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Comparative Effects of Funneliformis Mosseae on Growth and Nutrient Uptake in Tomato (*Lycopersicon esculentum*) and Fenugreek (*Trigonella foenum-graecum*)

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ABSTRACT

The research compared the effects of the mycorrhizal fungus *Funneliformis mosseae* on growth and nutrient uptake in *Lycopersicon esculentum* (tomato) and *Trigonella foenum-graecum* (fenugreek) plants. Mycorrhizal biofertilizer (*Funneliformis mosseae*) was applied to clay, peatmoss, and mixed soils, followed by planting tomato and fenugreek seeds. Growth parameters such as germination rate, biomass, root colonization, and vegetative growth were assessed. Root and shoot samples were analyzed for nutrient content and protein concentration. The results showed significant improvements in germination, with tomato reaching 95% and fenugreek 80% in clay soil inoculated with mycorrhiza. Mycorrhizal frequency was highest in clay soil, with tomato at 94.14% and fenugreek at 76.24%. Root and shoot biomass, root length, and nutrient concentrations also increased significantly in mycorrhizal treatments, with tomato outperforming fenugreek across all parameters. *Funneliformis mosseae* significantly ($p \leq 0.05$) enhanced plant growth and nutrient uptake compared to control treatments. Tomato plants grown in clay soil with mycorrhizal treatment recorded the highest values: root biomass (0.83g), shoot weight (29.5g), and nutrient concentrations (N: 6.12%, P: 1.99%, K: 7.34%, protein: 31.25%). Fenugreek exhibited similar improvements. These findings highlight the role of *Funneliformis mosseae* in enhancing plant growth and nutrient uptake.

1. INTRODUCTION

Lycopersicon esculentum (tomato) is the second-largest vegetable crop in the world after potato, with an estimated global production of 186 million tons per year [1]. This plant is widely cultivated under a large-scale production system [2]. The tomato belongs to the Solanaceae family [3]. Tomatoes are considered beneficial to human health due to the presence of essential nutrients such as carbohydrates, proteins, phosphorus, calcium, and various vitamins [4]. They are also rich in antioxidants, which contribute to their health-promoting properties. In addition to being consumed fresh, tomatoes are widely used in processed products such as sauces, juices, and ketchup [5]. *Trigonella foenum-graecum* (fenugreek) is a widely grown food herb in Asia, and its seeds are used in the treatment of many diseases, including diabetes. The leaves and seeds contain a group of compounds that play an important role in medical treatment [6]. Fenugreek is an herbaceous plant characterized by white flowers, thin pods, and clover-like pinnate, compound, trifoliate leaves [7]. Its medical importance is concentrated in the seeds and leaves. Fenugreek has nutritional and tonic properties. The fenugreek plant is also used as a laxative and carminative, and to treat digestive system problems. It is useful for chest inflammation and lymphatic suppuration. In addition, crushed and boiled fenugreek seeds are used to increase body weight in humans and increase milk production in lactating mothers [8].

Arbuscular mycorrhizal fungi obligately coexist with the roots of more than 80% of higher terrestrial plants. They are considered beneficial organisms that enhance plant growth, improve growth parameters, and help plants resist pathogens [9, 10]. This type of symbiosis facilitates a two-way exchange of nutrients. Organic nutrients, such as carbon, flow from the plant to the fungus, while inorganic nutrients move from the fungus to the plant. This interaction promotes communication and contact between plant roots and the soil, leading to improved nutrition and enhanced absorption of both major and minor nutrients. Root infection begins with arbuscular mycorrhizal (AM) fungi and helps to increase root absorption efficiency through the development of root hairs [11]. In most cases, the presence of these fungi in the soil enhances tolerance to various stress conditions, including drought, salinity, nutrient deficiency, mineral imbalance, and even harmful levels of soil acidity [12].

The presence of mycorrhizae improves the nutritional quality of tomato plants. Ibiang et al. [13] indicated that the fungus *Funneliformis mosseae* enhanced the growth of the fenugreek plant by increasing root and shoot weight, as well

as root and shoot length. In addition, it increased the percentage of mycorrhizal colonies. Ghoroori et al. [14] also studied the effect of *Funneliformis mosseae* on the morphological and physiological traits of the fenugreek plant. The studied traits included plant fresh and dry weights, number of pods, 1000-seed weight, photosynthesis pigments, soluble carbohydrate, total phenol, flavonoids, total protein, and antioxidant activity. They observed a significant increase in all of these traits. *Funneliformis mosseae* (AM) colonization improved the mineral nutrient status, such as potassium (K), phosphorus (P), calcium (Ca), zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu), in fenugreek and nigella plants compared to non-AM colonized plants. Increases in growth, yield components, and chlorophyll content were also observed in AM-colonized plants. When plant species are colonized with AM fungi, yield advantages are likely due to the complementary use of resources by the plants [15].

There was a considerable increase in plant height when *Funneliformis mosseae* colonized the plants, with an 80.9% increase in height. Total root length increased by 68.9%, projected area by 48.7%, root surface area by 34.4%, and root volume by 78.5%. Additionally, chlorophyll a content increased by 34.2%, chlorophyll b content by 68.4%, total chlorophyll content by 44.5%, and carotenoid content by 84.0%, all compared to the control [16]. Inoculation with more effective isolates of *Funneliformis mosseae* was found to stimulate N and P uptake in the plant tissues of tomato (both shoot and root). Nitrogen uptake increased significantly by 29.0-38.0%, while P uptake increased by 34.6-36.5%. Additionally, biomass (both shoot and root) and fruit yields increased by 18.4-25.4% and 8.8-12.0%, respectively [17].

The present study aimed to evaluate the impact of *Funneliformis mosseae* on the growth, nutrient uptake, and physiological characteristics of tomato and fenugreek grown in different soil conditions, including clay soil and peat moss. Specifically, the study sought to assess the effects of mycorrhizal inoculation on germination rates, root colonization, vegetative growth, and nutrient accumulation in both plant species. It is hoped that the findings of this research will not only advance scientific understanding of plant-mycorrhiza interactions but also present scalable, sustainable practices that can be readily adopted in agroecosystems to boost productivity, reduce chemical inputs, and improve soil fertility.

2. MATERIALS AND METHODS

2.1 Source of fungal biofertilizer

Mycorrhizal *Funneliformis mosseae* biofertilizer was obtained from the Research and Studies Department, Horticulture Department of the Ministry of Agriculture. The fertilizer contained spores, mycelium, and infected roots, all incorporated into dry, pre-examined mixed soil.

2.2 Preparation of soil materials

Clay and mixed soils were collected from the surface layer at a depth of 0-30cm. The soil was air-dried and passed through a sieve with a diameter of 2 mm. The soil was washed with water to remove most of the nutrients and silt it contained by placing it in a plastic container filled with water. After mixing, the soil was left for 15 seconds to allow the sand particles and some impurities to settle. The floating water was then removed, and this process was repeated four times to ensure that the soil was poor in nutrients and had a sandy texture [18].

2.3 Assessment of germination percentage in tomato and fenugreek seeds

Twenty seeds of both tomato and fenugreek were separately placed in container pots filled with soil. The pots were watered and provided with the appropriate heat and humidity conditions. The seed germination percentage for each plant was then calculated using the following equation:

$$Germibation\ Percentage\ = \frac{No.of\ Germinated\ Seeds}{Total\ No.of\ Seeds} \times 100$$

2.4 Experimental design and planting

A total of 48 kg of sterilized and washed soil was prepared for each selected plant in the research and distributed across 18 pots, with 6 treatments and a control group for each plant. Pre-prepared fungal fertilizer was then applied to each pot using the pillow method, ensuring a depth of 3 cm, as per the experimental design [19]. Five grams of mycorrhizal fungal fertilizer were added to the surface of the soil in each sterilized and perforated pot. The fertilizer was then covered with an equal weight of sterilized soil before planting the *Funneliformis mosseae* fungus individually. Three replicates were used for each treatment. The selected plant seeds were planted at a rate of 20 seeds per pot following sterilization. Fifty grams of sterilized mixed soil were then added to each pot, followed by the application of 750 mL of water (half the field capacity) to each pot. The plants were monitored and watered as necessary to maintain soil moisture.

2.5 Determination of mycorrhizal colonization and frequency in root systems

Six root samples were collected from each treatment after 15 days of cultivation. For each mycorrhizal treatment, 30 random 1cm root segments were selected and stained with acid fuchsin dye to examine the roots colonized by mycorrhizae. The percentage of mycorrhizal frequency of the root system was estimated [20] using the following equation:

$$Frequency\ Percentage\ (F\%) = \frac{No.of\ root\ pieces\ infected\ with\ mycorrhizae}{The\ total\ No.of\ root\ pieces} \times 100$$

The weight of dry mycorrhizal roots was calculated by multiplying the percentage of mycorrhizal frequency by the dry weight of the root system in grams [21].

2.6 Morphometric and biomass analysis of tomato and fenugreek shoots and roots

The shoot samples were obtained by cutting them from an area near the surface of the soil. They were then washed under a stream of calm water to remove any dust. The roots were air-dried using blotting paper, and the following measurements, weights, and tests were conducted. The length from the area where the stem connected to the soil to the growing tip was measured using a metric tape. The height of three selected tomato and fenugreek plants from the experimental unit was

measured, the total height was divided by their number, and the average was calculated. To determine the fresh weight of shoots (g), the vegetative part of each experimental unit was cut, and the fresh weight of the plants was calculated. This weight was then divided by the average, and the mean was extracted. For the root system measurement, the roots of both plants selected in the study were extracted from each experimental unit using water, and the shoots were separated from the root systems. The soil mass and roots were placed on a perforated plastic sieve under a gentle stream of water, and the soil was removed. The roots were then air-dried using blotting paper, and measurements such as length of the root system (cm) and weight of the root system (gm) were taken. The length of the root system (cm) was measured from the point of the crown to the farthest point in it using a metric tape. The lengths of the roots of both plants from each experimental unit were measured, and the average was recorded. Concerning the weight of the root system (gm), the roots of both plants were collected from each experimental unit. Their fresh weights were measured, divided by the number of roots, and the average fresh weight was determined.

2.7 Quantitative estimation of major nutrients in plant root systems

Plant samples were collected after 60 days of cultivation. The roots were first washed with ordinary water, followed by distilled water, then dried at 70°C in an electric oven until a constant weight was achieved. The dried samples were ground, homogenized, and digested according to the method proposed by Chen et al. [22]. Elemental analysis was subsequently carried out following the same method [23].

2.8 Determination of protein concentration in leaf and root samples

The percentage of protein in the roots after 60 days of cultivation was estimated based on nitrogen according to the method described by Tandon et al. [23].

2.9 Statistical analysis

The data were analyzed using the Statistical Analysis System (SAS) program [24]. The data were presented as means, and statistical analysis was done using one-way analysis of variance (ANOVA). Mean comparisons were analyzed using the least significant difference (LSD) test, with a p-value < 0.05 indicating statistical significance.

3. RESULTS AND DISCUSSION

3.1 Influence of *Funneliformis mosseae* on germination of tomato and fenugreek seeds

The results of the germination percentage of tomato and fenugreek after 60 days of planting, as shown in Figure 1, revealed that the highest germination rates, 95% for tomato and 80% for fenugreek, were recorded in the clay soil treatment with mycorrhiza. This enhanced germination may be attributed to the positive interaction between the plant roots and the mycorrhizal fungus *Funneliformis mosseae*. The fungus facilitated phosphorus uptake by the plants, converting it into a plant-available form and subsequently into the enzyme acid phosphatase. Notably, this enzyme was observed on the hyphae of the mycorrhizal fungus [25]. Phosphorus plays a crucial role in supporting vital physiological processes in plants and enhances the uptake of essential nutrients, such as N, K, Mg, Cu, and Fe, with the aid of mycorrhizal fungi. These nutrients contribute significantly to the germination and growth of tomato and fenugreek plants [26, 27].

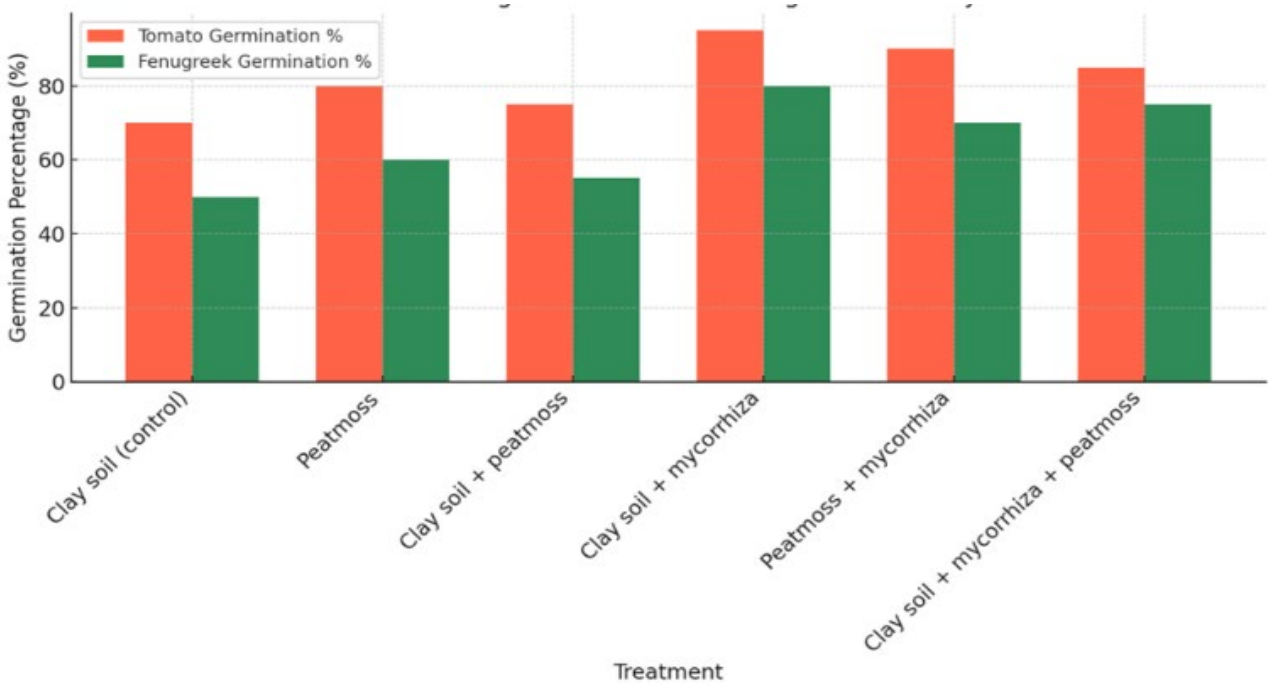

Figure 1. Germination response of tomato and fenugreek plants to different soil treatments after 60 days of cultivation

3.2 Effect of soil type on mycorrhizal frequency in tomato and fenugreek roots inoculated with *Funneliformis mosseae*

The results presented in Table 1 show a significant increase in mycorrhizal frequency in the roots of both tomato and fenugreek plants across all treatments involving the fungus *Funneliformis mosseae*. The mycorrhizal treatment with clay soil resulted in the highest mycorrhizal frequency, with tomato plants reaching 94.14% after 60 days of planting, followed by fenugreek at 76.24%. In contrast, the mycorrhizal treatment with peat moss recorded the lowest mycorrhizal frequency for both plant species. Tomato and fenugreek reached mycorrhizal frequencies of 54.94% and 43.35%, respectively, after 60 days of cultivation. The results also revealed that the mycorrhizal frequency was higher in tomato than in fenugreek across all treatments and at the same time points. These findings align with those of Daynes et al. [28], which indicated that mycorrhizal activity is higher in nutrient-poor soils, such as clay soil. In contrast, mycorrhizal colonization was lower in peat moss, likely due to its high content of trace elements, which negatively affect mycorrhizal effectiveness. Poor soils, however, promote increased mycorrhizal colonization. Thus, an increase in supplying the tomato plant with elements such as N, P, K, Cu, Zn, and other elements, increasing the process of photosynthesis and providing the mycorrhizae with organic carbon in larger quantities, as well as various effects on the growth of the host plant, which leads to an increase in mycorrhizal colonies [29].

Table 1. Effect of mycorrhizal frequency of *Funneliformis mosseae* on the roots of tomato and fenugreek plants during 60 days of cultivation

Treatment	Tomato Plant					Fenugreek Plant				
	15 days	30 days	45 days	60 days	ME	15 days	30 days	45 days	60 days	ME
A	25.55	49.87	72.73	94.14	60.57	17.84	36.52	60.44	76.24	47.76
B	15.29	28.42	43.34	54.94	35.50	11.64	19.45	30.12	43.35	26.14
C	21.65	36.53	51.81	66.48	45.46	14.32	24.33	36.35	58.77	33.44
LSD (0.05)		12.365*			4.968		9.265*			3.467*
Effect of No. of weeks	20.83	38.27	55.96	71.85		14.60	26.77	42.30	59.45	
LSD (0.05)		9.103*					7.132*			

A: Clay soil +mycorrhiza; B: Peatmoss+mycorrhiza; C: Clay soil + mycorrhiza+ peatmoss; ME: Mycorrhizal effect

3.3 Enhanced root biomass in tomato and fenugreek plants inoculated with *Funneliformis mosseae*

There was a significant increase in the dry weight of mycorrhizal roots in both tomato and fenugreek plants across all treatments involving the fungus *Funneliformis mosseae* (Table 2). The highest dry root weight was observed in the tomato plants grown in clay soil with mycorrhizal inoculation after 60 days of cultivation, reaching 0.83g plant^{-1}. This was followed by fenugreek plants under the same treatment, which recorded a dry root weight of 0.55g plant^{-1}. In contrast, the lowest dry root weights were recorded in the mycorrhizal treatments with peat moss, measuring 0.53g plant^{-1} for tomato and 0.37g plant^{-1} for fenugreek after 60 days. The increase in the weight of mycorrhizal dry roots may be attributed to the role of mycorrhizae in enhancing nutrient uptake by the plant. Mycorrhizal fungi supply essential nutrients such as N, P, K, and other micronutrients in significant quantities. This improved nutrient availability promotes plant growth, enhances photosynthesis, and supports other vital physiological processes. In return, the plant supplies the fungi with larger amounts of organic carbon, which encourages the expansion of mycorrhizal colonies within the roots. As these colonies grow, they further enhance the plant's access to nutrients and water. This mutualistic relationship results in an increased frequency of mycorrhizal colonization, which in turn contributes to the observed rise in mycorrhizal root dry weight. Thus, there is a direct correlation between the extent of mycorrhizal colonization and the increase in root biomass [28, 29].

Table 2. Effect of *Funneliformis mosseae* dry root biomass on tomato and fenugreek root development over 60 days

Treatment	Tomato Plant					Fenugreek Plant				
	15 days	30 days	45 days	60 days	ME	15 days	30 days	45 days	60 days	ME
A	0.17	0.24	0.48	0.83	0.43	0.10	0.16	0.33	0.55	0.29
B	0.08	0.14	0.31	0.53	0.27	0.06	0.11	0.23	0.37	0.20
C	0.14	0.17	0.35	0.58	0.31	0.09	0.14	0.25	0.43	0.23
LSD (0.05)		1.158*			0.487*		1.032*			0.385*
Effect of the number of weeks	0.13	0.18	0.38	0.35		0.08	0.14	0.27	0.45	
LSD (0.05)		0.959*					0.799*			

A: Clay soil + mycorrhiza; B: Peatmoss+mycorrhiza; C: Clay soil+mycorrhiza+peatmoss; ME: Mycorrhizal effect

3.4 Enhanced vegetative growth of tomato and fenugreek by mycorrhizal inoculation in clay soil over 60 days

There was a significant increase in the length of the vegetative parts of both tomato and fenugreek plants treated with mycorrhizae in clay soil compared to the control treatment (clay soil without mycorrhizae) over a 60-day period, as shown in Table 3. The maximum vegetative lengths were recorded in the mycorrhizae and clay soil treatment after 60 days, reaching 33.3cm for tomato and 27.4cm for fenugreek. In contrast, the lowest values were observed in the control treatment, with lengths of 19.3 cm for tomato and 16.6cm for fenugreek over the same period. The results also indicated that, across all treatments and at each time point, the vegetative length was consistently higher in tomato than in fenugreek.

Table 3. Vegetative growth length of tomato and fenugreek under different treatments

Treatment	Tomato Plant				Fenugreek Plant			
	15 days	30 days	45 days	60 days	15 days	30 days	45 days	60 days
Clay soil (control)	9.8	12.2	15.4	19.3	8.1	10.7	13.5	16.6
Peatmoss	11.4	14.6	18.2	22.8	9.9	12.4	15.9	19.5
Clay soil+peatmoss	12.5	15.9	21.3	26.3	10.8	13.9	17.6	21.3
Clay soil+mycorrhiza	16.6	20.3	27.7	33.3	15.7	19.5	22.9	27.4
Peatmoss+mycorrhiza	14.3	18.2	24.4	29.7	11.3	16.3	19.9	24.5
Clay soil+mycorrhiza+peatmoss	15.5	19.4	25.6	31.3	13.7	17.2	20.7	25.3
LSD (0.05)			4.441*				3.455*	
Effect of the number of weeks	13.4	16.8	22.1	27.1	11.6	15.0	18.4	22.4
LSD (0.05)			3.228*				2.742*	

3.5 Comparison of shoot fresh weight in tomato and fenugreek plants treated with mycorrhizae in clay soil

The results presented in Table 4 showed a significant increase in the fresh weight (g) of the shoots of both tomato and fenugreek plants treated with mycorrhizae in clay soil compared to the control treatment (clay soil alone) over 60 days. The maximum fresh weight was recorded in the mycorrhizae and clay soil treatment after 60 days, reaching 29.5 grams for tomato and 24.3 grams for fenugreek. In contrast, the lowest values were observed in the control treatment, with fresh weights of 10.5 grams for tomato and 7.9 grams for fenugreek, respectively. These differences in shoot fresh weight were evident over the same period. Additionally, the results indicated that the fresh weight of the shoot system was consistently higher in tomato plants than in fenugreek plants across all treatments and time points.

Table 4. Fresh vegetative weight of tomato and fenugreek plants under different treatments after 60 days of cultivation

Treatment	Tomato Plant				Fenugreek Plant			
	15 days	30 days	45 days	60 days	15 days	30 days	45 days	60 days
Clay soil (control)	4.2	6.0	8.3	10.5	2.4	4.5	6.5	7.9
Peatmoss	5.3	7.6	10.6	13.7	2.8	4.8	7.9	9.2
Clay soil+peatmoss	6.4	8.6	11.0	14.1	3.7	5.9	8.7	11.3
Clay soil+mycorrhiza	13.4	17.4	23.9	29.5	9.4	14.0	18.0	24.3
Peatmoss+mycorrhiza	9.0	12.6	16.7	21.5	5.5	8.6	11.6	14.2
Clay soil+mycorrhiza+peatmoss	11.0	15.1	20.0	26.4	7.0	11.8	15.6	20.5
LSD (0.05)			6.637*				4.887*	
Effect of the number of weeks	8.2	11.2	15.1	19.3	5.1	8.3	11.4	14.6
LSD (0.05)			4.471*				3.234*	

3.6 Comparative analysis of root length in tomato and fenugreek under mycorrhizal and clay soil treatments

The results presented in Table 5 demonstrated a significant increase in root length (cm) in both tomato and fenugreek plants treated with mycorrhizae and clay soil compared to the control treatment (clay soil) over 60 days. After 60 days, root lengths in the mycorrhizae and clay soil treatment reached their maximum values of 28.5 cm for tomato and 23.2 cm for fenugreek, while the control treatment with clay soil recorded the lowest values (12.3 cm for tomato and 7.1 cm for fenugreek). Additionally, the results showed that root length was consistently greater in tomato plants than in fenugreek plants across all treatments and time points.

Table 5. Root length of tomato and fenugreek under different treatments over 60 days of cultivation

Treatment	Tomato Plant				Fenugreek Plant			
	15 days	30 days	45 days	60 days	15 days	30 days	45 days	60 days
Clay soil (control)	4.1	6.6	8.3	12.3	2.4	3.5	5.9	7.1
Peatmoss	5.3	7.9	10.4	14.2	2.9	3.8	7.4	9.5
Clay soil+peatmoss	6.4	8.9	11.0	15.6	3.5	4.8	8.4	11.5
Clay soil+mycorrhiza	13.4	17.4	23.9	28.5	9.4	12.0	18.0	23.2
Peatmoss+mycorrhiza	9.4	12.5	16.7	19.1	5.5	7.8	11.3	14.2
Clay soil+mycorrhiza+peatmoss	11.0	15.1	20.0	24.4	7.5	10.0	15.6	20.5
LSD (0.05)			6.787*				4.999*	
Effect of the number of weeks	8.3	11.4	15.1	19.0	5.2	7.0	11.1	14.3
LSD (0.05)			4.451*				3.344*	

3.7 Comparison of root fresh weight in tomato and fenugreek under mycorrhizal and clay soil treatments

The results presented in Table 6 indicated a significant increase in the fresh weight of the roots (g) in both tomato and fenugreek plants treated with mycorrhizae in clay soil compared to the control treatment (clay soil alone) over 60 days. The highest fresh weight values were recorded in the mycorrhizae and clay soil treatment after 60 days, reaching 33.7 grams for tomato and 24.0 grams for fenugreek. In contrast, the lowest values were observed in the control treatment, with fresh weights of 14.1 grams for tomato and 9.2 grams for fenugreek during the same period. Additionally, the results showed that the fresh weight of the root system was consistently higher in tomato plants than in fenugreek plants across all treatments and time points.

Table 6. Fresh root weights of tomato and fenugreek under different treatments over 60 days

Treatment	Tomato Plant				Fenugreek Plant			
	15 days	30 days	45 days	60 days	15 days	30 days	45 days	60 days
Clay soil (control)	4.3	6.7	9.7	14.1	2.2	4.3	6.4	9.2
Peatmoss	5.6	7.6	11.7	14.3	3.2	5.4	8.2	11.1
Clay soil+peatmoss	6.8	9.4	13.8	19.6	4.2	7.7	9.3	13.7
Clay soil+mycorrhiza	14.8	19.8	25.5	33.7	10.5	13.3	18.4	24.0
Peatmoss+mycorrhiza	10.9	14.9	19.7	24.5	6.6	9.2	14.6	19.1
Clay soil+mycorrhiza+peatmoss	12.9	17.8	22.5	30.0	7.9	11.0	16.9	21.4
LSD (0.05)			6.742*				5.146*	
Effect of the number of weeks	7.1	9.7	13.4	17.7	4.5	6.7	9.5	12.9
LSD (0.05)			5.063*				4.153*	

3.8 Mechanisms underlying growth improvement by *Funneliformis mosseae* inoculation

The results presented in Tables 3-6 indicate that the mycorrhizal treatment in clay soil produced superior outcomes compared to the control. This can be attributed to the ability of *Funneliformis mosseae* to enhance nutrient uptake and produce growth regulators such as gibberellins, auxins, and cytokinins, which stimulate plant cell division and elongation. These findings are consistent with those reported by Rahi et al. [30]. Ibiang et al. [13] reported that *Funneliformis mosseae* enhanced the growth of fenugreek by increasing root and shoot length, root and shoot biomass, and the percentage of mycorrhizal colonization. The observed germination percentage is attributed to the positive interaction between the roots of both plants and *Funneliformis mosseae*, which facilitated phosphorus uptake by converting it into a plant-available form. This process is associated with the activity of the enzyme acid phosphatase, which was observed on the hyphae of *Funneliformis mosseae* [25].

Ghoroori et al. [14] studied the effect of *Funneliformis mosseae* on morphological and physiological traits in the fenugreek plant. The studied parameters included plant fresh and dry weights, number of pods, 1000-seed weight, photosynthesis pigments, soluble carbohydrate, total phenol, flavonoids, total protein, and antioxidant activity. They observed a significant increase in all of these parameters. Phosphorus is essential for the completion of vital physiological processes in plants and contributes to increased uptake of other essential nutrients, such as N, K, Mg, Cu, and Fe, with the assistance of mycorrhizal fungi. It also activates key hormones, including cytokinins, which stimulate cell division, and auxins, which promote cell elongation. These findings are consistent with our results, which showed increased root length in radish and watercress plants. Additionally, the mycorrhizal fungus *Funneliformis mosseae* was found to enhance the supply of Zn to the plants. In relation to cell expansion and elongation, Al-Kaisi et al. [27] reported that plants inoculated with mycorrhizae exhibited superior performance in terms of leaf area, number of leaves, chlorophyll content, and nutrient concentrations in the leaves (N, P, K). These improvements may contribute to an increase in the fresh vegetative weight of the plants. The increases in root length may be attributed to increased absorption of P and other elements from ready and unready sources with the help of *Funneliformis mosseae* in a facilitated manner, which increases resistance to environmental stress in the soil, which achieving the development of the root system. The expansion of mycorrhizal hyphae into the soil helped absorb potassium and some nutrients, improve the water relationship, and increase the surface area of the roots. Inoculation with more effective isolates of *Funneliformis mosseae* was found to stimulate N and P uptake in the plant tissues of tomato (shoot and root), which increased significantly by 29.0-38.0% and 34.6-36.5%, respectively, while the biomass (shoot and root) and fruit yields increased by 18.4-25.4% and 8.8-12.0%, respectively [17].

From the results presented, it was observed that the mycorrhizal dry root weights were consistently higher in tomato than in fenugreek across all treatments and at the same cultivation duration. The observed higher mycorrhizal dry root weights in tomato compared to fenugreek can be attributed to differences in root architecture and physiological traits between the two species. Tomato plants typically develop more extensive and fibrous root systems, providing a greater surface area for colonization by AM fungi, such as *Funneliformis mosseae*. This extensive colonization enhances nutrient uptake, particularly phosphorus, leading to increased root biomass [31]. In contrast, fenugreek possesses a less branched root system, which may limit the extent of AM fungi colonization and, consequently, nutrient acquisition and root biomass accumulation [32]. Furthermore, the physiological responses of tomato roots, including higher metabolic activity and greater production of root exudates, may further promote AMF colonization and function, contributing to the observed differences in mycorrhizal dry root weights between the two species [33].

3.9 Enhanced nutrient and protein concentrations in tomato and fenugreek roots due to mycorrhizal colonization in clay soil

The results in Table 7 showed a significant increase in the percentage concentrations of nitrogen, phosphorus, potassium, and protein in the roots of both tomato and fenugreek plants treated with mycorrhizae in clay soil, compared to the control treatment (clay soil alone) over 60 days. In the mycorrhizae and clay soil treatment, the highest values after 60 days were recorded in tomato roots as follows: nitrogen (6.12%), phosphorus (1.99%), potassium (7.34%), and protein (31.25%). Similarly, in fenugreek roots, the maximum values were nitrogen (5.22%), phosphorus (1.92%), potassium (7.76%), and protein (27.32%). In contrast, the lowest values were observed in the control treatment. In tomato roots, nitrogen, phosphorus, potassium, and protein concentrations were 2.28%, 0.49%, 4.22%, and 9.06%, respectively. For fenugreek roots, the corresponding values were 1.20% for nitrogen, 0.50% for phosphorus, 4.04% for potassium, and 7.89% for protein. The results also indicated that the concentrations of nitrogen, phosphorus, potassium, and protein in the root system were consistently higher in tomato plants than in fenugreek plants across all treatments and time

points.

The increase in nitrogen, phosphorus, potassium, and protein concentrations in the mycorrhizal roots grown in clay soil, compared to other mycorrhizal treatments and the control, is attributed to the high efficiency of *Funneliformis mosseae* in supplying essential nutrients. This efficiency stems from its vital role in absorbing elements from clay soil, thereby enhancing various vegetative and root growth parameters. Improved plant growth, in turn, resulted in greater carbon allocation to the mycorrhizal fungi and increased both the quantity and quality of root exudates. These changes boosted the activity of the mycorrhizal network and enhanced nutrient availability, particularly N, P, and K. Furthermore, *Funneliformis mosseae* (arbuscular mycorrhizal colonization) significantly improved the mineral nutrient status, especially K, P, Ca, Zn, Mn, Fe, and Cu, in fenugreek and *Nigella* species compared to non-mycorrhizal controls. Increases in growth, yield components, and chlorophyll content were observed in AM-colonized plants. When plant species are colonized by AM fungi, yield benefits are likely due to the complementary use of resources by the plants [15].

Phosphorus is important in completing the tomato's vital and physiological processes and increasing the concentrations of other elements needed by the plant with the help of mycorrhizal fungi, nutrients such as N, K, Mg, Cu, and Fe [26]. The availability of a high amount of nitrogen led to increased protein synthesis in the plant. Additionally, washing and sterilizing the soil created favorable conditions for mycorrhizal activation, which enhanced the supply of nutrients to the plant. This improvement was reflected in higher nutrient concentrations in plant tissues, as confirmed by researchers [30]. However, to our knowledge, no previous studies have compared the effects of mycorrhizae on tomato and fenugreek plants.

Table 7. Effect of *Funneliformis mosseae* on root NPK and protein content in tomato and fenugreek after 60 days

Treatment	Tomato Plant				Fenugreek Plant			
	N (%)	P (%)	P (%)	Protein (%)	N (%)	P (%)	K (%)	Protein (%)
Clay soil (control)	2.28	0.49	4.22	9.06	1.20	0.50	4.04	7.89
Peatmoss	2.70	0.96	4.57	11.63	1.59	0.65	4.28	10.31
Clay soil+peatmoss	3.20	0.99	4.85	14.75	2.05	0.79	4.62	13.19
Clay soil+mycorrhiza	6.12	1.99	7.34	31.25	5.22	1.92	7.76	27.32
Peatmoss+mycorrhiza	4.44	1.35	5.89	22.75	4.11	1.22	5.51	20.44
Clay soil+mycorrhiza+peatmoss	5.36	1.55	6.46	28.25	4.87	1.43	6.06	25.19
LSD (0.05)			2.461*				2.237*	
Effect of the number of weeks	4.02	1.20	5.60	19.62	3.20	1.10	5.38	17.39
LSD (0.05)			1.654*				1.502*	

4. CONCLUSIONS

The findings of the study demonstrated that *Funneliformis mosseae* significantly enhanced the growth and nutrient uptake of *Lycopersicon esculentum* (tomato) and *Trigonella foenum-graecum* (fenugreek), with more pronounced effects in tomato. Inoculation in clay soil resulted in higher germination rates, mycorrhizal colonization, root biomass, vegetative length, shoot and root fresh weights, and nutrient concentrations (N, P, K, protein) compared to controls. The mycorrhizal fungus improved nutrient absorption and facilitated growth through enhanced root expansion and nutrient mobilization, highlighting its potential as a biofertilizer for improving crop yield, particularly in nutrient-deficient soils like clay. Future studies should explore the long-term effects of *Funneliformis mosseae* on fruit yield and quality in tomato and fenugreek. Additionally, assessing its performance under field conditions across different soil types and environmental stresses would provide practical insights. Molecular studies on gene expression related to nutrient uptake and stress resistance could further elucidate the underlying mechanisms. Testing synergistic effects with other beneficial microbes may also enhance its biofertilizer potential.

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