Sustainability Science and Resources, Vol. 8:4, 2025, pp. 80 - 99

The Effect of Plant Growth-Promoting Fungal Species on Tef [*Eragrostis tef* (Zucc.) Trotter] Growth, Yield, and Grain Nutrient Uptake

Zerihun Tsegaye

Ethiopian Biodiversity Institute, Addis Ababa, Ethiopia
Email: zerihuntsegaye1970@gmail.com

Received: 26 December 2024 Accepted: 07 July 2025 Published: 09 July 2025

Abstract

This study investigates the impact of plant growth-promoting fungi (PGPF) on the growth, yield, and nutrient uptake of tef (*Eragrostis tef*). We evaluated the effects of three fungal species—*Trichoderma harzianum* Rifai BGB, *Penicillium italicum* Wehmer, and *Aspergillus* v. *Tiegham* BGB on various growth and yield parameters, including plant height, panicle size, shoot and root dry weight, and grain yield per plant. Additionally, we assessed their influence on the nutrient content of tef grains, specifically nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), zinc (Zn), and iron (Fe). Results showed that *Trichoderma harzianum* Rifai BGB and *Penicillium italicum* Wehmer significantly ($P \leq 0.001$) enhanced plant height, panicle size, and the number of fertile tillers compared to the control and Aspergillus. Both fungi also significantly increased shoot and root dry weight, as well as grain yield per plant. Regarding nutrient uptake, Trichoderma and Penicillium markedly improved nitrogen, phosphorus, magnesium, calcium, zinc, and iron content in tef grains. Penicillium showed notable improvements in these nutrients compared to the control and Aspergillus, while Trichoderma was superior in nitrogen content. Our findings suggest that *Trichoderma harzianum* Rifai BGB and *Penicillium italicum* Wehmer are effective in promoting tef growth, enhancing yield, and improving grain nutritional quality. These results indicate the potential of using these fungi as biofertilisers to optimise tef cultivation and address nutrient deficiencies in tef grains.

Keywords: *Bioinoculant, Biofertilisers, plant growth promoting, Rhisobacteria, Tef.*

Introduction

Tef [*Eragrostis tef* (Zuccagni) Trotter] is a staple crop indigenous to Ethiopia, which is also the centre of origin and diversity for this crop (Vavilov, 1951). Tef belongs to the Poaceae family (Kebede Haile *et al*., 1989) and the genus *Eragrostis*, which includes over 350 species, 54 of which are found in Ethiopia (Kibebew Assefa *et al.,* 2013). Among these species, 14 (26%) are endemic to the country (Seifu Ketema, 1993).

Tef is a highly valued crop due to its adaptability to diverse agroecological conditions, nutritional benefits and cultural significance (Seifu Ketema, 1993). It thrives at altitudes of up to 2,800 meters above sea level and under various rainfall levels (750 to 850 mm), temperatures (10 to 27°C), and soil types. Tef performs well on both waterlogged vertisols and clay soils in the highlands, as well as in water-stressed areas of semi-arid regions across the country (Abraha Misan *et al*., 2017).

Tef is used to make injera, a delicious traditional fermented pancake, which is one of the staple and popular foods for about 50 million people (60% of the entire population) (Geren *et al*., 2019). Tef grain has an excellent nutritional profile with a high level of dietary fibre, protein, minerals, and carbohydrates (Gebremariam Mekonnen *et al*., 2014). Doris (2010) reported that tef contains 11% protein and is an excellent source of essential amino acids. It has a low glycemic index, is free from gluten, and serves as an alternative food source for people with type 2 diabetes and celiac disease (Kaleab Baye, 2014), sparking growing global interest in this ancient grain.

In Ethiopia, about 6.5 million smallholder farmers cultivate tef, accounting for 30% of the total area allocated to cereals, making it the most widely grown cereal in the country (CSA, 2019). Despite its importance and extensive cultivation, tef productivity remains low due to various biotic and abiotic factors, including poor soil fertility and limited use of modern agricultural practices. Ethiopian soils, particularly in tef-growing regions, are often deficient in essential nutrients such as nitrogen (N) and phosphorus (P), which are critical for plant growth and development (Chala Girma *et al.*, 2022). The reduction in soil fertility, coupled with the high cost and limited availability of chemical fertilisers, exacerbates these challenges. This situation underscores the need to explore alternative and sustainable methods to enhance soil fertility and crop productivity.Plant growth-promoting fungi (PGPF) have emerged as a promising tool in sustainable agriculture (Mandal and Tiru, 2022). These beneficial fungi can enhance plant growth, yield, and nutrient uptake through various mechanisms such as nitrogen fixation, phosphate solubilisation, and the production of growth-promoting hormones and lytic enzymes such as cellulase, protease, chitinase and glucanase (Devi *et al*., 2020). Koza *et al*. (2022) reported that potential PGPF are involved in phosphate solubilisation, production of indole-3-acetic acid (IAA), siderophore and enzyme, either directly or indirectly, mechanisms to promote plant growth and stimulate disease resistance.

The use of plant growth-promoting fungi (PGPF) as biofertilisers has gained significant attention in recent years as a means to address agricultural challenges (Yapa *et al*., 2022). Fungi such as *Trichoderma*, *Aspergillus*, and *Penicillium* species are known to enhance plant growth by improving nutrient availability, inducing systemic resistance to pathogens, and promoting root and shoot development (Hossain *et al*., 2017). These fungi establish nonsymbiotic relationships with plant roots, leading to enhanced nutrient uptake efficiency and overall crop performance.

The application of PGPF in crop cultivation presents an opportunity to improve crop production and productivity while minimising reliance on chemical fertilisers, which can be both costly and environmentally harmful. Romera *et al*. (2019) reported that *Penicillium*, *Trichoderma*, *Fusarium*, and *Phoma* are among the most important PGPF for improving plant growth and yield and nutrient uptake. Various studies have demonstrated that *Trichoderma* species (*Trichoderma viride*, *Trichoderma harzianum*) and *Penicillium chrysogenum* promote the growth of tomatoes and other crops. Similarly, Saba *et al*. (2017) found that rice seeds treated with *Trichoderma* sp. exhibited better nutrient uptake. Additionally, Shukla *et al*. (2012) reported that *Trichoderma harzianum* significantly increased the drought tolerance and water-holding capacity of rice plants. However, research on the application of PGPF in tef cultivation remains limited. Given the unique agroecological conditions of Ethiopia and the significance of tef, it is crucial to explore the potential of PGPF to enhance tef productivity and nutrient quality.

This study aims to investigate the effect of different plant growth-promoting fungal species on the growth, yield, and grain nutrient uptake of tef. The findings of this research could provide valuable insights into the potential of PGPF as a sustainable agricultural practice for improving tef production, productivity, and nutrient content, thereby contributing to food security and the livelihoods of Ethiopian farmers.

Materials and Methods

Study Area and Experimental Soil Profile

The greenhouse experimental trial was conducted at the Debrezeit Agricultural Research Centre (DZARC), located in the Oromia National Regional State, Ethiopia. The site is situated at 08° 44' N latitude and 38° 58' E longitude, with an altitude ranging from 1860 to 1900 meters above sea level.

The soil used for the pot experiment is characterised as silt loam, with a composition of 54% silt, 32% sand and 14% clay. The organic carbon content of the soil is 1.26%, which is considered low according to *Arunrat et al.* (2020). The phosphorus (P) content of the soil, as per Recena *et al*. (2015) P rating, is below 3 mg/kg, indicating a low level of available phosphorus. The average soil pH was measured at 6.96, which falls within the suitable range for tef production (pH 4–8). The total nitrogen (N) content of the soil was 0.12%, classified as medium according to Havlin *et al*. (1999).

Materials Used for the Experimental Trials

The seeds from two tef varieties, Magna (DZ-01-1960) and Dukem (DZ-01-974), were obtained from the Debrezeit Agricultural Research Centre (DZARC). These varieties were selected for their agronomic significance and adaptability to local growing conditions. The experiment utilised three previously characterised and identified plant growth-promoting fungal species: Aspergillus, Penicillium, and Trichoderma. These fungal species were chosen for their diverse range of plant growth-promoting traits, including nutrient solubilisation, phytohormone production, stress tolerance, and different metabolic properties.

Treatment, Experimental Design, and Fungal Inoculation

The experiment was conducted using a Complete Randomised Design (CRD) to ensure unbiased results. The design included three treatments and 40 replications. Four different treatments were implemented, involving individual applications of potential plant growth-promoting fungi (PGPF): (Control, *Aspergillus* species, *Penicillium*, *Penicillium* species and *Trichoderma* species). Each treatment was replicated 5 times to ensure statistical robustness and reliability. Soil was collected from a local farm with a history of tef cultivation, ensuring relevance to the crop being studied. The collected soil was sieved and sterilised using an autoclave to eliminate existing microbes. Surface-sterilised plastic pots (12 cm × 12 cm) were filled with 500 grams of the sterilised soil. Tef seeds were surface sterilised to prevent contamination. They were then inoculated with individual PGP fungal species at concentrations of 10^6 to 10^8 CFU/mL (OD550=0.5 to 1.5) and also with nutrient broth as a control. The inoculated seeds were shade-dried before planting. Ten seeds from each treatment were sown into each prepared pot. To reduce competition for resources, seedlings were thinned to four plants per pot after emergence. Five days after seedling emergence, a second fungal inoculation was performed, where 5 mL of inoculum (10^6 to 10^8 CFU/mL, OD550=0.5 to 1.5) was added per pot. Fifteen days after seedling emergence, a third boosting dose was performed, using the same concentration as the previous inoculation. All pots were regularly watered with sterile distilled water until the plants reached full physiological maturity, ensuring that the plants received sufficient moisture without introducing external microbial influences.

Data Collection and Measurement

At physiological maturity, a comprehensive set of data related to plant growth, yield, and yield-related components was collected. These data were gathered both before and after harvest, following the standard guidelines provided in the list of tef descriptors. The specific parameters measured are outlined below:

Pre-Harvest Data Collection

- Plant Height: The height of the plants was measured from the soil surface to the tip of the panicle.
- Number of Tillers: The total number of tillers (both fertile and non-fertile) per plant was recorded.
- Number of Panicles per Plant: The number of panicles produced by each plant was counted.
- Panicle Length: The length of the panicles was measured from the base to the tip.

Post-Harvest Data Collection

- Grain Yield per Plant: The total grain weight produced by each plant was measured after threshing.

- Biomass Yield per Plant: The total above-ground biomass of each plant was weighed after drying.
- Harvest Index: The harvest index was calculated as the ratio of grain yield to the total above-ground biomass.
- Grain Nutrient Content: The nutrient content (e.g., nitrogen, phosphorus, potassium) of the harvested grains was analysed to assess nutrient uptake.

Tef Grain Nutrient Analysis

The nutrient analysis of tef grains was conducted following the methodology outlined by Miyazawa *et al.* (1999). This analysis focused on determining both the macro- and micronutrient content of the grains produced under different treatments. The procedure is detailed below:

<u>Sample Preparation</u>

Grain Sample: A 100-gram sample of tef seed powder was prepared from each treatment group for nutrient analysis.

<u>Nutrient Analysis Procedures</u>

The N concentration in the tef grains was determined through complete digestion in concentrated H_2SO_4 (Hauser, 2016). Following digestion, the nitrogen content was quantified using the micro-Kjeldahl method, which involves distillation and titration to measure ammonia produced from the digested sample. The total phosphorus content in the grains was determined using the metavanadate colourimetry method (Webb *et al*., 2005). This involved reacting the digested sample with ammonium metavanadate and ammonium molybdate to produce a yellow complex, which was then measured spectrophotometrically. Potassium levels were measured using a flame photometer, which quantifies the intensity of the flame's colour as the potassium ions are excited and emit light at a specific wavelength (Doni *et al*., 2014). The total calcium and magnesium contents were analysed using an inductively coupled plasma–atomic emission spectrometer (ICP-AES) (Khan and Mohiddin, 2018). This technique involves ionising the sample in a plasma and measuring the emitted light at characteristic wavelengths for calcium and magnesium. Zinc content was also determined using ICP-AES, similar to the analysis for calcium and magnesium. The precise and sensitive nature of ICP-AES allowed for accurate quantification of zinc even at low concentrations.

Methods of Data Analysis

All collected data were analysed using R software (version 4.2), employing statistical methods suitable for a Completely Randomised Design (CRD) in a factorial experiment. The CRD was specifically tailored to evaluate the interactions between different factors, such as tef varieties and PGPF treatments. An analysis of variance (ANOVA) was conducted to test the significance levels of the variables under study. The significance level was set at $p<0.05$, meaning that any p-value below this threshold indicated a statistically significant difference between treatments. For the comparison of means across individual treatments, the Least Significant Difference (LSD) test and Tukey Honest Significant Difference (HSD) test (with a 95% family-wise confidence level) were employed. These post-hoc analyses identified which specific treatments differed significantly when a significant effect was detected in the ANOVA.

Results and Discussions

Soil analysis for different parameters

Table 1 shows the average contents of organic carbon (1.63%), phosphorus (P) (5.0%), and total nitrogen (N) (0.46%) in the soil. These values represent an increase compared to previous soil physical and chemical element compositions. The observed increases in organic carbon, phosphorus, and total nitrogen can be attributed to the inoculation of Plant Growth-

Promoting Fungi (PGPF). The increase in organic carbon, phosphorus, and total nitrogen after PGPF inoculation indicates that these fungi positively affect soil fertility. They enhance soil organic matter, phosphorus availability, and nitrogen content through their roles in decomposing organic residues and boosting microbial activity. This leads to improved soil health and potentially better plant growth outcomes.

Table 1. Results of soil physicochemical analysis test

Soil type	pH	EC	TN	Av. P	%OM	%C
Sandy	6.88	0.07±0.03	0.44±0.06	6.12±0.30	3.15±0.05	1.83±0.05
Clay	6.78	0.11±0.01	0.56±0.03	6.11±0.24	1.90±0.04	1.52±0.04
Silt	6.83	0.02±0.00	0.37±0.01	4.17±0.64	1.95±0.01	1.55±0.01

Note: EC=electrical conductivity, TN=Total nitrogen, Av.P=average phosphorus, OM=organic matter, C=Carbone,

Variance on growth and agronomic traits analysis

Table 1 presents the analysis of variance (ANOVA) for various growth, yield, and yield-related parameters. Treatment (TM) shows a highly significant effect on plant growth, yield, and related parameters across all measured traits, with a p-value < 0.001. This indicates that the different treatments applied have a strong and consistent impact on the parameters measured, suggesting that the treatments are effective in enhancing various aspects of plant performance. Doni *et al*. (2014) reported that rice plants inoculated with *Trichoderma* sp. significantly increased growth and yield compared to NPK treatment and control. The plant variety (VT) has a significant effect on root dry weight with a p-value < 0.001. This implies that different varieties of tef exhibit varying responses in terms of root biomass, which could be influenced by genetic factors. The interaction between treatment and variety (TM*VT) is also significant for root dry weight with a p-value < 0.001. This indicates that the effect of treatments on root dry weight varies depending on the plant variety. Certain varieties may respond differently to the treatments applied, highlighting the importance of considering both treatment and variety when optimising for root biomass.

Table 2. Variance analysis

SOV	DF	Growth, yield, and yield-related parameters						
		PH	PS	NTS	NFT	SDW	RDW	GYPP
TM	3	240.6***	374.0***	98.0***	1.6*	15.2***	0.6***	8.9***
VT	1	2.7NS	5.9NS	5.0 NS	0.4 NS	0.4NS	0.2***	0.1 NS
TM: VT	3	9.8 NS	4.4 NS	2.7NS	0.8 NS	0.6 NS	0.2***	0.4*
Error	16	14.25	12.3	3.5	0.3	0.6	0.003	0.01

Note: SOV=source of variation, DF=degree of freedom, TM=treatment, VT=variety, PH=plant height, PS=panicle sise FT= fertile tillers, SDW=shoot dry weight, RDW=root dry weight, and GYPP=grain yield per plant, *, **, ***: statistically significant at P≤0.05, P≤0.01, and P≤0.001 probability level, respectively and NS: not significant

Effect of PGPF inoculation on tef growth and growth-related parameters

Table 2 revealed the impact of various treatments on tef growth-promoting traits, including plant height (PH), plant size (PS), and number of fertile tillers (FT). Both *Trichoderma harzianum* Rifai BGB and *Penicillium italicum* Wehmer significantly increased plant height and panicle size compared to the control and *Aspergillus* v. *Tiegham* BGB for both tef varieties ($p < 0.05$). The significant increases in plant height and panicle size with *Trichoderma* and *Penicillium* indicate their strong effects on enhancing vertical and lateral growth. Furthermore, *Trichoderma harzianum* Rifai BGB and *Penicillium italicum* Wehmer significantly increased the number of fertile tillers compared to the control and *Aspergillus* v. *Tiegham* BGB ($p < 0.05$). The increased number of fertile tillers with *Trichoderma* and

Penicillium demonstrates their effectiveness in enhancing reproductive growth. *Aspergillus* showed some improvement but was less effective compared to *Trichoderma* and *Penicillium*. Druzhinina et al. [2006] reported that plants such as strawberries, tomatoes, soya beans, apples, cotton and grey mangroves, which were inoculated with *Trichoderma* spp., showed increased growth. Doni *et al*. (2014) reported that rice plants inoculated with *Trichoderma* spp. Significantly increased rice growth and growth-related parameters compared to NPK treatment and control. Wakelin *et al*. (2007) reported that inoculation of lentil seed with *Pencillium radicum* increased its growth by 5.5%.

Table 3. Individual treatment analysis on growth-related traits

Treatment	**Tef growth-promoting traits**					
	PH		PS		FT	
	Magna	Dukem	Magna	Dukem	Magna	Dukem
Control	166.3^{f}	163.3^{d}	45.3^{d}	42.7^{d}	2.3^{d}	2.3^{d}
***Aspergillus* v. *Tiegham* BGB**	171.3^{bc}	173.6^{b}	44.6c	44.6^{c}	$3.0a^{b}$	2.7^{c}
***Penicillium italicum* (Wehmer)**	176.3^{ab}	174.0^{b}	53.0^{b}	51.3^{b}	3.3^{b}	3.0^{b}
***Trichoderm a harzianum* Rifai BGB**	183.0^{a}	180.3^{a}	61.0^{a}	61.3^{a}	3.5^{a}	3.7^{a}
LSD (0.05) %	6.9	7.29	5.90	7.21	1.2	0.94
P. adj	0.0013	0.002	0.0011	0.0001	0.042	0.041

Note: LSD, least significant difference, P.adj=adjusted p-value, PH=plant height, PS=panicle size, TF= fertile tillers, and different letters indicate significant differences at P< 0.05according to the LSD test.

Effect of PGPF inoculation on tef yield and yield-related parameters

Table 3 presents the impact of various fungal treatments on tef yield and yield-related traits, including shoot dry weight (SDW), root dry weight (RDW), and grain yield per plant (GYPP). Both *Trichoderma harzianum* Rifai BGB and *Penicillium* significantly increased shoot dry weight, root dry weight and grain yield per plant for both tef varieties compared to the control, *Aspergillus* v. *Tiegham* BGB, and *Penicillium italicum* Wehmer ($p < 0.05$). Also showed a significant increase in SDW compared to the control and *Aspergillus*. Imran *et al*. (2021) reported that inoculating wheat crops with plant growth-promoting fungal species had a stimulatory effect on growth and yield attributes, such as plant shoot length, spikelet, ear and grain number, seed yield, and protein content. In addition, Illescas *et al*. (2022) reported that wheat seeds inoculated with Trichoderma species increase grain yield by 19.5% compared to the control.

Table 4. Individual treatment on yield-related traits

Treatment	**Tef yield and yield-related traits**					
	SDW		RDW		GYPP	
	Magna	Dukem	Magna	Dukem	Magna	Dukem
Control	6.1d^{e}	6.3d^{e}	0.73^{d}	0.60^{d}	1.1^{d}	1.05d
***Aspergillus* v. *Tiegham* BGB**	6.5c	6.5^{c}	0.87^{c}	0.82^{c}	2 .39^{c}	2.39c
***Penicillium italicum* (Wehmer)**	7.5b	7.5b	0.88^{c}	0.98b	2.93^{b}	2.93b
***Trichoderma harzianum* Rifai BGB**	9.8^{a}	9.8a	1.14^{a}	1.14^{b}	4 .21a	4.21a
LSD (0.05) %	1.51	1.37	0.1	0.11	0.67	0.44
P. adj	0.0012	0.0001	0.0011	0.0001	0.0001	0.0001

Note: LSD, least significant difference, P.adj=adjusted p-value, SDW=Shoot dry weight, RDW=Root dry weight, GYPP= Grain yield per plant, and different letters indicate significant differences at P< 0.05according to the LSD test.

Effect of PGPF inoculation on tef grain nutrient uptake

Table 4 presents the effect of various fungal treatments on the nutrient content of tef grain, including nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), zinc (Zn), and iron (Fe). *Trichoderma harzianum Rifai* BGB exhibited the highest nitrogen content (1.98%), significantly higher than the control (1.33%), *Aspergillus* v. *Tiegham* BGB (1.89%), and *Penicillium italicum* Wehmer (1.94%) (p < 0.05). Both *Trichoderma* and *Penicillium* significantly increased nitrogen and phosphorus content in tef grains, suggesting their strong role in enhancing nutrient uptake and improving grain quality. *Penicillium* also improved these nutrients compared to the control and *Aspergillus*. *Trichoderma* and *Penicillium* showed significant increases in phosphorus content compared to the control and *Aspergillus*. *Trichoderma harzianum* Rifai BGB and *Penicillium italicum* Wehmer significantly improved magnesium content compared to the control and *Aspergillus*, demonstrating their effectiveness in enhancing magnesium availability in the grains. Both *Penicillium* and *Trichoderma* enhanced calcium, zinc, and iron contents in tef grains compared to the control and *Aspergillus*. These results suggest that *Penicillium* and *Trichoderma* are effective in improving the mineral content of tef grains. Silletti *et al*. (2021) reported that wheat crops inoculated with *Trichoderma* species improve macro and micro nutrient levels compared to the control.

Table 5. Individual treatment on plant grain uptake

Treatment	N %	P %	K %	Mg %	Ca %	Zn %	Fe %
Control	1.33[c]	0.60[c]	0.44[a]	0.11[a]	0.03[b]	0.02[a]	0.02[a]

***Aspergillus* v. *Tiegham* BGB**	1.89^{ab}	2.33^{b}	0.46^{a}	0.20^{a}	0.12^{b}	0.01^{a}	0.03^{a}
***Penicillium italicum* (Wehmer)**	1.94^{ab}	2.88^{ab}	0.54^{a}	0.21^{a}	0.18^{a}	0.05^{a}	0.06^{a}
***Trichoderma harzianum* Rifai BGB**	1.98^{a}	3.66^{b}	0.63^{a}	0.23^{a}	0.09^{b}	0.06^{a}	0.07^{a}
LSD (0.05)	0.188	1.32	0.13	0.15	0.07	0.02	0. 11
P.adj	0.0232	0.012	0.053	0.061	0.046	0.056	0.055

Note: LSD, least significant difference, P.adj=adjusted p-value, N=Nitrogen, P=Phosphorus, K= Potassium, Mg= Magnesium, Ca= Calcium, Zn= Zinc and Fe=Iron and different letters indicate significant differences at $P< 0.05$according to the LSD test.

Correlation Analysis of Grain Yield with Other Parameters

Correlation analysis reveals the strength of relationships between various growth and yield-related parameters and grain yield per plant. The correlations between plant height, panicle size, number of fertile tillers, shoot dry weight, root dry weight, and grain yield per plant were examined.

The correlation coefficient between plant height and grain yield per plant is 0.85***, indicating a strong positive relationship. This suggests that taller plants are associated with higher yields. Likewise, the correlation coefficient for panicle size with grain yield per plant is 0.76**, showing a significant positive relationship. Larger panicle sises are associated with increased grain yield. In addition, the correlation coefficient for shoot dry weight with grain yield per plant is 0.83***, demonstrating a robust positive correlation. Greater shoot biomass is associated with higher grain yield. Moreover, the correlation coefficient between root dry weight and grain yield per plant is 0.82***, indicating a strong positive relationship. Higher root biomass correlates with increased grain yield. These strong positive correlations suggest that improvements in plant height, panicle size, shoot dry weight, and root dry weight are associated with higher grain yield per plant. This highlights the importance of these growth parameters in influencing yield outcomes.

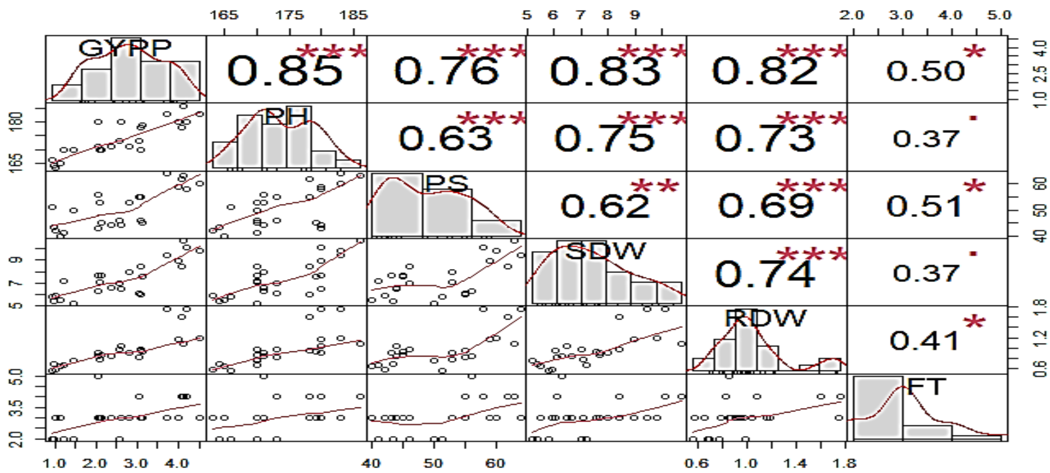

Figure 1: Correlation Analysis Result

Regression analysis

The regression analysis was conducted to evaluate the relationship between plant growth-promoting fungi (PGPF) inoculation and tef yield per plant. The high R value of 0.89 and R^2 value of 0.82 suggest a strong relationship between the predictors (PGPF inoculation) and the dependent variable (yield per plant). This indicates that PGPF treatments collectively have a significant impact on tef crop yield under greenhouse conditions. Approximately 82% of the variance in tef yield performance can be explained by the PGPF inoculation effects. The remaining 18% of the variance is attributed to other variables not included in this study (Table 5). The low standard error of the estimate (0.23) further indicates that the model provides a good fit to the data, with minimal variability in predicting yield performance based on the applied treatments. This analysis underscores the effectiveness of PGPF inoculation in enhancing tef yield and demonstrates the robustness of the regression model in explaining the variability in crop performance.

Table 6. The model summary for the regression analysis is as follows: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.89[a]	.82	.730	.23

a. Predictors: (Constant), Treatment (PGPF inoculants)

Source: own survey, 2024

Conclusions and Recommendations

This study demonstrated that plant growth-promoting fungi (PGPF), specifically *Trichoderma harzianum Rifai* BGB and *Penicillium italicum* Wehmer, significantly enhance various growth and yield parameters of tef (*Eragrostis tef*). Both fungal species notably improved plant height, panicle size, number of fertile tillers, shoot and root dry weight, and grain yield per plant compared to the control and *Aspergillus* v. *Tiegham* BGB. Additionally, they significantly increased the nutrient content of tef grains, including nitrogen, phosphorus, magnesium, calcium, zinc, and iron. *Trichoderma* was particularly effective in boosting nitrogen content, while *Penicillium* also showed substantial improvements in multiple nutrient levels. These results underscore the potential of these fungi as biofertilisers to optimise tef production, enhance growth, increase yield, and improve the nutritional quality of tef grains. Conduct further field trials to validate the greenhouse results under different environmental conditions and farming practices. This will help in understanding the practicality and scalability of using these fungi in commercial tef production. In addition, develop and test optimised formulations and application methods for *Trichoderma* and *Penicillium* to maximise their effectiveness in various soil types and climatic conditions. Furthermore, integrate the use of these PGPF with other nutrient management practices to achieve balanced soil fertility and sustainable agricultural practices.

Acknowledgement

We extend our heartfelt gratitude to the Ministry of Innovation and Technology and the Ethiopian Biodiversity Institute for their financial support in conducting this research. We also sincerely thank the Microbial Biodiversity Research Lead Office for providing the essential materials required for the study. Our appreciation is also extended to the Debrezeit Agricultural Research Centre for facilitating the experimental area necessary for carrying out the research.

References

Abraha Misan Tesfay, Hussein Shimelis, Laing, M. and Kibebew Assefa. (2017). Achievements and gaps in tef productivity improvement practices in the marginal areas of Northern Ethiopia: implications for future research directions. I. J. A. S, 15 (1): (2017): 42-53.

Arunrat, N., Kongsurakan, P., Sereenonchai, S., & Hatano, R. (2020). Soil organic carbon in sandy paddy fields of Northeast Thailand: A review. Agronomy, 10(8), 1061.

Central Statistics Agency (2019). Agricultural Sample Survey: Report on Area and Production of Major Crops, Federal Democratic Republic of Ethiopia

Chala G, Kassa S, Tadele T, Assefa K, Teshome H, Agegnehu G (2022). Yield response of tef (Eragrostis tef) to nitrogen, phosphorus, potassium and sulphur under balanced fertilisation on Vertisols in different agroecological zones of Ethiopia. Experimental Agriculture. 58: e12.

Devi, R., Kaur, T., Kour, D., Rana, K. L., Yadav, A., & Yadav, A. N. (2020). Beneficial fungal communities from different habitats and their roles in plant growth promotion and soil health. Microbial Biosystems, 5(1), 21-47.

Doni, F., Isahak, A., Che Mohd Zain, C.R. et al (2014). Physiological and growth response of rice plants (Oryza sativa L.) to Trichoderma spp. Inoculants. AMB Expr 4, 45

Doris-Piccinin, M.S.D. (2010). More about Ethiopian food: Teff development of nutrition and food science, University of Washington, America.12:1-8

Dukare, A.S.; Singh, R.K.; Jangra, R.K.; Bhushan, B. (2022). Non-Fungicide-Based Promising Technologies for Managing Post-Production Penicillium-Induced Spoilage in Horticultural Commodities: A Comprehensive Review. Food Rev. Int. 38, 227–267.

Gebremariam Mekonnen, Martin, Z and Thomas, B. (2014). Teff (Eragrostis tef) as a raw material for malting, brewing and manufacturing of gluten-free foods and beverages: a review. Journal of Food Science and Technology, 51 (11): 2881-2895.

Geren, H., Kavut, Y. T., & Kır, B. (2019). Effect of different row spacings on the yield and some yield characteristics of teff (Eragrostis teff) crop grown under Söke ecological conditions.

Giday, O., Gibrekidan, H., & Berhe, T. (2014). Response of teff (Eragrostis tef) to different rates of slow release and conventional urea fertilisers in Vertisols of Southern Tigray, Ethiopia. Advances in Plants & Agriculture Research, 1(5), 1-8.

Hauser, P. C. (2016). Determination of alkali ions in biological and environmental samples. The Alkali Metal Ions: Their Role for Life, 11-25.

Havlin JL, Beaton JD, Tisdale SL, Nelson WL (1999). Soil fertility and fertilisers. 6th ed. Prentice Hall. New Jersey. 499 p.

Hossain, M. M., Sultana, F., & Islam, S. (2017). Plant growth-promoting fungi (PGPF): phytostimulation and induced systemic resistance. Plant-Microbe Interactions in Agro-Ecological Perspectives: Volume 2: Microbial Interactions and Agro-ecological Impacts, 135-191.

Illescas M, Morán-Diez ME, Martínez de Alba ÁE, Hermosa R, Monte E. (2022). Effect of Trichoderma asperellum on Wheat Plants' Biochemical and Molecular Responses, and Yield under Different Water Stress Conditions. Int J Mol Sci. 17;23(12):6782.

Imran, M., Abulreesh, H.H., Monjed, M.K. et al 2021). Multifarious functional traits of free-living rhizospheric fungi, with special reference to Aspergillus spp. Isolated from North Indian soil, and their inoculation effect on plant growth. Ann Microbiol 71, 31

Kaleab Baye. (2014). Synopsis: Teff: nutrient composition and health benefits. Ethiopia Strategy Support Program, 34: 1-17.

Kebede Haile, Johnson, R.C. and Ferris, D.M. (1989). Photosynthetic response of Eragrostis tef to temperature [carbon isotope composition, C4 photosynthesis]. Physiologia Plantarum, 77(2):262-266.

Kibebew Assefa, Solomon Chanyalew and Girma Metaferia (2013a). Conventional and Molecular Teff Breeding. In Achievements and Prospects of Teff Improvement, edited by Kibebew Assefa, Solomon Chanyalew, and Zerihun Tadele, 33–51. Proceedings of the Second International Teff Workshop, Debre Zeit, Ethiopia

Koza, N.; Adedayo, A.; Babalola, O.; Kappo, A. (2022). Microorganisms in Plant Growth and Development: Roles in Abiotic Stress Tolerance and Secondary Metabolites Secretion. Microorganisms, 10, 1528.

Mandal, P. and Tiru, Z. (2022). Soil application of plant growth-promoting fungi for sustainable agriculture in the new decade. In Plant Stress: Challenges and Management in the New Decade (pp. 321-330). Cham: Springer International Publishing.

Miyazawa, A., Fujiyoshi, Y., Stowell, M., and Unwin, N. (1999). Nicotinic acetylcholine receptor at 4.6 Å resolution: Transverse tunnels in the channel. J. Mol. Biol. 288, 765–786.

Ravindran, V., Ravindran, G., & Sivalogan, S. (1994). Total and phytate phosphorus contents of various foods and feedstuffs of plant origin. Food Chemistry, 50(2), 133-136.

Recena, R., Torrent, J., del Campillo, M. C., & Delgado, A. (2015). Accuracy of Olsen P to assess plant P uptake in relation to soil properties and P forms. Agronomy for sustainable development, 35, 1571-1579.

Saba HDV, Manisha M, Prashant KS, Farham H, Tauseff A (2012) Trichoderma: a promising plant growth stimulator and Biocontrol agent. Mycosphere.

Seifu Ketema (1993). Tef [*Eragostis tef*: Breeding: Genetic resource, Agronomy utilisation and role in Ethiopian agriculture. Institute of Agricultural Research, Addis Ababa, pp.80

Shukla N, Awasthi RP, Rawat L, Kumar J (2012). Biochemical and physiological responses of rice (*Oryza sativa* L.) as influenced by Trichoderma harzianum under drought stress. Plant Physiol Biochem 2012, 54: 78–88.

Silletti S., Di Stasio E., Van Oosten M.J., Ventorino V., Pepe O., Napolitano M., Marra R., Woo S.L., Cirillo V., Maggio A. (2021). Biostimulant activity of Azotobacter chroococcum and Trichoderma harzianum in durum wheat under water and nitrogen deficiency. Agronomy. 11:380.

Vavilov, I. (1951). *The Origin, Variation, Immunity and Breeding of Cultivated Plants*. Translate from Russian. Ronald Press Co., New York, pp.70.

Wakelin SA, Gupta VV, Harvey PR, Ryder MH (2007). The effect of Penicillium fungi on plant growth and phosphorus mobilisation in neutral to alkaline soils from southern Australia. Can J Microbiol. 53(1):106-15. doi: 10.1139/w06-109. PMID: 17496956.

Webb, E., Amarasiriwardena, D., Tauch, S., Green, E. F., Jones, J., & Goodman, A. H. (2005). Inductively coupled plasma-mass (ICP-MS) and atomic emission spectrometry (ICP-

AES): versatile analytical techniques to identify the archived elemental information in human teeth. Microchemical Journal, 81(2), 201-208.

Yapa, N., Lakmali, D., Zoysa, D., Silva, K. S., Manawadu, C., Herath, B. M. and Bamunuarachchige, C. (2022). Biofertilisers: An Emerging Trend in Agricultural Sustainability.