible for the formation of aromatic compounds and essentials oils.

As for the application of mycorrhiza, combined with fungicides, there was a significant increase in the content of essential oils, especially in the combined treatment, which may be attributed to the positive effect of the treatments on the growth of the plants, as well as the stimulation of the processes of the secondary metabolites.

The Stab cultivar yielded higher essential oils than the Tea cultivar, with the untreated Stab plants being the best and infected Tea plants being the worst.

As shown in Table (7), there was an increase in the activity of catalase (CAT) due to the infection of Fusarium and this is indicative of the formation of an oxidative stress defense response and the activation of the antioxidants' defense.

As for the application of mycorrhiza and fungicides, the variable effects of the treatments were characteristic, with the control treatments showing higher CAT activity, which was not the case for the fungicide and mycorrhiza combined treatments. The highest CAT activity was displayed by the Tea cultivar as compared to the Stab cultivar, exhibiting a defense response of varying genetic nature. The interaction effects indicated the highest activity of the enzyme in the infected Tea plants, whereas the non-infected Stab plants exhibited the least activity.

As shown in Table (8), Fusarium infection appears to inhibit SOD activity. As for mycorrhiza and fungicide treatments, there was little to no improvement on the activity of the enzyme. When comparing the two cultivars, Brenes *et al*. (2024) [20] suggest that the Tea cultivar is more active in SOD than the Stab cultivar (which displayed the least activity) and that SOD activity is generally highest in non-infected plants.

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