HAWASSA UNIVERSITY
COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCE
DEPARTMENT OF BIOLOGY

EFFECT OF ARBUSCULAR MYCORRHIZAL FUNGI INOCULATION ON PHOSPHATE FERTILIZATION EFFICIENCY, GROWTH, AND PRODUCTIVITY OF TEFF UNDER FIELD CONDITIONS IN SIDAMA HAWASSA

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M.Sc. THESIS

June, 2024

HAWASSA, ETHIOPIA

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THE THESIS SUBMITTED TO THE DEPARTMENT OF BIOLOGY, COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES, SCHOOL OF GRADUATE STUDIES, HAWASSA UNIVERSITY

HAWASSA, ETHIOPIA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCES IN APPLIED MICROBIOLOGY

June, 2024

HAWASSA, ETHIOPIA

SCHOOL OF GRADUATE STUDIES

HAWASSA UNIVERSITY

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This is to certify that the Thesis entitled **"*Effect of arbuscular mycorrhizal fungi inoculation on phosphate fertilization efficiency and teff growth and productivity under field condition*"** submitted in partial fulfillment of the requirements for the Master`s with specialization in Applied Microbiology, the graduate program of Department of Biology, and has been carried out by **Huwatu Petros (GpApMiR/0004/13)** under my supervision. Therefore I recommend that the student fulfill the requirements and hence thereby can submit the Thesis to the department.

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We, the undersigned, members of the Board of Examiners of the final open defense by **Huwatu Petros** have read and evaluated his/her thesis entitled **"*Effect of Arbuscular Mycorrhizal Fungi Inoculation on Phosphate Fertilization Efficiency and Teff Growth and Productivity Under Field Condition*"**, and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree of Master of Sciences in Applied Microbiology.

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ACKNOWLEDGEMENT

First of all, I would like to thank almighty God, who led me through those challenges that were difficult to overcome. And, I want to bring my thanks to my advisory, Dr. Beyene Dobo, for not only his advice but also his kindness. Then I want to give thanks to Hawassa University and Biology Department for all their contribution.

Finally, my thanks go to my family and my friends for their direct and indirect contributions.

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ABBREVIATION/ACRONYMS

ANOVA	Analysis of variance
AMF	Arbuscular Mycorrhizal Fungi
SPSS	Statistical Package For Social Science
P	Phosphorus
VAM	Vascular Arbuscular Mycorrhizae
LSD	Least significance difference
HI	Harvest index
RCBD	Randomized Complete Block Design
CSA	Central Statistical Agency
MD	Mycorrhizal Dependency
PGPR	Plant growth promoting rhizo-microorganisms
PUE	Phosphorus use efficiency
HARV	Humic Acid Rich Vermicomposting
CF	Chemical Fertilizer

ABSTRACT

Phosphorus (P) is one of plant macronutrients required for Teff (Eragrostis tef) production. However, P is difficult to control in worn soils, and fertilization practices are inefficient because it becomes unavailable for uptake by plant roots. Plant-arbuscular mycorrhizal fungus (AMF) symbiosis promotes plant growth and boosts P uptake from the soil that is not immediately available to the roots. Thus, the goal of this study was to evaluate how inoculation with consortia of AMF and phosphate fertilization interacts and effects the growth and productivity of Ethiopia's traditional staple food crop, teff. In 2023, the field trial was carried out at the research Village of Hawassa University. The administration of phosphate (0, 25, 50, 75, and 100% concentrations of the required level) during crop sowing was done in split plots using a randomized block design, and AMF crude inoculants were applied to all treatments except the control. The results demonstrated that the application of AMF inoculants and varying rates of phosphorus had a substantial impact on teff dry matter yield, yield components, and all evaluated growth parameters. When compared to the control and the other two varieties, the applications of AMF+50%, AMF+75%P, and AMF+100% for white teff produced the highest teff grain yield (10550kg ha^{-1}). When the teff is red at AMF+50%P, mixed at AMF+100%P, and white at AMF+100%P, it benefits greatly. Mixed variety had the highest mycorrhizal dependency (MD) of 44%. For AMF+25%P treatments, the maximum Phosphorus usage efficiency (PuE) was regularly observed. The white variety had a greater harvest index (2.63). Furthermore, with increased P treatment, there is a continuous drop in both the spore density and root length colonization (RLC). In summary, all the results indicate that increasing the P level decreases AMF colonization and spore density, although in certain situations it increases biomass yield. To sum up, more study combining current agricultural practices with traditional methods from the area is required to gain a better knowledge of the application of AMF in teff cultivation and P fertilizer application.

Key words: Arbuscular mycorrhizal fungi, efficiency, inoculation, productivity, phosphorus, teff

1. INTRODUCTION

1.1 Background of Study

The genus *Eragrostis tef* Zucc, commonly known as "Teff," is an indigenous cereal crop of Ethiopia. Teff is one of the major crops and has the largest value in terms of both production and consumption (Nandeshwar *et al*., 2020; Lee, 2018; Minten *et al*., 2016). It is mostly used to prepare a spongy flatbread called "Injera" (Wato, 2019) and is consumed by more than 70% of the Ethiopian people as a staple food (Tamirat and Tilahun, 2020; Firdisa, 2016).

With high levels of dietary fiber, minerals, proteins, and carbohydrates, teff grain has an exceptional nutritional profile (Baye, 2014). According to Doris (2002), teff is a great source of essential amino acids and has 11% protein. It is gluten-free, has a low glycemic index, and can be used as a substitute food source by those who have type 2 diabetes and celiac disease (Baye, 2014).

Teff is grown as a major staple food crop only in Ethiopia. When compared to other cereals grown in Ethiopia, teff has the lowest yield and is the primary crop in terms of area coverage. However, it ranks second in terms of total annual production, after maize (Lakew and Berhanu, 2019; Tesfahun, 2018).

Approximately 2.97 million hectares, or nearly half of Ethiopia's farmland under cereals, are covered in teff (Habtegebrial *et al*., 2007; CSA, 2014). As local and international market demands rise, its production area does occasionally expand (Hailu and Seyfu, 2000). On the prepared farm field, teff is manually broadcast, with its seeds left exposed (Sate and Tafese, 2016). Three main groups can be distinguished in Ethiopia: mixed (sergegna), red (qui), and

white (Nech). White teff typically grows best in the highlands of Ethiopia and needs reasonably favorable growing conditions. But red teff, which is thought to be more nutrient-dense, has also been more well-liked recently among Ethiopia's health-conscious consumers (Baye, 2014).

Ethiopia's main crop class is cereals, with 10.22 million hectares under cultivation, 25.38 million metric tons of grain produced, and 16.24 million smallholder farmers involved in the crop. But in contrast to other cereal crops, Ethiopia has produced relatively little teff (Evangelista *et al.*, 2013). Depletion of organic matter and low soil fertility are factors affecting teff productivity. Ethiopian teff productivity is low, with an average national grain yield of 1.379 tons per hectare, despite its wider adaptation (Zhao *et al*., 2016).

Phosphorus (P) is the second essential macronutrient for plant growth and development. It accounts for 0.2% of plant dry weight and limits the growth of plants and crop yield (Sharma *et al*., 2013). Phosphorus contributes remarkably to photosynthesis, energy and sugar production, nucleic acid synthesis, and N_2 fixation in legumes (Saber *et al*., 2005). The mineral nutrition of plants mainly depends on soil P content, which can be assimilated as a soluble phosphate (Ehteshami, 2011). It increases the strength of cereal straw, promotes flower formation and fruit production, stimulates root development, and is also essential for seed formation (Sharma *et al*., 2011).

Arbuscular Mycorrhizal Fungi (AMF) is a group of obligate symbiotic association with the roots of a living host plant in order to grow and complete their life cycle (Parniske, 2008). The term “mycorrhiza” literally derives from the Greek mykes and rhiza, meaning fungus and root, respectively. AMF can symbiotically interact with almost all the plants that live on the Earth. They are found in the roots of about 80-90% of plant species (mainly grasses, agricultural crops

and herbs) and exchange benefits with their partners, as is typical of all mutual symbiotic relationships(Wang and Qiu, 2006).

Arbuscular mycorrhizal fungi are also highly effective in taking up nutrients from nutrient-deficient soils, which can help crops survive and increase yields (Kayama and Yamanaka, 2014).

Even though phosphorus supply is highly needed to ensure food security for the world's growing population, the huge and regular application of phosphorus (P) fertilizers requires a lot of energy for processing, distribution, and transportation thus increasing the cost of production and environmental risks (Pizzeghello *et al*., 2011). Phosphorus is among the most deficient macronutrients in agricultural soils and its natural soil reserves are depleting at a higher rate (Wahid *et al*., 2016). The various strategies evolved by plants, including beneficial interactions with soil microorganisms to enhance phosphorus availability in soils and optimize phosphorus uptake capacity, should therefore be fully harnessed (Bapaume and Reinhardt, 2012; Rai *et al*., 2013).

Several phosphate solubilizing bacterial and fungal species are involved in soil bio-functioning in the rhizosphere of plants , and Arbuscular Mycorrhizal Fungi (AMF) are regarded as major elements of the soil/plant interface (Duponnois *et al*., 2012). They increase soil inorganic nutrient uptake, particularly P (Neumann and George, 2010). The roots of cultivated plants are generally colonized by AMF and when establishing symbiosis, the proliferation of mycelial hyphae into the soil increases the prospecting volume concerning plant mineral resources. These hyphae can alter the complex forms of P and transfer the bio-available P to the plant (Duponnois *et al.*, 2012). In the context of sustainable agriculture, farmers are constrained by the global economic crisis to try to reduce the input of P fertilizers using AMF inocula (Berruti *et al.*,

2016). In addition to the possible pollution of underground water reservoirs, the continuous application of high levels of fertilizer to soil drastically alters the interaction between microbial communities and plants (Berruti *et al*., 2014).

Despite the various plant growth promotion and biocontrol benefits associated with AMF, research conducted to examine the effect of native AMF application on teff to improve growth, yield, and nutrient uptake is limited. Therefore, this study aims to examine the effect of consortium native AMF inoculation on the growth, yield, and yield-related traits as well as nutrient uptake of teff varieties under field conditions.

1.2 Statement of the Problem

The heavy use of chemical inputs (pesticides, herbicides, and fertilizers) in Ethiopian teff production and productivity improvement practices is currently the norm. This practice may hurt the fertility of the soil and the nutritional value of harvests. By accumulating heavy metals and other hazardous substances, excessive use of those chemical inputs leads to environmental pollution, which in turn has a significant negative influence on the health of humans and animals (Tchounwou *et al*., 2012).

Chemical fertilizers raise the acidity of the soil and negatively impact the biological diversity of the agricultural land because they contain acid radicals such as sulfuric and hydrochloride radicals. Certain plants can absorb resistant substances from contaminated soil, which can lead to systemic disorders in their users (Alori and Babalola, 2018).

In addition to these, the continuously increasing fertilizer costs and the low use efficiency of the applied fertilizer have become two of the causes of the low productivity of teff in Ethiopia. Therefore, the increasing awareness of low fertilizer use efficiency, environmental pollution, and

product contamination due to the indiscriminate use of chemical inputs (phosphorus input in the current case) has led to the search for new biological technology to improve crop productivity and grain quality without threatening consumers' health. They are environmentally friendly and renewably provide nutrients to maintain soil health and biology without affecting the environment or human health. Therefore, the main objective of this research is to study the effect of arbuscular mycorrhizal fungi inoculation on phosphate fertilization efficiency, teff growth, and productivity under field conditions.

1.3 Objectives

1.3.1 General Objective

The main objective of this research was to evaluate the effect of arbuscular mycorrhizal fungi inoculation on phosphate fertilization efficiency, teff growth, and productivity under field conditions.

1.3.2 Specific Objective

- To examine the effect of arbuscular mycorrhizal fungi on the growth and biomass yield of teff.
- To evaluate the effect of both arbuscular mycorrhizal fungi and phosphorus together on the growth and biomass yield of teff.
- To examine the mycorrhizal dependency of teff under different AMF inoculations and control.
- To examine the nutrient uptake of teff under the influence of arbuscular mycorrhizal fungi and phosphorus application.

1.4 Research Questions

- Do inoculations of arbuscular mycorrhizal fungi affect teff's growth and biomass yield?

- What is the effect of the inoculation of arbuscular mycorrhizal fungi and the application of phosphorus on teff's growth and biomass yield?
- What is the mycorrhizal dependency percentage of teff?
- Does inoculation of arbuscular mycorrhizal fungi and phosphorus application increase the nutrient uptake of teff?

1.5 Significance of the Study

The significance of this study is to examine and investigate the effect of arbuscular mycorrhizal fungi and phosphorus on the growth and biomass yield of teff and its progressive effect in enhancing the height, leaf area index, shoot dry weight, and grain yield teff, and to check the negative effect in reducing the above-mentioned term factors. Finally, the findings of this study could serve the regional agriculture offices and academic community as baseline information.

1.6 Organization of the Study

This study is organized into five chapters. The first chapter deals with the background of the study, the statement of the problem, the objectives of the study, research questions, and the significance of the study. The second chapter presents a review of relevant literature. Chapter three presents the methodology, including the biological material, experimental design, and methodology of data analysis. The fourth chapter deals with data presentation, analysis, and interpretation. The final chapter is related the conclusions and recommendations of the study.

2. REVIEW OF LITERATURE

2.1 Teff Production and Constraints in Ethiopia

Teff (Eragrostis tef (Zucc.) Trotter) is a small-grained cereal that has been grown as food crop in East Africa for thousands of years (D"Andrea 2008). It covers about 2.8 million hectares of land per year accounting 22.95% of the grain crop area, which is more than any other major cereals such as maize 16.91%, sorghum 14.85 % and wheat 13.33% (CSA, 2016). Despite of its these all importance and large area coverage, the productivity of teff is very low which is on average nationally 1.56 ton ha-1 , compared that of other major cereals like wheat, maize, sorghum and barley whose productivity is 2.5, 3.3, 2.3 and 1.9 ton ha-1 , respectively (CSA, 2016). Teff performance in Ethiopia is good in medium altitude (1700-2400 masl). The length of growing period considering rainfall of 450 to 550 mm and evapo-transpiration of 2-6 mm day-1 ranges from 60 to 180 days. Depending on variety and altitude, teff requires 90 to 130 days for growth (Gebretsadik et al., 2009).

Decline in the soil fertility is one of the major bottlenecks to agricultural production, productivity in the world particularly in Africa and specifically in Ethiopia (Okubay Giday et al., 2014). Agricultural production (particularly cereal production) must increase to meet the challenge of food security (Rosegrant et al., 2001). Therefore, greater use of mineral fertilizers is crucial for increasing food production and slowing the rate of soil degradation in Ethiopia since severe soil nutrient depletion is a major sever problem for boosting production and productivity of teff. In Ethiopia in general, specifically in the central highlands, 70 to 80% of the fertilizer purchased by smallholders is known to be applied to teff fields (Kenea et al., 2001).

2.2 Arbuscular Mycorrhizal Fungi

To characterize the symbiotic relationship between plant roots and fungi, Albert Bernhard Frank (1885) created the term "mycorrhiza." In literal terms, mycorrhiza means "fungus root." Mutualism between the roots of higher plants and specific fungi gives rise to mycorrhiza. These fungi live in soil all over the world and work in symbiotic relationships with the roots of most land plants. It is rare for a plant to lack a mycorrhizal root system in natural environments. Consequently, it is possible to argue that mycorrhizal association is a very widespread or nearly universal phenomenon in the kingdom of plants (Bagyaraj, 2011); the arbuscular type of mycorrhizal association is the most prevalent type found in crops that are significant in horticulture and agriculture. "Fungus roots" refers to a symbiotic relationship that occurs between a particular type of fungus and host plants at the root system. The fungus benefits from the carbon compounds that the host plant produces through photosynthesis, and the host benefits from the availability of necessary but inaccessible nutrients like P, Ca, Cu, and Zn thanks to the fungus's ramifying fine-absorbing hyphae (Sheraz Mahdi *et al*., 2010).

According to Smith and Read (2008), fungi are crucial to numerous ecological and microbiological processes, such as the breakdown of organic matter, improving soil fertility, cycling of minerals, and supporting plant nutrition and health. In natural settings, this advantageous interaction is priceless; in agricultural practices, it is even more so. Therefore, it is crucial to protect these fungal communities' soil habitat and to practice agriculture in a way that promotes their survival. AMFs, or arbuscular mycorrhizal fungi, are fungi that live in mutualistic symbiosis with plant hosts. Because of their ability to boost nutrient uptake in plants and their potential to increase grain yield in cereal crops, AMFs have been dubbed "bio-fertilizers" (Barrow, 2012).

According to Brundrett *et al.* (2018), the earliest AMF interactions with land plants occurred approximately 460 million years ago. Furthermore, Redecker *et al*. (2000) found that the phylum Glomeramycota is where the first land plants associated with fungi originated. The majority of plant species, including cereal crops, have arbuscular mycorrhizal fields (AMFs), which are present in over 85% of them. The fungal infection that causes these relationships is typified by the fungus growing inside the cells of the host without breaking through the plasma of the cell, resulting in branched structures known as arbuscular (Finlay, 2008). In return for an increased ability to absorb nutrients from the soil and resistance to a variety of abiotic stressors, the host plant gives the fungus carbon through photosynthesis (Sun *et al*., 2018).

2.3 Arbuscular mycorrhizal symbiosis

The arbuscular mycorrhizal symbiosis is a complex morphological, physiological, and biochemical changes which are formed gradually in several developmental stages in both symbiotic partners. The life cycle of AMF starts with germination of fungal spores in the soil under favorable environmental conditions, spontaneously without the presence of the host plant (Gianinazzi-Pearson, 1996; Requena *et al*., 2007). Fungal colonies expand several centimeters and characteristic growth structures are formed (Giovannetti *et al*., 1994). This a symbiotic phase turns into presymbiotic one characterized by extensive hyphal branching caused by presence of the host plant (Giovannetti *et al.*, 1993). This is crucial stage in the AMF life cycle based on the chemotaxis abilities of AMF that allow the growth of the hyphae to the roots of host plant and represent a significant mechanism functional to host root location, appressorium formation and symbiosis establishment (Sbrana & Giovannetti, 2005).

The symbiosis phase begins by fungal hyphae connection with the plant roots through appressorium and fungi penetrate into the cortex (Giovannetti *et al.,* 1993) to form morphologically distinct specialized structures – inter- and intracellular hyphae, vesicles, and arbuscules (Figure 1). The arbuscules represent the place of active bi-directional transfer of nutrients between plant and fungus (Requena *et al.,* 2007) and play a major role in arbuscular mycorrhizal symbiosis. The hyphae penetrate outside of the roots, into the soil, create extra-radical mycelium, and complete life cycle by the formation of new asexual spores in extra-radical mycelium (Requena & Breuninger, 2004). Under this symbiosis, the AMF stimulate growth and reproduction of plants through better access to nutrients (P and N) and increased absorption of water from the soil by the extra-radical and intra-radical mycelium (Bago*et al.,* 2001). Conversely, the plant provides carbon in the form of saccharides produced by photosynthesis (Pfeffer *et al.,* 1999) transferred to the fungi via active or passive mechanisms (Doidy *et al*., 2012) by intra-radical fungal structures. Once AM fungi colonize the plants, they persist with the root systems and can be moved into other soil (Mishra *et al*., 2018). Rhizosphere affected by mycorrhizas described by the term, "mycorrhizosphere" has unique characteristics (Li *et al.,* 1991). Mycorrhizal fungi take over the role of root hairs and expand root system of plants leading to increasing of the plant absorption area, improved absorption capacity of roots, and better utilization of hardly available nutrients.

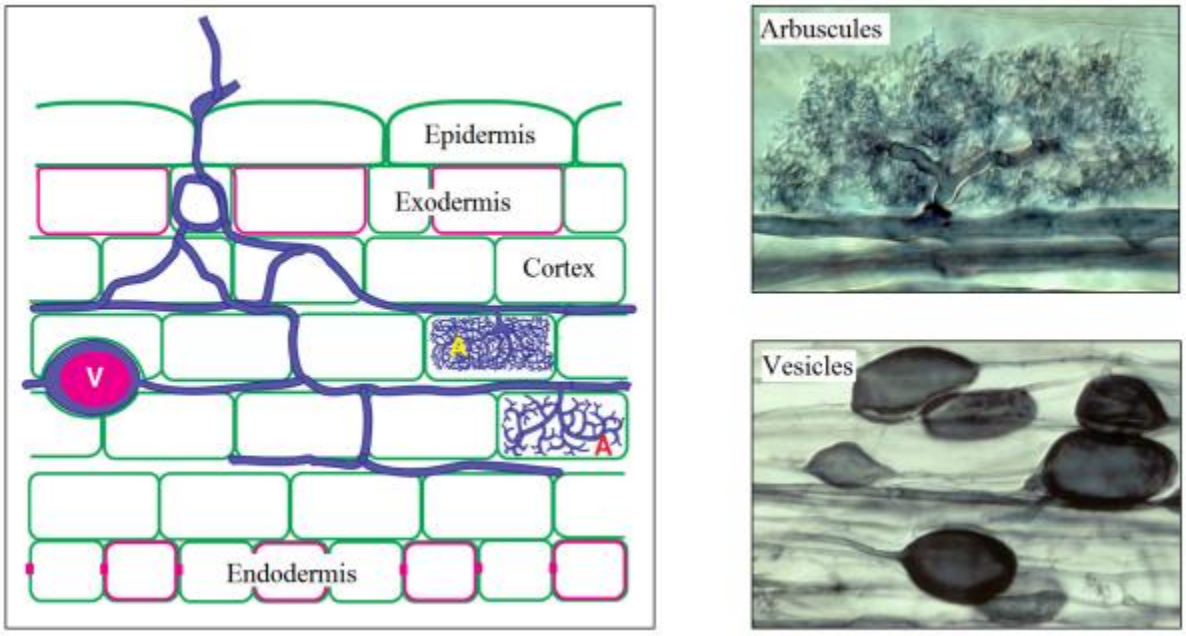

Figure 1.Typical intracellular structures (A – arbuscules and V – vesicle) of arbuscular mycorrhiza produced by Glomus species (left). A mature arbuscule (right up) and vesicles (right down) of Glomus (Brundrett, 2008, photos © Mark Brundrett with permission)

2.4 Role of AM in soil sustainability

Not merely in nutrient and water uptake, AMF has an important role in the improvement of soil structure and quality (Madhya, 2016), as external hyphal network promote soil aggregation by creating a skeletal structure in the mycorrhizosphere (Mardhiah *et al*., 2016). AMF improve soil structure by releasing various proteinaceous and non-proteinaceous organic compounds; the most effective protein glomalin to bind soil particles and these aggregates remain stable after six months of disappearance of the network. Arbuscular mycorrhization improves the soil organic matter content and water-holding capacity (Bitterlich *et al*., 2018; Zhang *et al*., 2019), which helps to maintain the conservation of the soil ecosystem. The extended hyphae play a crucial role to overcome water deficit in dry soil and reduce evaporation (Jayne and Quigley, 2014).

2.5 Benefit of AM in agriculture

The AM symbiosis is the potential component for sustainable agricultural systems as they have found positive effects on host plant nutrition, mineral cycling, and growth (Chahal *et al*., 2020; Thirkell *et al*., 2017). The symbiosis also increases chlorophyll, carotenoids, phenolics, etc. (Baslam *et al*., 2011; 2013). The early enhancement in chlorophyll and growth provides plant vigor and reproductive health boosting the yield. Improvement of growth and productivity of plants by the application of AM inocula has been established (Elbon and Whalen, 2015). Several recent works have been conducted with different crops like tomato, rice, wheat; maize, yam, potato etc. have shown the positive influence of plant growth and productivity (Hijri, 2016; Lu *et al*., 2015; Sabia *et al.,* 2015). Moreover, the food quality of the crop in terms of antioxidants, flavonoids, vitamin C, etc. enhance by AMF colonization has been reported (Hart *et al*., 2015; Lu *et al*., 2015). AM may be used as a potential amendment to improve soil fertility, crop productivity, and yield quality as well as the revival of agro-ecosystem (Chen *et al.,* 2018); The utilization of the beneficial effect of AM inoculated farming enhancing the plant growth and product quality of their hosts may be incorporated as sustainable agricultural systems *(*Bardgett, 2018).The AMF has potential use as a biofertilizer and replaces the fertilizer requirements of crop production. Therefore, a reduction in the need for chemical fertilizer takes place. AM plants produce phytochemicals like, carotenoids, flavonoids, etc., that reduce oxidative damages, beneficial for human health *(Sbrana et al., 2014).*

2.6 Impact of fertilizers and doses on AMF

The high P concentrations in plant induced by high P-fertilization in soil is found responsible for inhibition of mycorrhizal symbiosis (Balzergue *et al*., 2013). At high P fertilizer application, plant can up take enough phosphorous without sharing its carbohydrate *(García-Caparros et al.,*

2021*;* Kiers *et al.*, 2011; Willmann *et al.,* 2013). The P fertilizer application decreases the supply of soluble carbohydrate in roots; absence of signal carbohydrates reduces the appresoria formation and fresh infection *(García-Caparros et al*., 2021; Lopez-R aez *et al.,* 2017). AM colonization, specially, arbuscle formation and active P transfer to plants is reduced in high P content in soil (Kobae *et al*., 2016). AM fungi demands carbon source from plant in exchange of phosphate. The existence and activity of AM depends on cooperation of both partners; and plant itself choose the most compatible and efficient strains by partitioning more resources with them (Kiers *et al.,* 2011; Arguello *et al.,* 2016). In high P content in soil, plant exudates less strignolactone to modulate the symbiosis nature *(*Lopez-Raez *et al.,* 2017) and allocate less resource to inefficient AM that are mostly parasitic burden, though plant species vary in their ability to cut off resources (Balzergue *et al*., 2013). The host plant's P requirement and level of soil available P will also influence the extent of plant response to mycorrhizae. The P use quotient of the plants decreased as the amount of P applied increased, and the P use efficiency index increased at low P levels and decreased at high P levels. The highest mycorrhizal efficiency was observed when the soil contained between 7.8 and 25 mg kg-1 of P *(*Balota *et al.,* 2012).

2.7 AMF Role in Soil Stability

Fungal symbiosis expands from the mycorrhizal root to form a complex, ramifying network into the surrounding soil during AM development. This network can reach up to 30 meters of fungal hyphae per gram of soil (Wilson *et al*., 2009). According to Riley *et a*l. (2002), this network can account for up to 50% of the fungal mycelium in soil, making up a significant portion of the soil microbial biomass (Leake *et al*., 2004). Mycelial networks can bind to soil and enhance its structure. Furthermore, glomalin (*Rillig et al., 2002*), a hydrophobic, "sticky" proteinaceous

substance secreted by AM fungi, plays a role in soil stability and water retention (Bedini *et al*., 2009). According to Riley and Mummey (2006), glomalin secretion in conjunction with a vast hyphal network is thought to play a significant role in stabilizing soil aggregates, which in turn promotes improved soil structural stability and quality (Kohler *et al*., 2006).

2.8 Factors Affecting Arbuscular Mycorrhizal Fungi Colonization

The symbiotic interaction between AMF and plant roots is one of the tactics that can be used to improve water and nutrient uptake of plants under stress conditions. The degrees to which these benefits manifest in practice are affected by various factors such as environmental conditions, host plant species, fungal species diversity, and soil conditions. Plants and soil microorganisms alike require substantial amounts of N to grow and multiply. Arbuscular mycorrhizal fungi generally have a higher N concentration per unit of biomass than the plants they colonize. This can lead to competition between host and fungus in N-deficient soils, with AMF being superior (Helgason and Fitter, 2009; Hodge and Fitter, 2010).

2.8.1 Effect of organic matter on AMF colonization

In the research conducted by Maji et al.(2017) it was uncovered that humic acid-rich worms-made compost, also identified as HARV, had a remarkable positive influence on plant and soil vitality compared to chemical fertilizers (CF) (Maji *et al.*, 2017). This study illuminates the advantages of utilizing natural fertilizers over their synthetic counterparts. One of the significant discoveries of this research was that HARV increased the soil-based microbial variety. This is crucial for sustaining a healthy ecosystem, as diverse microbial communities are pivotal in nutrient cycling and disease control. In contrast, CF negatively affects microbial diversity because of its high salt content and lack of organic material. In addition, (Maji *et al.*, 2017)]established that organic fertilizers enhanced the formation of root nodules and the colonization

of arbuscular mycorrhizal fungi (AMF). Root nodules are crucial for nitrogen fixation in leguminous plants, while AMF establishes symbiotic relationships with plant roots, enhancing the absorption of nutrients.

2.8.2 Effect of soil pollutants on AMF colonization

In the research by Kuang et al. (2023) the scholars aimed to explore the impacts of diverse cadmium (Cd) levels on the translocation ratio and mycorrhizal efficiency in *E. grandis* with AMF colonization. The findings revealed intriguing discoveries that illuminated the interaction between cadmium (Cd), AMF, and plant physiology (Kuang *et al.*, 2023). The scientists administered varying quantities of Cd to *E. grandis*, with a range of sizes from 50 μm to 500 μm. It was observed that with the rise of Cd concentration, the translocation ratio of Cd in *E. grandis* steadily declined. Specifically, at a Cd concentration of 50 μm, the translocation ratio exhibited a 56.41% decrease compared to untreated plants in the control group. The decline became more conspicuous as the amount escalated, with reductions of 62.89%, 66.67%, and 42.79% transpiring at concentrations of 150 μm, 300 μm, and 500 μm, respectively *(*Kuang *et al.*, 2023).

2.8.3 Effect of Soil pH on AMF Colonization

The research conducted by Ouzounidou *et al.* (2015) aimed to explore the chemical makeup and growth responses of Chia plants to arbuscular mycorrhiza fungal inoculum in various soil pH treatments. The researchers were particularly intrigued by how Chia plants respond to acidic and alkaline soil circumstances. The outcomes of the research uncovered some intriguing discoveries. Firstly, it was observed that Chia plants displayed inhibited growth when cultivated in acidic soil *(*Ouzounidou *et al.*, 2015). This indicates that the plants could not flourish and reach their maximum potential in these conditions. However, when grown in alkaline soil, the Chia plants demonstrated increased fresh biomass, suggesting a more advantageous environment

for their development. They (Ouzounidou *et al.,* 2015) also analyzed the chemical composition of Chia plants. The finding showed increased concentrations of stearic, oleic, linoleic, and A-linolenic acids in acidic and alkaline soil conditions. This research provides valuable knowledge about the impact of different soil pH treatments on Chia plant development and chemical composition.

2.8.4 Effect of temperature on AMF colonization

Carvalho and his study peers conducted a study in 2015 to establish the relationship between soil temperature and the efficacy of AMF colonization in selected farming environments. Before this investigation, they were suggestive of the potential variability based on the plant variety. To explore this concept, (Carvalho *et al.,* 2015) conducted a bioassay utilizing non-sterile soil to test their hypothesis. Contrary to their initial assumption, it was discovered that the impact of temperature on AMF did not depend on the type of host plant. This suggests that soil temperature is crucial to AMF growth, regardless of the studied plant variety. Findings by (Carvalho *et al.,* 2015) have significant implications, particularly in the farming sector, where many farmers depend on AMF to improve nutrient uptake and plant growth. As Carvalho *et al. (*2015) disclosed, acquiring knowledge about how soil temperature affects AMF can enable farmers to elevate their farming techniques and attain the utmost crop output.

2.8.5 Effect of light on AMF colonization

In the study carried out by Saha *et al*.,(2022) the scholars set out to explore the impacts of a reduced ratio of red to far-red light (R:fr) on tomato crops and their interaction with the insect herbivore *Chrysodeix ischal cites*. They also analyzed the influence of mycorrhizal inoculation on these interactions. The results of this study unveiled that when exposed to low R: fr light conditions, tomato plants without mycorrhizal support exhibited a triggering of the shade

avoidance syndrome (SAS), which resulted in increased biomass production *(*Maji *et al*., 2017*)*. This response can be attributed to the plants' endeavor to compete for limited light resources by elongating their stems. The heightened biomass production in these plants might benefit agricultural practices. Despite initial expectations, incorporating symbiotic fungi had an opposing influence on the systemic acquired resistance (SAS) reaction. The presence of symbiotic fungi reduced stem elongation in tomato plants exposed to low red-to-far-red light ratios. This suggests that symbiotic fungi may play a role in modulating the growth responses of plants in diverse environmental conditions. Likewise, *(*Maji*et al*., 2017*)* observed that AMF inhibited the induction of defense genes in tomato plants in response to herbivory.

2.9 Arbuscular Mycorrhizal Fungi and Nutrient Uptake

Arbuscular mycorrhizal fungi are important participants in the soil's nutrient cycle. One major advantage of AMF to the plants they colonize is the conversion of immobile, organic nutrient sources like P to inorganic nutrient substrates. In exchange for organic C, AMF actively converts and absorbs nutrients like N, P, and Zn before delivering them to the plant (Smith and Read, 2008; Al-Karaki and Al-Raddad, 1997; Al-Karaki and Clark 1998 ;). According to Kayama and Yamanaka (2014), arbuscular mycorrhizal fungi are also very good at removing nutrients from soils that are low in nutrients, which can prolong crop life and boost yields.

AMF form symbiotic relationships with roots in order to absorb vital nutrients from the host plant and then give back mineral nutrients, such as N, P, K, Ca, Zn, and S. Thus, even in unsuitable conditions inside the root cells, AMF give the plants nutritional support. AMF create fungal structures called arbuscules that aid in the exchange of inorganic minerals as well as carbon and phosphorus compounds, giving host plants a significant boost in vitality (Li *et al*., 2016b; Prasad *et al.*, 2017). As a result, they can greatly increase the concentration of

phosphorus in both root and shoot systems (Al-Hmoud and Al-Momany, 2017). Mycorrhizal association enhances phosphorus supply to the infected roots of host plants in phosphorus-limited environments (Bucher, 2007).

2.10. Phosphorus

The second most important component for crop production is phosphorus (P). Plant growth is restricted by its inadequate availability in the soils (Rowell, 2014). In the humid and sub-humid tropical highlands of East Africa, phosphorus is one of the nutrients that most restrict crop productivity (Sanchez *et al*., 1997). Similarly, Nordt and Driese (2010) proposed that P is the nutrient most lacking in Vertisol agricultural production, with Ethiopian soils exhibiting this deficiency. Because of the use of frequent cultivation and low-input agriculture, the problem of nutrient mining is made worse in the nation. Seventy percent of the studies on the majority of the Vertisols in the Ethiopian highlands reported low available P content, meaning less than 5 parts per million (Khitrov, 2016).

According to Miller and Donahue (1995), strong stalks that can withstand lodging and increased root growth have been linked to a good P supplier. Brady and Weil (2002), made a similar suggestion, saying that in cereal crops, adequate P nutrition strengthens structural tissues like straw or stalks and so helps to prevent lodging. It follows that the application of P fertilizers is necessary for sustainable crop production (Sanchez *et al*., 1997). The reliable symbiont that can provide the plants with the scarce phosphorus in such soils is arbuscular mycorrhizal fungi. Accordingly, application of AMF in P deficient soils is recommended for such types of soils.

2.10.1 Crop response to phosphorus fertilizer

Phosphorus plays a critical role in the life cycle of plants. It is needed in especially large amounts in the meristematic tissues, where cells are rapidly dividing and enlarging. Among them most significant functions of plants on which P has an important effect are reproduction, photosynthesis, N-fixation, crop maturation (flowering and fruiting including seed formation), root development (particularly of the lateral and fibrous rootlets), strength of straw in cereal crops thus helping to prevent lodging and finally, quality and quantity of products (Brady and Weil, 2002) and it promotes the formation of buds and roots development (Hall, 2002). Phosphorus fertilizer trial on teff according to the finding of Alemayehu Assefa *et al.* (2006) reported that the highest grain yield was obtained with the highest P fertilizer rate (80 kg P_2O_5 ha^{-1}) in most Vertisols and the highest grain yield in most Nitosols were obtained at 60 kg P_2O_5 ha-1with interaction of 100 and 60 kg N ha^{-1}, respectively. Similarly, phosphate fertilizer's effect on most of the agronomic parameters of teff was discussed. Mehreteab Haileselassie (2008) conducted a study on the effects of phosphate fertilizer on the growth and development of tef, a cereal grain widely cultivated in Ethiopia. The study found that increasing the level of phosphate fertilizer significantly reduced the number of days to heading and maturity, indicating that phosphate fertilizer can accelerate the growth and development of plants.

However, the study also found that increasing the level of phosphate fertilizer had negative effects on some other growth parameters, such as panicle length, plant height, and number of nodes. This suggests that while phosphate fertilizer can be beneficial for teff growth and development, it is important to use it in moderation to avoid negative effects on other plant characteristics.

2.10.2 Phosphorus (P) As Nutrient for Crop

Without P, neither animals nor plants can grow. As the second most important element for crop production, phosphorus is lacking in the majority of soils worldwide, making it difficult to grow crops with the highest possible yields (Brady and Weil, 2002). Unlike those lacking N, plants lacking P are often dark green and stunted. In addition, compared to plants with an abundance of phosphate, maturity is frequently delayed (Brady and Weil, 2002).

Many aspects of plant physiology, including the basic process of photosynthesis, flowering, seed formation, and maturation, are enhanced by adequate P (Brady and Weil, 2002). The second most important element for crop production is phosphorus (P), whose low availability in the soil limits plant growth (Rowell, 2014).

A sufficient P supply has been connected to robust stalks that can resist lodging and increased root growth (Miller and Donahue, 1995). Adequate P nutrition in cereal crops strengthens structural tissues like straw or stalks, which helps prevent lodging, according to Brady and Weil's (2002) suggestion. According to Sanchez et al. (1997), crop production cannot be sustained in the absence of P fertilizers.

Phosphorus has been recognized as one of the important elements in plant nutrition (Dotaniya *et al.*, 2014a). Phosphorus is an important nutrient especially for pulses to enhance their productivity. Phosphorus stimulates early root development, leaf size, tillering, flowering, and grain yield and hastens maturity. It is a constituent of certain nucleic acids, that is, phospholipids, chromosomes, and the coenzymes nicotinamide adenine dinucleotide (NAD), adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADP). Phosphorus is essential for cell division, and seed and fruit development. A range of research experiments was

conducted to define its chemistry in the soil-plant system. Soils are known to vary widely in their capacity to supply P to crops, as only a small fraction of it in soil solution is in available form to crops (Dotaniya *et al*., 2014b). In addition to this, phosphorus occurs in very low concentrations in soil solution. Its uptake by crops results in a further decrease of its concentration in the soil solution especially near the plant root zone (Dotaniya *et al*., 2013b). As a result, P deficiency has become a limiting factor in crop production in agricultural soils worldwide (Dotaniya *et al*., 2013c).

2.10. 3 Seed Germination

For better seedling vigor and seed germination, seed P content is crucial. The only P that is available to plants during germination is seed P, which promotes the growth of seedlings early on. While mature plants do not place much emphasis on this P pool, young seedlings benefit greatly from it in terms of nutrition and quicker establishment. Following seed germination, growing media is absorbed by the roots of the plant to meet P requirements.

Zhu and Smith (2001) observed that high-P wheat seeds absorbed more P from the soil than low-P seeds. The primary cause of this was that seeds with high P reserves had better-developed root systems (Zhu and Smith, 2001). In the initial stages of seedling growth, hydrolysis of seed phytate P results in the remobilization of non-phytate P, this sustains the growth of maize seedlings (Nadeem *et al*., 2011, 2012). Certain genotypes were found to be sensitive, but in other reports, lower seed P concentrations did not differ from high seed P plants in terms of seedling vigor, plant biomass, or yield (Rose *et al*., 2012; Pariasca-Tanaka *et al.*, 2015).

3. MATERIALS AND METHODS

3.1 Description of the study area

Hawassa University is located in the Ethiopian Rift Valley, 275 km south of Addis Ababa, and lies between 7^0 3'1.35" N latitude and $38^0$29'43.8" E longitudinal with an altitude of about 1736 meters above sea level. Hawassa University Research Village where the research is conducted is located at the eastern corner of the main campus.

3.2 Soil sampling

500g of 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, ground, passed through a 2mm sieve, and analyzed for soil physicochemical parameters using standard procedures. The soil analysis was carried out in the soil laboratory of the College of Agriculture at Hawassa University.

3.3 Biological material.

Three varieties of teff *(Eragrostis tef* Zucc.): white (Nech), red (Qui), and mixed (Sergegna) were obtained from the Southern Agricultural Research Center of Ethiopia. Indigenous consortia of AMF inoculum were obtained from Hawassa University, Department of Biology. Then, Sorghum was used as host plant. The plant was left to grow for 45 days after which the crude inoculum was harvested. The AMF crude inoculum (spores, podocarps, and the soil substrate in which the host plant is grown) contained about 2600 spores per 100g of the crude inoculum after mass growth; the inoculum was preserved in plastic bags until used.

3.4 Experimental design and treatments.

A fully randomized block design with partitioned plots with three replications was the experimental setup employed. In the plots, P_2O_5 fertilizer and AMF inoculants were

administered. According to Raij and Cantarella (1998), the P quantities applied matched 0, 25, 50, 75, and 100% of the suggested doses for the teff crop in the region. P_2O_5 values as a result were 0, 0.015, 0.03, 0.045, and 0.06 kg ha^{-1} respectively. 250 grams of consortia AMF inoculum were utilized. Each plot (2m × 3m) had three rows, and inter-row spacing of 0.50cm leaving 25cm as periphery throughout the 2m × 3m width & length of each plot. Each plot also got a dose of the matching phosphate fertilizer. Table 1 below illustrates how the design is arranged.

Table 1Experimental design (CRBD)

White (Nech)						
1	AMF	100	C	AMF +AMF	25AMF	50
2	75	C	100	50	100	75
3	25	75	25	AMF	C	50
Mixed (Sergegna)						
1	100	C	25	AMF	50	C
2	C	75	100	25	AMF	50
3	100	AMF	50	25	75	75
Red(Qui)						
1	C	50	AMF	C	25	75
2	50	75	100	75	100	25
3	100	AMF	25	50	AMF	C

Key: AMF= arbuscular mycorrhizal fungi, C= control, the number between 25 upto100 are represent % of phosphorus rate added to teff varieties.

3.5 Conduct of the experiment

Each dose of P_2O_5 was adjusted and applied to the corresponding plots. AMF Inoculation of the linear furrows within each plot was carried out before sowing by adding 250g of the crude inoculums uniformly throughout the 3m length of the plot except the control plot. After covering the inoculums with a flush of fine soil from the same plot, teff seeds (white, mixed, and red

varieties) were sown and covered with a flush of fine soil, as mentioned above. Sowing was done manually, following the plot lines. All the experimental blocks were sown simultaneously and left to germinate and grow. Regular monitoring was carried out, and when there was a rain deficiency, the plots were irrigated manually. Weed management was done manually after full-blown growth of all varieties. The growth parameters, such as height, leaf area, and stem collar diameters, were measured after 45 days. The harvest was performed manually after grain maturation.

3.6 Crop Data Collection and Measurements

3.6.1 Growth data

Plant height (cm): The plant height was measured using the tape meter from randomly selected plants from central rows (excluding the boarder rows) of each plot starting from base of the main stem to the tip of the main shoot panicle at maturity and the average was considered for statistical analysis.

Leaf area index (cm^2): it was measured as leaf length multiply by leaf area and of plants by tape meter ($l \times w \times 0.578$)

Stem diameter (mm): with the same time of plant height and leaf area index were measured, it was measured by digital caliper

3.6.2 Yield and yield components

Grain yield (kg /ha): After the biomass was thought to be completely dried, it was trashed and recorded by weighing the grain yield harvested from the net plot. Finally, the weight was converted to kilogram per hectare. It was determined by taking the grain yield of plants harvested.

Above ground biomass yield (kg/ ha): It was recorded from plants when the harvested biomass from the $6m^2$ area of each net plot was completely oven dried and attained constant weight which

was converted to kilogram per hectare. It was recorded as the weight of the aboveground biomass of plants harvested from the net plot area after sun drying it.

Straw yield (kg/ha): straw yield was obtained by subtracting grain yield from total aboveground biomass yield.

Harvest index (%): It was calculated as the ratio of grain yield to the total aboveground biomass harvested and is expressed in per cent.

HI (%) = Grain yield (kg/ ha) / Total dry biomass yield (kg/ ha) * 100.

3.7 AMF Spores density

To investigate the AMF spore density in the field experiment, 500-gram soil samples were taken from each treatment and dried at room temperature for 15 days. 100g of the dried soil samples were mixed in a two-liter-capacity beaker containing 1.5 liters of water. The soil in the water was agitated by stirring vigorously by hand and left to settle down. The suspension was then sieved through sieves having a mesh size of 500µm, 105µm, and 50µm, following the wet sieving and decanting method (Gerdemann and Nicolson, 1963). The last (50µm) sample was transferred to four 250ml centrifuge tubes and centrifuged at 2000 rpm for five minutes, then suspended in a 60% sucrose solution and thoroughly mixed and a centrifuged at 2000 rpm for a minute. The spores were rinsed with tap water and transferred to Petri dishes, and the spores of the sample were observed under a stereomicroscope

3.8 Mycorrhizal colonization

About 0.5 mg of roots from each plot were thoroughly cleaned with tap water, cleared with a 10% KOH solution in a water bath at 90 ^{o}C for 1 hour, neutralized in 1% aqueous HCl, stained with a 0.05% trypan blue in a lactic acid and distained using an acidified glycerol solution. The root samples were then left overnight in the Lacto glycerol distaining solution (1:1:1; Lactic acid,

glycerol, and distilled water) in a dark room to remove coloration from root cells. Then, only fine roots were cut into segments of about 1 cm long. Finally, root segments were mounted on microscopic slides and covered with a cover slip. AMF colonization was rated using the magnified intersection method of McGonagall *et al.* (1990) as arbuscular and vesicular colonization. The rating was done after examining 100–150 intersections per sample.

RLC= 100[(**G-N**)/**G**], the percentage of root length colonized by hyphae only, hyphal colonization **HC**= **100**(**H/G**), the percentage of root length colonized by arbuscules, arbuscular colonization

AC= **100**(**A/G**) and the percentage of root length colonized by mycorrhizal vesicles, vesicular colonization **VC**= **100**(**V/G**). **RLC**, **N**, **A**, **V** and **G** are designated as **RLC**,(total root length colonization), N (no fungal structure), A(arbuscules), V (vesicles) and G(total intersection) respectively. All were quantified by examining 150 intersections per sample.

3.9 Mycorrhizal dependency

Mycorrhizal dependency (MD) of the three teff varieties was calculated according to Planchette (1983) as follows: MD (%) = [(M-NM)/M] x 100

Where: M is the total dry biomass of the mycorrhizal plant; NM is the total dry biomass of the non-mycorrhizal plant.

3.10 Phosphorus use efficiency

The following formula was used to calculate the phosphorus use efficiency of the three types of teff:

Apparent P use efficiency is equal to (P uptake by plant with P application minus P uptake by plant without P application) / the amount of P applied. This gives a fair estimate of P use efficiency by the three varieties of teff with the application of different rates of phosphorus.

3.11 Nutrient content

Plant tissue analyses were undertaken at Hawassa University in the College of Agriculture following standard procedures. The P content in the plant tissues was analyzed by the vanadomolybdate method after the wet digestion, followed by photometry (Cavell, 1955).

3.12 Dry matter production and teff yield

Teff variety yield and dry matter production were calculated using Holliday's (1976) and Nichiporovich's (1967) methods. A crop's yield might be described from an economic or biological perspective. The harvest index (I), or the percentage of the harvested crop, is used to associate biological yield (Yb), which is the total dry matter production, with economic yield (Ye), which is the economically relevant fraction of biological yield as shown in the formula:

Ye = Yb x I

The equation shows that raising the harvest index, or total dry matter production, will raise the economic yield, such as grain yield. The biological and economic yields of many crops are equal, but not in the case of grains. Modern wheat cultivars have a harvest index of 35 to 40%, while older cultivars have a number in the range of 23 to 30% (Melel and Kirkby, 1982). When it comes to rice, the harvest index is often lower and grows more slowly than the overall production of dry matter (Murayama, 1967).

3.13 Data analysis

Statistical analysis for comparison of all growth parameters (plant height, shoot dry weight, leaf area, stem collar diameter, and among treatments and controls) was carried out using the SPSS

software package (version 27.1.0). The significance of differences in AM fungal spore abundance and percentage of root colonization between the treatments was tested using Duncan's multiple range test at $p < 0.05$ after a two-way analysis of variance (ANOVA). The growth of plants was computed as the percentage dry weight of inoculated plants over non-inoculated plants (Giovannetti and Mosse, 1980) and the phosphorus rate applied. Total phosphorus levels were analyzed from oven-dried ground plant shoots using standard methods.

4. RESULT AND DISCUSSION

4.1 Results

4.1.1 Soil physicochemical properties

Before the experiment, the basic physicochemical properties of the experimental soil were examined. These characteristics included total nitrogen (TN), pH, electrical conductivity (EC), available phosphorus (Aval.P), and texture. The pH of the soil was 6.20 (slightly acidic), and its EC values were 81.2 (μS/cm). 14.2 mg/kg of available phosphorus, 0.32% of total nitrogen, and a soil texture consisting of sand (48), clay (18), and silt (34), with a soil water ratio of 1:2.5, were recorded. The soil's bulk density of 1.2 g/cm3 is optimal for plant growth in loam soil, as the value is less than 1.4 g/cm3. The porosity of the test soil was 52.8%.

4.1.2 Effect of AMF alone and AMF+Phosphorus levels on the growth and yield of red teff.

Table 2 shows the growth parameters of red teff variety. The variety was treated with arbuscular mycorrhizal fungi and various phosphorus concentrations. After harvesting, growth parameters such as shoot dry weight, yield, and straw were measured. The analysis of variance showed that the combination of arbuscular mycorrhizal fungi inoculation and phosphorus rates had a significant ($P \leq 0.001$) effect on the height of red teff. The maximum mean plant height (34.71 cm) was recorded from AMF+75%P, while the minimum plant height (23.80 cm) was recorded from the control. For the leaf area index, the maximum mean value (28.73 cm^2) was recorded from the control treatment, while the minimum mean value (20.20 cm^2) was recorded from the AMF alone inoculation. And also for the stem diameter, maximum mean value was recorded from the AMF alone, and AMF+100%P (2.40 mm), while minimum mean value was recorded from AMF+25%P (2.06 mm). The combination of arbuscular mycorrhizal fungi and fifty percent

phosphorus (AMF+50%) produced the highest mean values for shoot dry weight, grain yield, and straw yield, which were 240(g/6m^2), 5(g/6m^2), and 227(g/6m^2), respectively. The minimum mean values for shoot dry weight (176.00 g/6m^2), yield (2.50 g/6m^2, and straw (142.0 g/6m^2) were obtained from the control group.

Table 2 (Mean±SEM**)** of effects of AMF alone and AMF+Phosphorus levels on the growth and yield of Red teff plant.

Treatment	**H(cm)**	**LA(cm^2)**	**SD(mm)**	**SDW(g/6m^2)**	**Yield(g/6m^2)**	**Straw(g/6m^2)**
AMF	25.85±0.44^{e}	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^{b}	26.85± 0.49^{c}	2.06±0.14^{a}	223.3±28.5^{d}	3.33± 0.33^{b}	210.3±28.70^{b}
AMF+50%P	28.91±2.26^{d}	23.82± 0.76^{b}	2.30± 0.05^{c}	240.0±21.57^{e}	5.00± 0.57^{c}	227.0±20.03^{a}
AMF+ 75%P	34.71± 2.58^{a}	26.77± 3.73^{c}	2.30± 0.00^{c}	180.0±10.78^{b}	4.66± 0.66^{cd}	167.3±10.17^{e}
AMF+100%P	31.85±0.83^{c}	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^{f}	28.73± 0.25^{d}	2.20±0.10^{b}	176.00±46.0^{a}	2.50± 1.50^{a}	142.0±21.00^{f}

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≤0.05, P≤0.01, and P≤0.001.*

4.1.3 Effects of AMF alone and AMF+Phosphorus levels on Sergegna teff plant growth and yield.

One of the three varieties of teff chosen is the sergenga variety, which received the same period of growth time, phosphorus, and AMF. When comparing the shoot dry weight of sergegna teff variety to the control, the analysis of variance showed that the combinations of AMF+50%P, AMF+75%P, and AMF+100%P had a significant (P≤ 0.009, p≤0.05, and p≤0.01) effect (Table 3). AMF+100%P produced a maximum mean plant height value of 35.67 cm, while the control plant produced a minimum mean plant height value of 27.00 cm. When it comes to the leaf area index, the AMF+75%P produced the highest mean value (39.00cm$^{2)}$, and the control plants produced the lowest mean value (25.00cm^2). For stem diameter, the maximum mean value

(2.53mm) was recorded from the AMF alone inoculation, while minimum mean value (2.20mm) was recorded from control treatment.

The highest recorded mean values for shoot dry weight and straw came from AMF +100%P and were 274.64 g/6m^2 and 266.33 g/6m^2, respectively. The highest recorded mean value for yield came from AMF +75%P and AMF +100%P, and was 5.67 g/6m^2. From control plants, the minimum mean values of shoot dry wet, yield, and straw were measured, they were 153.00, 3.33, and 141.00 g/6m^2, respectively.

Table 3 (Mean±SEM) of effects of AMF alone and AMF+Phosphorus levels on Sergegna teff plant 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.*

4.1.4 Effects of AMF alone and AMF+Phosphorus level on growth and yield of white teff plant.

The analysis of variance revealed that all AMF combinations with phosphorus fertilizer had a significant effect on the yield components of white teff variety when compared with the control. Besides, there is a significant effect on the yield of white teff variety when compared with AMF alone.

The maximum mean value of plant height was recorded from AMF+100%P (38.72cm), while the minimum mean value was from the control plant (23.97cm). The maximum mean value of the leaf area of the plant was recorded from AMF+100%P (34.88cm^2), while the minimum mean

value was recorded from the control (26.92cm^2). In the case of the stem diameter, the maximum mean value was recorded from AMF+100%P and AMF+75%P (2.30 mm), while the minimum value was recorded from control (2.22 mm). The maximum mean value was recorded from AMF+100%P (260.67 g/6m^2) for shoot dry weight, while the minimum mean value was recorded from control (197.00 g/6m^2).

In terms of yield, maximum mean values were recorded from AMF+50%P, AMF+75%P, and AMF+100%P (6.33 g/6m^2), while the minimum mean value was recorded from control (2.50 g/6m^2). And for the straw the maximum mean value recorded from AMF+100%P (253.00 g/6m^2), while the minimum values were recorded from control (179.00 g/6m^2).

Table 4 (Mean±SEM) of effect of AMF only and AMF+Phosphorus level on white teff plant 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^{e}
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**.**

4.1.5 Mean Grain Yield

The results of the analysis of variance indicated that the P fertilizer rate and AMF inoculation had a significant ($P \leq 0.05$) impact on the grain yield of teff varieties (Tables 2, 3, and 4). Nech teff had the highest grain yield, followed by mixed teff and in comparison to the control, the red one is better benefited (Figure 1). The maximum grain yield (10550 kg ha^{-1}) was obtained from

the application of 30, 45 & 60 kg P ha^{-1} while the minimum grain yield of tef was recorded from the unfertilized plots.

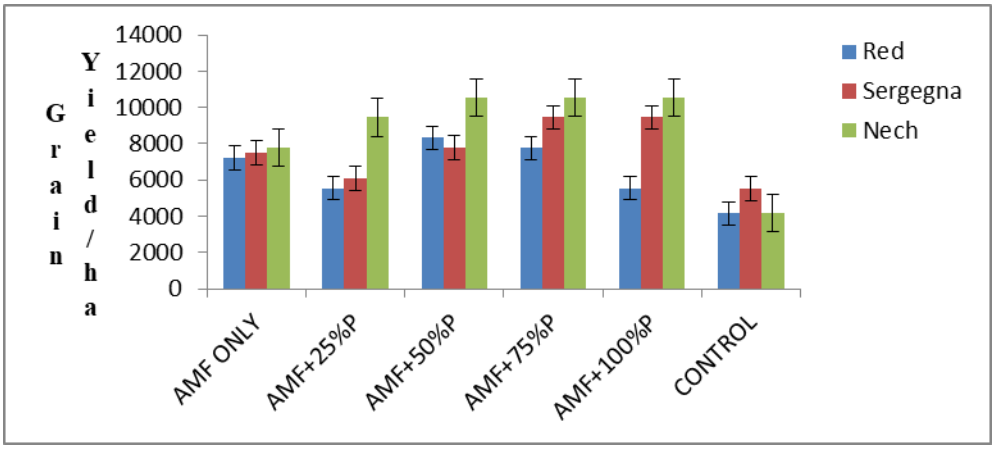

Figure 2 Teff varieties grain yield (Kg ha^{-1})

4.1.6 Mean straw yield

The application of P and the inoculation of AMF had a substantial ($P \leq 0.05$) impact on straw yield. Straw yields were generally higher when AMF and P were applied together (Figure 2). Thus, out of all the Nech teff treatments, the AMF inoculation plus phosphorus application in AMF+25%P, AMF+50%P, and AMF+75% produced the highest straw yield. For Qui teff in AMF+100% P recorded the highest straw yield. On the other hand, the control treatment yielded the least amount of straw.

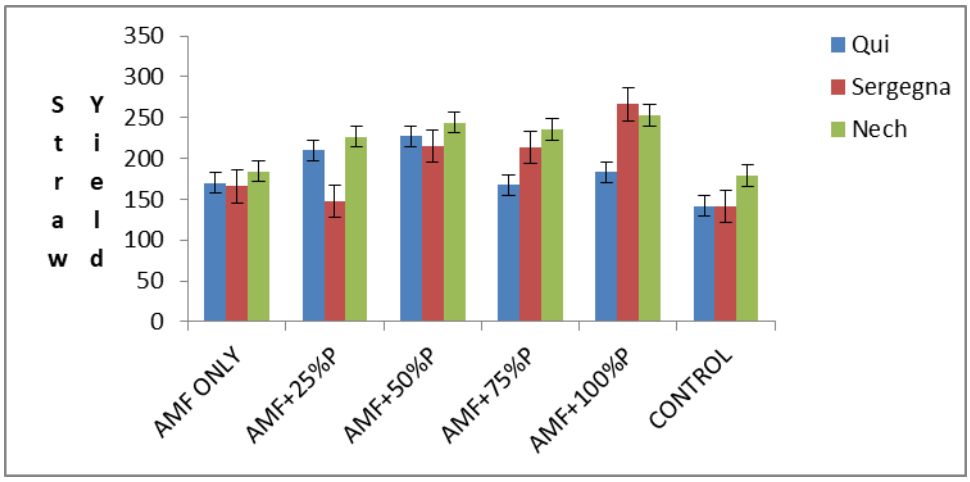

Figure 3 Mean straw yield (g/6m^2)

4.1.7 Mycorrhizal dependency

Table 5 shows the mycorrhizal dependency of three teff varieties (red, sergeant, and white) on the AMF. The highest percentage (44%) was recorded from AMF+100%P under the Sergenga teff variety, while the lowest percentage (2%) was recorded from AMF+25%P. Except for AMF alone (4.21), all combination treatments under white teff ranged between 10% and 40%. Except for AMF only and AMF +75%P (3 and 4, respectively), all combinations of AMF and phosphorus rates under red teff were between 10% and 40%. And excluding AMF+25%P mixed teff was recorded between 10% and 40%.

Table 5 Mycorrhizal dependence of teff varieties

Treatment	White teff	Red teff	Mixed teff
AMF only	4.21	3	15
AMF+25%P	16.76	21	2
AMF+50%P	22.54	27	19
AMF+75%P	17.91	4	32
AMF+100%P	24.42	10	44

4.1.8 Phosphorus uptake and use efficiency

AMF influenced the concentrations of P in the above-ground plant biomass. The increased concentration of P in the above-ground part of the teff is observed with the application of consortia of AMF and a lower concentration of P in comparison to the control. However, the rate of P uptake and P-use efficiency decreased with the higher P concentration, except in red teff, where the values are variable.

Table 6 Phosphorus uptake and efficiency

Treatment	P_2O_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

As shown in Figure 2 below, the maximum P use efficiency is recorded for AMF + 25% treatment. As the P level increases, the phosphorus use efficiency decreases.

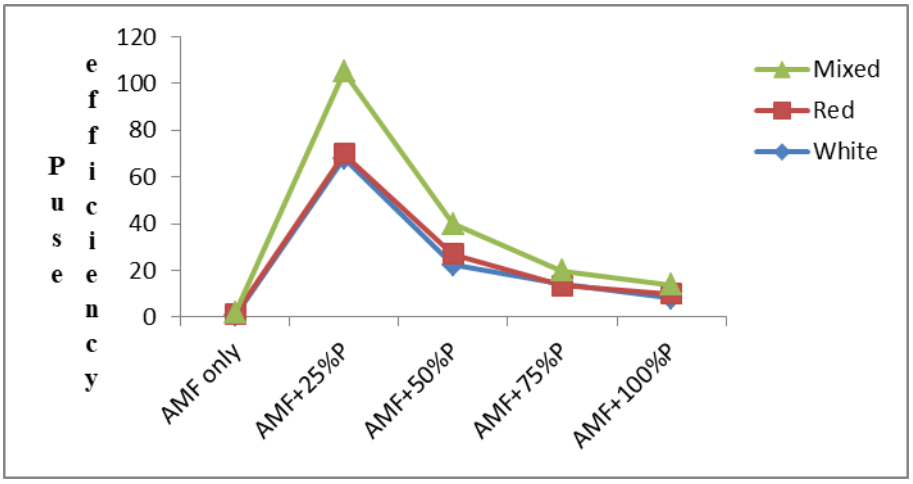

Figure 4 Trends in P use efficiency

4.1.9 Effect of Arbuscular mycorrhizal fungi inoculation and phosphorus level on teff harvest index

Table 6 below shows how phosphorus application and inoculation affect the dry matter production of the three types of teff: white, red, and sergegna. The maximum harvest index of

2.63g/6m^2 for white teff was recorded from AMF+75%P, followed by 2.59 g/6m^2 for red. The minimum harvesting index value was recorded for the control for all three varieties.

Table 7 Effect of an inoculation and phosphorus level of teff yield harvesting index (kgha^{-1})

Dry matter production	White teff	Sergegna teff	Red teff
AMF only	2.27	2.55	2.38
AMF+25%P	2.39	2.35	1.49
AMF+50%P	2.48	2.47	2.08
AMF+75%P	2.63	2.51	2.59
AMF+100%P	2.42	2.06	1.71
Control	1.26	2.17	1.42

4.1.10 Spore density

The spore density of teff varieties that are inoculated with AMF is presented in Table 6 below. The highest spore density (80/100g dry soil) was recorded from AMF+25%P for the white teff plant. Next to the white teff plant, a higher spore density (75/100g dry soil) was recorded from AMF+25%P for mixed teff varieties. For the red teff variety, 70/100g dry soil was recorded from AMF alone inoculation, while the lowest spore density was recorded from the control plant for all varieties. Also, there were significant differences between the main effect (AMF only) and combination effects (AMF + phosphorus rate).

The percentage of spore density decreased for all varieties as the phosphorus level increased, according to the results. In comparison to the AMF inoculation and phosphorus level, the control group exhibited a lower spore density. The treatment of AMF only and AMF+25%P yielded a higher percentage of spore density compared to other combination of AMF and phosphorus rate and control treatments. In the combined treatment, the lowest percentage was found at

AMF+100%P. A higher percentage of the control treatment was observed for the Sergegna teff variety. In contrast, there was zero percent for red teff.

Table 8 Spore density

Treatment	White teff/100g dry soil	Mixed teff/100g dry soil	Red teff/100g dry soil
AMF	74	70	70
AMF +25%P	80	75	65
AMF+50%P	60	55	60
AMF+75%P	40	42	51
AMF+100%P	32	38	35
Control	5	15	0

4.1.11 Root colonization

The percentage of roots that are colonized by arbuscular mycorrhizal fungi (AMF) describes the symbiotic relationship between AMF and plants. Compared to the control and the other two varieties, the red teff variety had a higher colonization rate (90%) at AMF+50%P, according to the current findings. The same red teff variety at AMF+25% inoculation had the next-highest colonization percentage (86%). Maximum value (82%) recorded at AMF+100%P treatment for mixed (sergegna) teff variety. The highest value (81%) for an AMF-only inoculation was found in the case of the white (Nech) variety. Additionally, it was observed that, for all three teff varieties, with the exception of a few uncommon instances in the red and mixed teff varieties, the percentage of roots colonized decreases as the phosphorus rate of application increases.

Table 9 Root colonization of AMF inoculation under teff varieties.

Treatments	Nech			Sergegna			Qui		
	A(%)	V(%)	RLC(%)	A	V	RLC	A	V	RLC
AMF	23	28	81	25	23	80	24	28	85

AMF+25%p	20	22	80	21	28	76	18	24	86
AMF+50%p	12	20	64	24	26	77	23	32	90
AMF+75%p	10	21	57	20	28	75	25	22	84
AMF+100%p	4	6	25	23	30	82	11	21	64
Control	5	14	30	4	11	28	3	7	20

4.2 Discussion

Teff grows widely in a range of temperatures, soil types, and rainfall patterns, from sea level to 2800 meters above sea level. As a result of its fixation with calcium in alkaline soils and aluminum and iron in acidic soils, phosphorus becomes deficient for plant uptake in the majority of tropical soils. Furthermore, most of the P fertilizers that are applied to these soils become fixed and are not absorbed by plants. Crop production becomes more sustainable when P-efficient genotypes are developed that have a high growth and yield potential in soils with low phosphorus availability. As a result, there is less pollution in the environment from the runoff and leaching of excess P fertilizer, and production costs related to P fertilizer applications are also decreased. The genotype may be phosphorus efficient if it can obtain P from a restricted supply of soil P or if it can yield a high yield for each unit of P acquired.

Apart from the impact of genetics, soil biology and its adaptability are important. Arbuscular mycorrhizal fungal associations with teff varieties and their ability to solubilize phosphate, especially in soils lacking in phosphate, are examples of helper microbial communities. Given these advantages, the current study used AMF inoculation as well as the application of various rates of P both AMF alone and in combination with phosphorus in five treatments. The results are discussed in the sections below.

4.2.1. Influence of Arbuscular Mycorrhizal Fungi (AMF) on Growth and yield Parameters

The primary goal of this study is to determine how arbuscular mycorrhizal fungi affect teff varieties growth and yield, as well as the effectiveness of phosphorus fertilizers. Plant nutrients are essential for many fundamental ecological processes, including photosynthesis, plant growth and competition, pathogen infection, decomposition, and coupled biogeochemical cycling (Bahram *et al.*, 2020). The extra radical mycelium of AMFs can aid in plants' uptake of nutrients from the soil by increasing the root surface (Etesami *et al.*, 2021).

Comparing the treated teff plant to the control treatment, our results demonstrated improvements in all growth parameters (height, and stem diameter, except leaf area) and yield parameters (shoot dry weight, grain yield, and straw). This may implied that AM fungi might be used as bio fertilizers to improve the growth and yield of teff varieties.

On the other hand, Osonubi (1994) proposed that AM inoculation enhanced drought resistance and P nutrition in low-P soil, thereby improving plant growth under aridities.

4.2.2 Effect of combination of AMF and AMF+Phosphorus rate on growth components of teff varieties

Plants need enough major nutrients such as phosphorus for healthy growth, and they also need a suitable environment with the right amount of light, water, and climate. Our findings show combination effect of arbuscular mycorrhizal fungi and phosphorus rate significantly affects the height of teff plants. Teff height increased in response to P_2O_5 doses because P is necessary for photosynthesis, respiration, energy storage, and transfer. Injecting AMF into the white teff variety aids in enhancing plant growth and phosphorus uptake. AMF symbiosis has resulted in increased phosphorus uptake, which has positively impacted plant growth. Fiorini et *al.* (2018)

also confirmed that phosphate fertilization causes an increase in the height of crop plants such as maize.

Significant differences existed between AMF+75%P and AMF+100%P for white and sergegna teff. But for the red teff plant had significant differences between all treatments on the growth. This variation among the varieties describes the genetic differences between plants. Similar findings reported .

4.2.3 Effect of combination of AMF+Phosphorus rate on yield components

As previously mentioned in Kayama and Yamanaka's (2014) review, arbuscular mycorrhizal fungi are also excellent at removing nutrients from low-nutrient soils, which can increase crop yields and extend crop life. The current study's findings suggest that the highest possible level of shoot dry weight yield, grain yield, and straw yield for white and sergegna teff varieties may be achieved by inoculating teff with mycorrhizal fungi and adding phosphorus rate. This indicates that both the interaction of arbuscular mycorrhizal fungi and phosphorus level increase phosphorus uptake from soil.

In field settings, Rafique & Ortas (2018) discovered that P fertilizer and mycorrhizal inoculation significantly increased the yield of peppers and eggplants. Comparable results were reported by Elia and Conversa (2012) and Salvioli et al. (2012).

Compared to crops that are not treated with AMF, crops treated with AMF require less chemical fertilizer and plant protection chemicals. AMF application improved crop quality because fewer chemical fertilizers and agrochemicals are applied (Rouphael *et al.*, 2015). Similar grain yield values were observed in white teff for AMF+50%P, AMF+75%P, and AMF+100%P, as reported

in the findings, demonstrating that white teff plants may use medium phosphorus fertilizer when inoculated with AMF and application of phosphorus.

4.2.4 Mycorrhizal dependency

Mycorrhizal dependency, according to Gerdemann (1975), is the extent to which a plant depends on mycorrhizal conditions to yield its maximum amount of yield at a particular fertility level. Various formulas based on the dry mass of both mycorrhizal and non-mycorrhizal plants have been used to quantify MD, according to Plenchette et al. (1983). Cruz and colleagues (1992) proposed three MD classes: (i) >41% classified as highly dependent, (ii) 10% - 40% classified as intermediate, and (iii) Less than 10% classified as non-dependent. The current study found that the sergegna teff had superior mycorrhizal dependence, followed by nech teff These results demonstrate that red varisety (27%) at AMF+50%P treatment, white variety (24.42%) at AMF+100%P treatments, and mixed (sergegna) teff are more dependent (44%) at AMF+100%P.

4.2.5 Phosphorus use efficiency

In our result, as shown, the rate of P uptake and P-use efficiency decreased with the higher P concentration, except in red teff, where the values are variable. Similar findings are Balota *et al*., (2012). reported that The host plant's P requirement and level of soil available P also influence the extent of plant response to mycorrhizae. The P use quotient of the plants decreased as the amount of P applied increased, and the P use efficiency index increased at low P levels and decreased at high P. The highest mycorrhizal efficiency was observed when the soil contained between 7.8 and 25 mg kg-1 of P.

4.2.6 Harvest index

The physiological ability of crop plants to convert dry matter into economic yield is measured by the harvest index. The observed difference in the result was may related to genotypic differences and is directly linked to the productivity or partitioning capacity of the crop. In agreement with this result, Ano (2005) reported that the differences in harvest index might be due to the inherent varietal characteristics, environmental factors, and other cultural practices.

4.2.7 AMF Spore density

The amount of AMF spores produced by the fungus that causes root infection decreases when soil P levels rise (Menge *et al.*, 1978). Spore density from arbuscular mycorrhizal fungi is reduced solely for control, as the current result has demonstrated, and it decreases as phosphorus levels rise. The application of fertilizer has been linked to a lower spore density, which is typically correlated with a lower spore production rate (Egerton-Warburton *et al.,* 2000; Bhadalung *et al.*, 2005; Zhang *et al.*, 2016, GezahagnGetachew *et al.,* 2019).

4.2.8 Root colonization

The extent to which AMF colonizes plant roots is known as mycorrhization. The ratio of colonized root segments to examined segments is used to calculate mycorrhization (Singh *et al*., 2020). The inhibition of mycorrhizal symbiosis is found to be caused by high P concentrations in plants that are caused by high P-fertilization in soil (Balzergue *et al.,* 2013). Plants can absorb sufficient amounts of phosphorous without sacrificing carbohydrates when high P fertilizer is applied (García-Caparros *et al.,* 2021; Kiers *et al.,* 2011; Willmann *et al.,* 2013). A high P content in the soil reduces AM colonization, specifically arbuscle formation and active P transfer to plants (Kobae *et al.,* 2016). In this experiment, arbuscular mycorrhizal fungi (AMF) root colonization reduced from a low rate of phosphorus to a maximum rate of phosphorus. This

demonstrates that as the phosphorus rate increases, the plant becomes less reliant on arbuscular mycorrhizal fungi and simply obtains nutrients from the soil.

Sadhana (2014) presents a similar idea. The uptake of P from the soil via AMF resulted in increased colonization of plant roots, which absorbed soil nutrients. Because P fertilizer application reduces the number of soluble carbohydrates in roots, appressoria formation and fresh infection are decreased when signal carbohydrates are absent (García-Caparros *et al.*, 2021; Lopez-Raez *et al.*, 2017).

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study concluded that the utilization of AMF bio inoculants either alone or in combination with phosphorus improves teff growth and yield.. Furthermore, sustained teff production and productivity without affecting grain yield and quality of the grain is an important agricultural practice to meet consumer's demand at the regional and national level. Further evaluation and demonstration could be conducted by inoculation of AMF inoculants on different crop varieties under different environmental conditions to explain the role of native AMF inoculants.

5.2 Recommendation

Based on the findings of this specific study the following recommendations are forwarded:

- Teff production in Ethiopia is heavily reliant on inorganic fertilizer as an agricultural input. But it has such a huge negative impact on the environment. As a result, it is strongly advised to apply bio inoculants, such as arbuscular mycorrhizal fungi, at lower to medium fertilizer rates.
- The utilization of arbuscular mycorrhiza inoculants in the production of crops, specifically teff, enhances plant resilience to stress, boosts crop yield, increases environmental stability, and facilitates the production of nutritious food. In order to preserve their agroecosystems and combine modern and traditional farming practices, local smallholder farmers and the agricultural sectors should endeavor to harness the natural composition of indigenous AMF.
- It has been demonstrated that varying teff varieties react differently to phosphorus fertilizer at different levels and to AMF inoculation. Thus, when growing a teff variety, it

is advised to choose a variety that corresponds to the proper rate of phosphorus rating plus soil inherent phosphorus concentration.

- Only one agro ecological zone and a restricted area were used for this study. Consequently, it is advised to conduct comparable research in the nation's various climate zones in order to gain a comprehensive understanding of the significance of applying bio-inoculants in order to decrease the rate at which inorganic fertilizers are applied.

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Appendex

Appendix I: Some Pictures

Teff Seeds (white, red, and sergenga)

AMF Inoculum

Teff sowing in the field

View of teff growth condition

Laboratory Activity

Root staining and spore density

APPENDIX II: RAW DATA

Raw data of growth and yield components from three teff varieties Sergegn teff

TREATMENT	Height	LA	SD	SDW	yield	Straw
	28.70	31.00	2.50	174.00	5.00	165.00
AMF ONLY	29.90	31.00	2.60	161.00	4.00	150.00
	24.70	30.00	2.50	194.00	4.50	182.00
	28.40	35.00	2.30	180.00	4.00	170.00
AMF+25%P	29.00	34.00	2.40	153.00	3.00	146.00
	27.00	31.00	2.20	135.00	4.00	127.00
	28.00	26.00	2.50	174.00	5.00	170.00
AMF+50%P	34.00	28.00	2.60	196.00	5.00	189.00
	31.00	31.00	2.40	196.00	4.00	186.00
	32.00	43.00	2.50	223.00	6.00	210.00
AMF+75%P	28.00	37.00	2.30	206.00	6.00	194.00
	32.00	37.00	2.50	246.00	5.00	236.00
	35.00	31.00	2.40	257.00	5.00	249.00
AMF+100%P	37.00	32.00	2.40	293.00	4.00	285.00
	35.00	29.00	2.30	274.00	8.00	265.00
	24.00	21.00	2.10	158.00	2.66	148.00
Control	30.00	29.00	2.30	148.00	4.00	134.00

Key teff

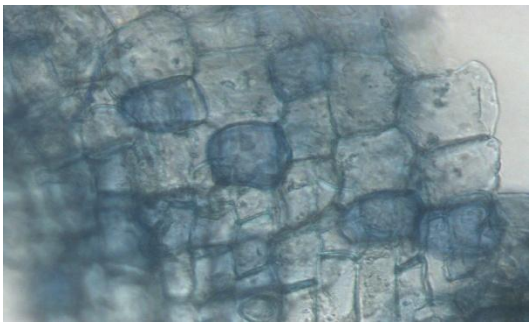
treatment	Height	LA	SD	SWD	yield	Straw
	26.62	22.01	2.4	200	5	188
AMF	25.8	18.78	2.5	180	5	170
	25.15	19.82	2.3	164	3	152
	32.89	26.84	1.8	201	4	190
AMF+25P	34.28	26	2.1	189	3	174
	29.83	27.71	2.3	280	3	267
	31.85	23.23	2.4	200	5	189
AMF+50P	30.42	22.91	2.2	274	6	257
	24.46	25.34	2.3	246	4	235
	29.76	26.18	2.3	163	4	153
AMF +75P	38.5	33.52	2.3	177	4	162
	35.87	20.61	2.3	200	6	187
	30.64	23.05	2.4	195	3	185
AMF+100P	33.44	22.35	2.4	180	4	165
	31.47	33.14	2.4	209	3	200

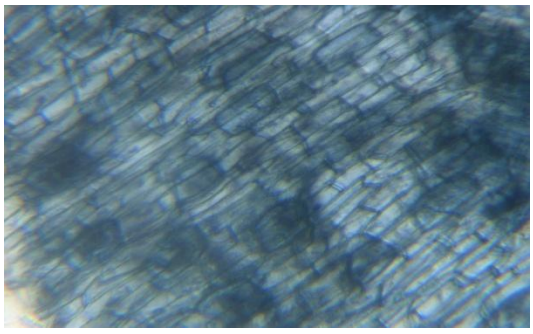
	23.85	28.98	2.3	130	4	121
Control	23.76	28.48	2.1	222	1	163

Nechteff

Treatment	Height	LA	SD	SDW	Yield	straw
	21.68	26.41	2.42	223	3	117
AMF	26.32	24.36	2.6	175	5	116
	28.25	26.18	2.6	181	6	164
	31.99	33.8	2.2	290	8	264
AMF+25P	37.67	35.74	2.2	218	5	224
	32.37	42.33	2.4	202	4	192
	30.14	28.31	2.3	240	7	230
AMF+50P	33.88	25.74	2.2	277	5	272
	30.8	28.37	2	246	7	230
	27.39	29.9	2.3	231	5	213
AMF+75P	29.1	31.98	2.3	223	6	217
	28.62	25.65	2.6	248	5	233
	36.04	30.45	2.2	305	5	294
AMF+100P	39.64	30.97	2	249	4	235
	40.49	43.22	2.3	228	5	218
	24.95	31.87	2.04	222	5	217
control	27.7	28.66	2.4	194	2	185

Appendix III: Pictures of root colonization and spores





Gigaspora