



Impact of Arbuscular Mycorrhizal Fungi Inoculation on Phosphate Fertilization Efficiency and Productivity of Teff in Field Conditions

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ABSTRACT

Phosphorus (P) is one of the plant macronutrients needed for Teff (*Eragrostis tef* (Zucc.) Trotter) growth. However, most agricultural soils do not have enough available P for plant roots to absorb. Thus, the purpose of this study was to determine how inoculation with Arbuscular Mycorrhizal Fungi (AMF) and phosphate fertilization interact and affect Teff growth and production. The administration of varied phosphate concentrations during crop planting was done in split plots using a randomized complete block design, and all treatments except the control received AMF crude inoculants. The findings revealed that the use of AMF inoculants and varied phosphorus rates had a significant impact on Teff dry matter yield, yield components, and all growth indices. In comparison to the control and the red and mixed tef, the applications of AMF+50%P, AMF+75%P, and AMF+100% for white Teff yielded the highest Teff grain yield (10550 kg ha⁻¹). Teff reaps significant benefits when it is red at AMF+50%P, mixed at AMF+100%P, and white at AMF+100%P. Mixed variety showed the highest mycorrhizal dependence (44%). The greatest phosphorus utilization efficiency (PuE) was consistently reported in the AMF+25%P treatments. The white cultivar had a higher harvest index (2.63). Furthermore, with increased P treatment, both spore density and root length colonization decrease steadily. All findings show that raising P levels reduces AMF colonization and spore density, while boosting biomass yield in some cases. In summary, more research integrating contemporary agricultural practices with traditional local ways is needed to acquire a better understanding of the use of AMF in Teff cultivation and P fertilizer application.

Keywords: Arbuscular mycorrhizal fungi, efficiency, inoculation, productivity, phosphorus, Teff.

INTRODUCTION

Teff, scientifically known as *Eragrostis tef* (Zucc.) Trotter is a remarkable cereal crop that holds a cherished place in Ethiopian agriculture. As one of the nation's most significant staples, Teff not only plays a vital role in food security but also boasts the largest value in production and consumption among Ethiopian crops (Nandeshwar et al., 2020; Lee, 2018). This unique grain is primarily used to make Injera, a spongy flatbread that is a dietary staple for over 70% of the Ethiopian population (Tamirat & Tilahun, 2020). With its exceptional nutritional profile, Teff is rich in dietary fiber, minerals, proteins, and carbohydrates, making it a powerhouse of essential nutrients (Baye, 2014). Notably, Teff provides 11% protein and is an excellent source of essential amino acids, all while being gluten-free and possessing a low glycemic

index, making it a suitable alternative for individuals with type 2 diabetes and celiac disease (Baye, 2014; Doris, 2002).

Despite its importance, Teff is cultivated exclusively in Ethiopia and faces challenges in yield compared to other cereals. While it covers approximately 2.97 million hectares, nearly half of the country's cereal farmland, its average national grain yield is only 1.379 tons per hectare (Habtegebrial et al., 2007; CSA, 2014; Zhao et al., 2016). Rising local and international market demands have led to occasional expansions in Teff production areas (Gebrehiwot et al., 2024). The main varieties of Teff include mixed (Amhric, Sergegna), red (Amharic, Qui), and white (Amharic, Nech), and yet the depletion of organic matter and low soil fertility continue to hinder its productivity.

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Phosphorus, a crucial agricultural input for Teff cultivation, is often deficient in agricultural soils, with natural reserves depleting rapidly (Wahid et al., 2016). To counteract this challenge, plants have evolved various strategies, including forming beneficial relationships with soil microorganisms to enhance phosphorus availability and optimize uptake (Bapaume & Reinhardt, 2012). Among these microorganisms, Arbuscular Mycorrhizal Fungi (AMF) play a pivotal role in the soil/plant interface, significantly increasing the uptake of inorganic nutrients, especially phosphorus (Duponnois et al., 2012; Neumann & George, 2010). By colonizing plant roots and extending mycelial hyphae into the surrounding soil, AMF enhance the prospecting volume for mineral resources, transforming complex forms of phosphorus into bioavailable forms for plants (Duponnois et al., 2012).

In the pursuit of sustainable agriculture, the reliance on chemical phosphorus fertilizers poses challenges, including environmental pollution and alterations to microbial communities (Berruti et al., 2016). Consequently, this study seeks to investigate the effects of native AMF inoculation and varying phosphorus application rates on the growth, yield, and nutrient uptake of different Teff varieties under field conditions. By exploring these interactions, we aim to contribute to more sustainable and productive Teff cultivation practices that benefit both farmers and the environment.

MATERIALS AND METHODS

Description of the study area:

Hawassa University is located in the Ethiopian Rift Valley, 275 km south of Addis Ababa, at an altitude of about 1736 meters above sea level. The coordinates are 7°31.35" N latitude and 38°29'43.8" E longitude. It has a sub-humid climate with two distinct rainy seasons. The main rainy season, Kiremt, occurs from June to October, with an average annual rainfall of about 1150 mm. The average annual temperature is 19.5°C, with the hottest months from February to April (29°C to 32°C) and the coolest months from June to September (24°C to 25°C). The research village is located at the eastern corner of the main campus.

Soil analysis:

Before the experiment, the basic physicochemical properties of the experimental soil; total nitrogen (TN), pH, electrical conductivity (EC), available phosphorus (Aval.P), and texture were examined. 500g soil sample was collected from the central and four corners of the experimental field from a depth of 0 to 20 cm and composited to take the needed 300g. The collected soil samples were dried at room temperature for about 15 days,

passed through a 2mm sieve, and analyzed for soil physicochemical parameters using standard procedures; Soil pH was measured in water at a ratio of 1:2.5 using a glass electrode pH meter. Soil texture was determined using the Bouyoucos hydrometer method (Day, 1965). Available phosphorus (P) was determined by the Olsen et al. (1954) extraction method. Total nitrogen (N) content in the soil samples was determined following the Kjeldahl method (Bremner et al., 1996). Bulk density (ρ_b) was measured from core samples dried in an oven at 105°C for 24 hours according to Martín et al. (2017). Total porosity was estimated from the values of bulk density (BD) and particle density (PD), with the latter assumed to have the generally used average value of 2.65 g/cm³ according to Landon (1991): Total porosity (%) = $[1 - (BD/PD)] \times 100$. The soil analysis was carried out in the soil laboratory of the College of Agriculture at Hawassa University.

Preparation of Biological Materials for AMF Inoculum

Three varieties of Teff (*Eragrostis tef* Zucc.); white (Nech), red (Qui), and mixed (Sergegna) were sourced from the Southern Agricultural Research Center in Ethiopia. Indigenous arbuscular mycorrhizal fungi (AMF) consortia inoculum was obtained from the Department of Biology at Hawassa University, using sorghum (*Sorghum bicolor*) as the host plant for a 45-day growth period. The harvested AMF crude inoculum, which included spores, sporocarps, and the soil substrate, was quantified at approximately 2600 spores per 100 g (Midega & Khan, 2016). The inoculum was then stored in plastic bags for subsequent use (Astatkie & Bimrew, 2018).

Experimental design and treatments:

The study on three varieties of Teff employed a fully randomized complete block design (RBCD) with three replications according to Montgomery (2017). The experiment evaluated the effects of varying phosphorus levels (0%, 25%, 50%, 75%, and 100%) and 250 grams of arbuscular mycorrhizal fungi (AMF) inoculants on Teff growth (Smith et al., 2018; Khan et al., 2020). Each plot was sized at 2m × 3m with three rows, a 0.50 m inter-row spacing, and a 25cm buffer (Assefa et al., 2016). Phosphate fertilizer was administered based on the designated phosphorus treatment levels (Tesfaye et al., 2019).

Effect of P₂O₅ Fertilizer and AMF Inoculation on the productivity of Teff Varieties

P₂O₅ fertilizer was carefully applied to specific plots, and arbuscular mycorrhizal fungi (AMF) inoculation was executed with 250g of crude inoculum, excluding the control plot. This inoculum was covered with fine soil for proper

contact (Gianinazzi et al., 2010). Teff seeds were then manually sown and likewise covered. All plots were sown simultaneously to promote uniform growth, with monitoring and manual irrigation in case of low rainfall. Weed management was performed by hand after the plants reached full growth (Lorenzo et al., 2018). Key growth parameters, such as plant height, leaf area, and stem collar diameter, were measured 15 days post-sowing to evaluate early plant development. Harvesting was done manually to ensure optimal yield when the grains matured (Hassan et al., 2021).

Growth Parameters of Teff Varieties

Growth data:

Plant Height (cm): Plant height was measured using a tape measure from randomly selected plants located in the central rows of each plot, while excluding the border rows. Measurements were taken from the base of the main stem to the tip of the main shoot panicle at maturity. The average of these measurements was used for statistical analysis (Wang et al., 2019).

Leaf Area Index (cm²): The leaf area index was calculated by measuring both the length and width of leaves with a tape measure. The leaf area was determined using the formula:

$$\text{Leaf Area} = \text{Leaf Length} \times \text{Leaf Width} \times 0.578$$

This formula incorporates a correction factor to improve accuracy (Bannayan et al., 2006).

Stem Diameter (mm): Stem diameter was measured using a digital caliper to ensure accurate readings (Khan et al., 2020).

Yield and Yield Components of Teff Varieties:

The assessment of grain yield for Teff varieties involved several systematic steps. After drying, plants were threshed, and grain yield from a 6 m² net plot was recorded in kg/ha (Hildebrand et al., 2021). The above-ground biomass yield was determined by air-drying the harvested biomass from the same plot and converting it to kg/ha. Straw yield was derived by subtracting grain yield from total biomass yield (Seyoum et al., 2019). Additionally, the harvest index (HI) was calculated as the ratio of grain yield to total biomass yield, expressed as a percentage applying the following formula:

$$\text{HI (\%)} = \left(\frac{\text{Grain yield } \left(\frac{\text{kg}}{\text{ha}} \right)}{\text{Total Dry biomass yield } \left(\frac{\text{kg}}{\text{ha}} \right)} \right) \times 100$$

This measure provides insight into the efficiency of biomass conversion into grain, which is critical for evaluating the productivity of Teff varieties (Mekonnen et al., 2020).

Determination of spore density in soil sample:

The assessment of spore density involved collecting 500 g soil samples from each treatment, which were air-dried for 15 days. A 100 g portion was mixed with 1.5 liters of water in a beaker, stirred, and allowed to settle. The suspension was then sieved through 500 µm, 105 µm, and 50 µm meshes using a wet sieving and decanting method (Gerdemann & Nicolson, 1963). The remaining fraction from the 50 µm sieve was centrifuged, re-suspended in 60% sucrose solution, and centrifuged again. Spores were isolated by rinsing, transferring to Petri dishes, and examining under a stereomicroscope. These methodologies are vital for mycological research, facilitating the recovery and identification of spores, which are crucial for understanding soil microbiomes and their ecological roles (Bani et al., 2020; Nardone & Rallo, 2019).

Determination of Mycorrhizal colonization in Root Samples:

Mycorrhizal colonization was assessed by cleaning approximately 0.5 g of roots from each plot with tap water. The roots were cleared in 10% KOH at 90°C in a water bath for 1 hour, neutralized in 1% HCl, and stained with 0.05% trypan blue in nitric acid. The samples were then destained overnight in an acidified glycerol solution (1:1:1; nitric acid, glycerol, water) in a dark room to remove root cell color.

Fine roots were cut into ~1 cm segment, mounted on slides, and covered with a cover slip. Arbuscular and vesicular colonization was quantified using the magnified intersection method of McGonagile et al. (1990), with 100–150 intersections examined per sample. This method ensures reliable quantification of mycorrhizal colonization in root samples.

Mycorrhizal dependency of Teff Varieties:

The mycorrhizal dependency (MD) of the three Teff varieties was determined following the method outlined by Planchette (1983). The calculation was performed using the formula:

$$\text{MD (\%)} = [(M - NM) / M] \times 100$$

Where: M denotes the total dry biomass of plants inoculated with mycorrhizal fungi, representing the growth performance under mycorrhizal conditions and NM represents the total dry biomass of plants grown without mycorrhizal inoculation, serving as a control to measure the effect of mycorrhizal association.

Phosphorus use efficiency Teff Varieties:

Phosphorus use efficiency was calculated for the three types of Teff using the following formula:

Apparent phosphorus (P) use efficiency was determined as

$$\frac{P \text{ uptake by plant with P application} - P \text{ uptake by plant without P application}}{\text{Amount of P applied}}$$

This method provided a reliable estimate of P use efficiency for the three varieties of Teff in response to different rates of phosphorus application.

Analysis of Nutrient content of Teff Varieties:

Nutrient content was assessed through plant tissue analyses conducted at Hawassa University in the College of Agriculture, adhering to standard procedures. The analysis involved wet digestion of the plant tissues, after which the phosphorus (P) content was determined using the vanadomolybdate method, followed by photometric measurement (Cavell, 1955).

Dry matter production and eff Yield:

Dry matter production and Teff yield were calculated using the methods described by Mian et al. (2021). Yield was analyzed from both economic and biological perspectives. The harvest index (I), defined as the percentage of the harvested crop, was employed to associate biological yield (Yb), representing total dry matter production, with economic yield (Ye), the economically relevant portion of the biological yield. This relationship was expressed using the formula:

$$Ye = Yb \times I$$

The equation indicated that an increase in the harvest index or total dry matter production resulted in a corresponding increase in economic yield, such as grain yield. While biological and economic yields are equal for some crops, this is not the case for grains. Modern wheat cultivars were reported to have a harvest index ranging from 35 to 40%, whereas older cultivars ranged between 23 and 30% (Mengel & Kirkby, 1982). For rice, the harvest index was found to be lower and to

increase more slowly compared to the overall dry matter production.

Data analysis:

Statistical analysis for comparing all growth parameters (plant height, shoot dry weight, leaf area, and stem collar diameter) among treatments and controls was performed using the SPSS software package (version 27.1.0). Differences in AM fungal spore abundance and root colonization percentage between treatments were tested using Duncan's multiple range test at $p < 0.05$ following a two-way analysis of variance (ANOVA).

RESULTS

Soil physicochemical properties:

The physicochemical analysis of the soil revealed a pH of 6.20, indicating slightly acidic conditions, and an electrical conductivity (EC) of 81.2 $\mu\text{S}/\text{cm}$. The soil contained 14.2 mg/kg of available phosphorus and 0.32% total nitrogen. Its texture was classified as 48% sand, 18% clay, and 34% silt, with a soil-to-water ratio of 1:2.5. A bulk density of 1.2 g/cm^3 was recorded, deemed optimal for plant growth in loam soils as it falls below the critical threshold of 1.4 g/cm^3 . The soil porosity was calculated to be 54.7%.

The effect of AMF and AMF+phosphorus on the growth and yield of three Teff varieties:

In a study on Red Teff, different treatments were tested for growth and yield (Table 1). The AMF-only treatment produced a height of 25.85 cm, a leaf area of 20.20 cm^2 , and a shoot dry weight of 2.40 mm, yielding 181.3 $\text{g}/6\text{m}^2$. The AMF+25%P treatment improved height to 32.33 cm and leaf area to 26.85 cm^2 , leading to a yield of 223.3 $\text{g}/6\text{m}^2$. The highest yield, 240.0 $\text{g}/6\text{m}^2$, was observed with the AMF+50%P treatment, which also recorded a height of 28.91 cm. The tallest plants at 34.71 cm were from the AMF+75%P treatment, but they yielded only 180.0 $\text{g}/6\text{m}^2$. The

Table 1: Effects of AMF and AMF+Phosphorus on Red Teff Growth and Yield

Treatment	H(cm)	LA(cm^2)	SD(mm)	SDW($\text{g}/6\text{m}^2$)	Yield($\text{g}/6\text{m}^2$)	Straw($\text{g}/6\text{m}^2$)
AMF	25.85±0.44 ^b	20.20± 0.95 ^a	2.40±0.05 ^d	181.3±10.41 ^{bc}	4.33± 0.66 ^{cd}	170.0±10.39 ^c
AMF+25%P	32.33±1.31 ^e	26.85± 0.49 ^c	2.06±0.14 ^a	223.3±28.5 ^d	3.33± 0.33 ^b	210.3±28.70 ^e
AMF+50%P	28.91±2.26 ^c	23.82± 0.76 ^b	2.30± 0.05 ^c	240.0±21.57 ^e	5.00± 0.57 ^c	227.0±20.03 ^f
AMF+ 75%P	34.71± 2.58 ^f	26.77± 3.73 ^c	2.30± 0.00 ^c	180.0±10.78 ^b	4.66± 0.66 ^{cd}	167.3±10.17 ^b
AMF+100%P	31.85±0.83 ^d	26.18± 3.48 ^{bc}	2.40±0.00 ^d	194.67±8.37 ^c	3.33± 0.33 ^b	183.3±10.13 ^d
Control	23.80± 0.0 ^a	28.73± 0.25 ^d	2.20±0.10 ^b	176.00±46.0 ^a	2.50± 1.50 ^a	142.0±21.00 ^a

Key: H=height, LA=leaf area, SD=stem diameter, SDW= shoot dry weight. Mean values followed by dissimilar letter/s in a column are significantly different at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$.

control group had the lowest results, yielding 176.00 g/6m² and measuring 23.80 cm in height.

In the study of Sergegna Teff (Table 2), the AMF-only treatment produced an average plant height of 27.77 cm and a yield of 176.33 g/6m². The addition of phosphorus (P) in varying percentages affected the results: the AMF+25%P treatment had a height of 28.13 cm but yielded less at 156.00 g/6m²; the AMF+50%P treatment yielded 188.67 g/6m²; and the AMF+75%P treatment yielded 225.00 g/6m². The highest yield was observed with the AMF+100%P treatment, which not only had the tallest plants at 35.67 cm but also yielded 274.67 g/6m². The control group yielded the least at 153.00 g/6m².

For White Teff, the AMF-only treatment resulted in a height of 26.19 cm ± 1.22 and a yield of 205.67 g/6m² ± 12.6. The addition of phosphorus with AMF improved yields, with AMF+25%P and AMF+50%P treatments achieving 236.67 g/6m² ±

11.46 and 254.33 g/6m² ± 11.46, respectively. The AMF+100%P treatment yielded the highest at 260.67 g/6m² ± 22.98, demonstrating significant benefits of phosphorus fertilization. The control group had the lowest yield at 197.00 g/6m² ± 3.00 (Table 3).

Overall, the analysis indicated that AMF, particularly in combination with phosphorus, positively influenced growth and yield in all Teff varieties, highlighting the significance of these treatments in enhancing crop performance.

Mycorrhizal dependency of Teff Varieties:

The results presented in Fig. 1 were analyzed to assess the relationship between mycorrhizal colonization and various treatments applied to different Teff varieties, which included white Teff, red Teff, and mixed Teff, each exposed to different levels of arbuscular mycorrhizal fungi (AMF).

In the "AMF only" treatment, the highest level of

Table 2: Effects of AMF and AMF+Phosphorus on Sergegna Teff Growth and Yield

Treatment	H(cm)	LA(cm ²)	SD(mm)	SDW(g/6m ²)	Yield(g/6m ²)	Straw(g/6m ²)
AMF ONLY	27.77±1.57 ^{bc}	30.67±0.33 ^{bc}	2.53±0.03 ^a	176.33±9.59 ^{cd}	4.50±0.33 ^{ab}	165.67±9.24 ^c
AMF+25%P	28.13±1.73 ^c	33.33±1.20 ^b	2.30±0.05 ^{bc}	156.00±13.7 ^{cd}	3.67±0.33 ^b	147.67±12.44 ^{cd}
AMF+50%P	31.00±1.73 ^{ab}	28.33±1.45 ^{cd}	2.50±0.05 ^a	188.67±7.33 ^c	4.67±0.33 ^{ab}	182.00±27.51 ^b
AMF+75%P	30.67±1.33 ^b	39.00±2.00 ^a	2.43±0.06 ^{ab}	225.00±11.59 ^b	5.67±0.33 ^a	213.33±12.23 ^b
AMF+100%P	35.67±0.66 ^a	30.67±0.88 ^{bc}	2.37±0.03 ^{abc}	274.67±10.39 ^a	5.67±1.20 ^a	266.33±10.41 ^a
Control	27.00±3.00 ^{bc}	25.00±4.00 ^d	2.20±0.10 ^c	153.00±5.00 ^d	3.33±0.50 ^c	141.00±7.00 ^d

Key: H=height, LA=leaf area, SD=stem diameter, SDW= shoot dry wet. Mean values followed by dissimilar letter/s in a column are significantly different at P≤0.05, P≤0.01, and P≤0.001.

Table 3: Effect of AMF and AMF+Phosphorus on White Teff Growth and Yield

Treatment	H(cm)	LA(cm ²)	SD(mm)	SDW(g/6m ²)	Yield(g/6m ²)	Straw(g/6m ²)
AMF ONLY	26.19±1.22 ^{cd}	27.35±1.05 ^{bc}	2.26±0.17 ^a	205.67±12.6 ^c	4.67±0.88 ^c	184.00±7.09 ^c
AMF+25%P	30.7±0.53 ^c	30.12±2.26 ^{ab}	2.26±0.06 ^a	236.67±27.06 ^{ab}	5.67±1.20 ^b	226.67±20.82 ^d
AMF+50%P	32.6±0.93 ^{bc}	30.58±1.40 ^{ab}	2.23±0.33 ^b	254.33±11.46 ^b	6.33±0.66 ^a	244.00±14.00 ^b
AMF+75%P	34.31±1.04 ^b	31.87±0.68 ^{ab}	2.30±0.00 ^{ab}	240.00±5.04 ^{ab}	6.33±0.88 ^a	235.33±7.88 ^c
AMF+100%P	38.72±1.36 ^a	34.88±4.17 ^a	2.30±0.57 ^{ab}	260.67±22.98 ^a	6.33±0.88 ^a	253.00±20.55 ^a
CONTROL	23.97±0.97 ^d	26.92±1.08 ^c	2.22±0.18 ^b	197.00±3.00 ^d	2.50±0.50 ^d	179.00±5.50 ^f

Key: H=height, LA=leaf area, SD=stem diameter, SDW= shoot dry wet. Mean values followed by dissimilar letter/s in a column are significantly different at P≤0.05, P≤0.01, and P≤0.001.

Table 4: Phosphorus uptake and efficiency of Teff Varieties

Treatment	P ₂ O ₅ Added (kg ha ⁻¹)	White (Nech) teff	PuE %	Red (Qui) teff	PuE %	Mixed (Sergegna) teff	PuE%
		P+ uptake		P+uptake		P+uptake	
AMF only	0	-	0.61	-	0.60	-	0.57
AMF+25%P	0.01(15g)	0.89	68	0.80	2	0.90	35
AMF+50%P	0.03(30g)	0.88	22.33	0.92	4.67	0.94	13
AMF+75%P	0.04(45g)	0.78	14.25	0.75	-0.75	0.81	6.5
AMF+100%P	0.06(60g)	0.70	8.17	0.89	1.87	0.77	3.67
Control	0	0.21		0.78		0.55	

Key: PuE-phosphorus use efficiency

Table 5: Root colonization and spore density/100g dry soil

Treatment	White teff				Mixed teff				Red teff			
	A	V	RLC	SD	A	V	RLC	SD	A	V	RLC	SD
AMF	23	28	81	74	25	23	80	70	24	28	85	70
AMF +25%P	20	22	80	80	21	28	76	75	18	24	86	65
AMF+50%P	12	20	64	60	24	26	77	55	23	32	90	60
AMF+75%P	10	21	57	40	20	28	75	42	25	22	84	51
AMF+100%P	4	6	25	32	23	30	82	38	11	21	64	35
Control	5	14	30	5	4	11	28	15	3	7	20	0

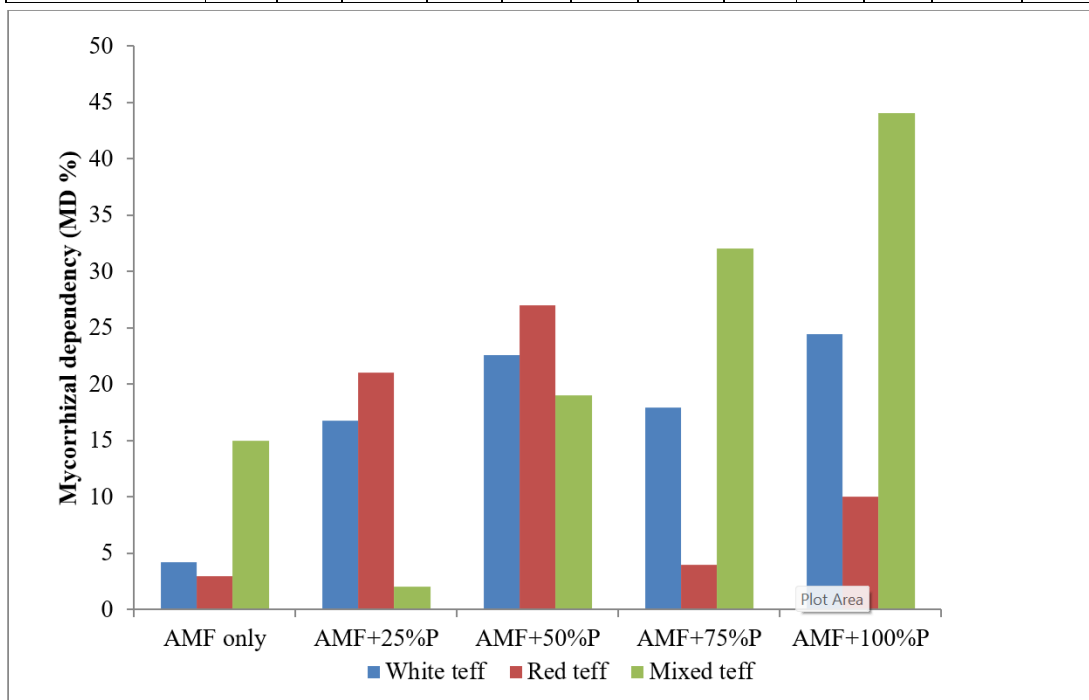


Fig. 1. Mycorrhizal dependence of teff varieties

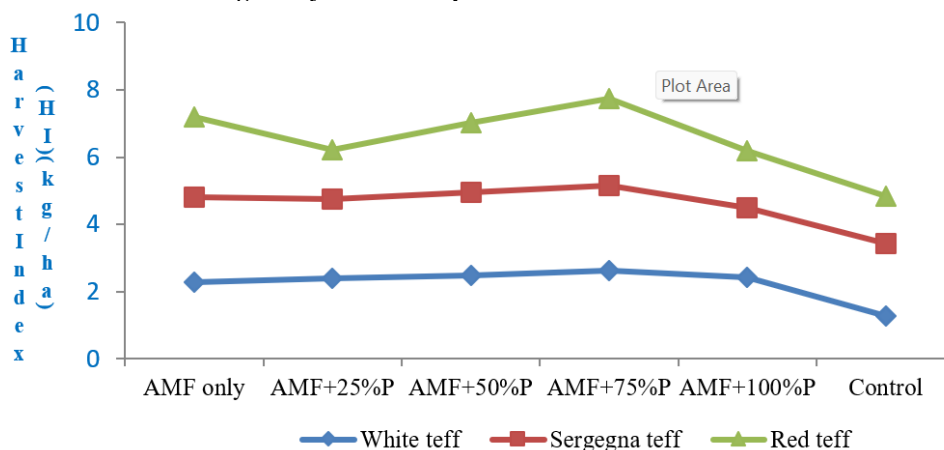


Fig.2: Effect of an inoculation and phosphorus level of teff yield harvesting index (kg^{ha}⁻¹)

dependency on mycorrhizal colonization was observed in mixed Teff, closely followed by white Teff, whereas red Teff exhibited the lowest level of dependency. This suggested that, in the absence of

additional phosphorus, mixed Teff was more responsive to mycorrhizal colonization.

As phosphorus levels increased in the treatments, including "AMF + 25% P," "AMF + 50% P," "AMF + 75% P," and "AMF + 100% P," a notable

increase in mycorrhizal dependency was observed across all Teff varieties. Mixed Teff, in particular, showed a pronounced increase in dependency at higher phosphorus levels, with the highest value recorded in the "AMF + 100% P" treatment.

The findings indicated that the combination of mycorrhizal fungi and phosphorus significantly impacted the mycorrhizal dependency of the Teff varieties. Mixed Teff demonstrated the greatest adaptability to varying nutrient conditions, highlighting the importance of these treatments in optimizing the growth and health of Teff crops. Overall, the results emphasized the potential benefits of using mycorrhizal fungi and phosphorus in Teff cultivation to enhance crop performance.

Phosphorus uptake and use efficiency of Teff Varieties:

The analysis in Table 4 focused on how different phosphorus applications affected phosphorus uptake efficiency (PuE%) in three varieties of Teff: white (Nech), red (Qui), and mixed (Sergegna). In the AMF-only treatment, no phosphorus was added, resulting in non-applicable uptake values. White Teff had a PuE% of 0.61, while red and mixed Teff recorded lower values. When phosphorus was added in varying amounts, significant improvements in PuE% were observed. The AMF+25%P treatment led to a 68% increase in white Teff's PuE% to 0.89. Red Teff reached 0.80% and mixed Teff achieved 0.90%. However, in the AMF+50%P treatment, white Teff slightly decreased to 0.88% while others improved further.

The AMF+75%P treatment saw a decline in uptake for all varieties, suggesting that higher phosphorus levels may adversely affect efficiency. Finally, in the AMF+100%P treatment, white Teff's PuE% dropped to 0.70, with red and mixed Teff also showing lower values. Overall, the study found that phosphorus application with AMF generally enhances uptake efficiency in Teff, but excessive phosphorus can decrease this efficiency, highlighting the importance of finding an optimal application rate.

Effect of Arbuscular mycorrhizal fungi inoculation and phosphorus level on Teff harvest index:

In the study of Teff varieties, the "AMF only" treatment showed low dry matter production, with mixed Teff achieving the best results. Adding 25% phosphorus significantly boosted dry matter, especially in red Teff, highlighting the positive impact of combining AMF with phosphorus. As phosphorus increased to 50% and 75%, production rose, with mixed Teff consistently performing well. However, at 100% phosphorus, a decline in dry matter was noted, indicating potential negative

effects of excess phosphorus. The control group without treatments had the lowest dry matter, further emphasizing the benefits of AMF and moderate phosphorus application for enhancing growth in Teff.

Root colonization and spore density:

Table 5 summarizes the analysis of root colonization (RLC) and spore density (SD) in three varieties of Teff (white, mixed, and red) under various treatments of arbuscular mycorrhizal fungi (AMF) and phosphorus (P_2O_5). In the AMF treatment, red Teff had the highest RLC at 85%, followed closely by white at 81% and mixed at 80%. For spore density, white and mixed Teff scored the highest at 74 and 70, respectively, while red Teff was slightly lower at 70. When phosphorus was added in the AMF + 25% P treatment, RLC slightly decreased for all varieties, though red Teff still led with 86%.

Spore density for red Teff declined to 65%. In the AMF + 50% P treatment, white Teff's RLC dropped to 64%, while mixed Teff improved to 77% and red Teff remained high at 90%. White Teff's spore density decreased to 60, indicating lower fungal activity. The AMF + 75% P treatment saw significant declines for white Teff, with RLC at 57%, while mixed and red Teff showed values of 75% and 84%, respectively.

Spore density for white Teff fell to 42. The AMF + 100% P treatment caused the sharpest decline in RLC across all varieties, with white Teff dropping to 25%, mixed to 82%, and red to 64%. Spore density hit its lowest for white Teff at 32. Overall, the control group had the lowest RLC and spore density, illustrating the positive influence of AMF and phosphorus treatments while excessive phosphorus had detrimental effects on both RLC and spore density, with moderate levels being more beneficial.

DISCUSSION

The physicochemical analysis of the soil highlights several key parameters that are favorable for Teff cultivation. The soil has a slightly acidic pH of 6.20, which is ideal for most crops as it enhances nutrient availability (Brady & Weil, 2008). Additionally, the electrical conductivity (EC) of 81.2 $\mu\text{S}/\text{cm}$ shows moderate salinity, beneficial for Teff, since excessive salinity can hinder plant growth (Sharma et al., 2015). The available phosphorus is measured at 14.2 mg/kg, adequate for supporting optimal growth, as phosphorus plays a crucial role in root development (Matusso et al., 2017). Furthermore, the nitrogen content of 0.32% is suitable for promoting robust vegetative growth (Bremner, 1996).

The soil texture, comprising 48% sand, 34% silt, and 18% clay, is classified as loamy, which

enhances drainage and root growth. Loamy soils are preferred for agricultural use due to their balanced water retention and aeration properties (Hillel, 2008). Moreover, the bulk density of 1.2 g/cm³ is below the critical threshold of 1.4 g/cm³, indicating a favorable soil structure for root penetration and nutrient uptake (Bohn et al., 2001).

The experimental results highlighted the positive impacts of arbuscular mycorrhizal fungi (AMF) and phosphorus (P) treatments on Teff growth and yield, particularly for red Teff. The AMF-only treatment yielded lower growth compared to phosphorus-enriched treatments (e.g., AMF + 25% P, AMF + 50% P), supporting the role of AMF in enhancing nutrient absorption (Smith & Read, 2008). The highest yield for red Teff was 240.0 g/6m² with AMF + 50% P, aligning with findings by Adholeya et al. (1996) that mycorrhizal associations improve plant responses with proper nutrient management.

Higher phosphorus levels (AMF + 75% P and AMF + 100% P) can lead to reduced yields, indicating a detrimental effect beyond a certain threshold. This aligns with findings by Barea et al. (2005), who highlighted that excessive phosphorus may disrupt mycorrhizal associations. A similar pattern was seen in serpegna and white Teff, where growth improved with moderate phosphorus before declining with higher applications.

Analysis of root colonization (RLC) and spore density (SD) revealed varying mycorrhizal dependencies among Teff varieties. Mixed Teff exhibited the highest dependency on mycorrhizal colonization under AMF-only conditions, indicating greater adaptability compared to red and white varieties. This supports Liu et al. (2014), who reported species variations in mycorrhizal dependency affecting nutrient uptake efficiency.

Phosphorus uptake efficiency (PuE%) increased with initial phosphorus applications alongside AMF, but excessive phosphorus reduced efficiency, consistent with Hodge & Storer (2014), who emphasized the importance of balanced nutrient applications for optimizing plant health and productivity.

In conclusion, this study highlights the importance of optimizing soil conditions and nutrient management for enhancing Teff growth and yield. The soil's slightly acidic pH, balanced texture, and moderate bulk density support healthy crop development. The findings emphasize the synergistic role of arbuscular mycorrhizal fungi (AMF) and phosphorus (P) in improving Teff performance, with moderate phosphorus levels (AMF+25%P and AMF+50%P) significantly boosting growth and yield across varieties. However, excessive phosphorus application (AMF+75%P and AMF+100%P) negatively

impacted yield and mycorrhizal activity, underscoring the need for balanced nutrient applications.

The study also revealed variety-specific responses, with Red Teff showing the highest root colonization under AMF-only treatment, and Serpegna and White Teff benefiting from phosphorus-enhanced treatments. These results reaffirm the importance of tailoring nutrient management strategies to optimize both AMF efficiency and phosphorus uptake for sustainable Teff production.

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