HAWASSA UNIVERSITY
COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES
DEPARTMENT OF BIOLOGY

THE SYNERGISTIC ROLE OF ARBUSCULAR MYCORRHIZAL FUNGI, RHIZOBIUM INOCULATION, AND IN-FIELD RAINWATER HARVESTING TECHNIQUES IN GROWTH AND YIELD IMPROVEMENT OF MAIZE IN YIRBA DUWANCHO DISTRICT, SIDAMA REGIONAL STATE, ETHIOPIA.

BY

DINKNESH DIKALE

ADVISOR: BEYENE DOBO (PhD)

APRIL 2025

HAWASSA, ETHIOPIA

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ADVISOR'S APPROVAL SHEET

This is to certify that the Thesis Proposal entitled *"The synergistic role of arbuscular mycorrhizal fungi, rhizobium inoculation, and in-field rainwater harvesting techniques in growth and yield improvement of maize in yirba duwancho district, sidama regional state, Ethiopia"* 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 **Dinknesh Dikale (GpApMiR/0002/15)**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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Co-advisor	Signature	Date

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We, the undersigned, members of the Board of Examiners of the final open defense by ***Dinknesh Dikale*** have read and evaluated his/her thesis entitled *"The synergistic role of arbuscular mycorrhizal fungi, rhizobium inoculation, and in-field rainwater harvesting techniques in growth and yield improvement of maize in yirba duwancho district, sidama regional state, Ethiopia"* 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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Remark

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LIST OF ABBREVIATIONS

AMF	Arbuscular mycorrhizal fungi
ANOVA	Analysis of Variance
C	Control
CT	Conventional tillage
EC	Electrical conductivity
FAO	Food and Agriculture Organization
FTC	Farmer's training center
GDP	Gross Domestic Product
GHG	Greenhouse gas
GRSP	Glomalin-related soil protein
HCL	Hydrochloric acid
INVAM	Internal Culture Collection of Vesicular Arbiscular Mycorrhizae
IRWH	In-field rain water harvesting techniques
LAI	Leaf area index
MBI	Menagesha Biotechnology Institute
MD	Mycorrhizal Dependency
N	Nitrogen
NM	Non-mycorrhizal
NPSB	Nitrogen, Phosphorous, Sulfur and Boron
NUE	Nitrogen use efficiency
OC	Organic carbon
R	Rhizobium
RCBD	Randomized complete block design
ROS	Reactive oxygen species
TR	Tied ridge
WS	Water stress

ABSTRACT

Various climatic factors, such as temperature and rainfall variability, have a significant impact on rain-fed agricultural productivity, especially in Ethiopia's water-stressed arid and semi-arid regions. The objective of this study was to assess the possible impact of arbuscular mycorrhizal fungus (AMF),Rhizobium® inoculation and in-field rain water harvesting system on maize (Zea mays) growth and production in a moisture-prone (low rainfall) location of Yirba duwancho village of Boricha woreda in Ethiopia. The experiment was laid out in a randomized complete block design (RBCD), with 8 treatments and 3 replication including the control. Consortia AMF inoculums and Rhizobia were used as bio-inoculants and a blended fertilizer in the form of NPSB was used as additional agricultural input. The highest height (140.6cm) growth was recorded for the maize-haricot bean intercropping treatment. This was followed by AMF+F (113.5cm) treatment. Stem collar diameter was bigger (1327mm) in maize-haricot bean intercropping followed by AMF+R (86.9mm). Records for Leaf area index, Shoot weight weight, Shoot dry weight, Root weight weight, and Root dry weight were inconsistent. The better (1853cm^2) Leaf area index was recorded for R treatment. Shoot dry weight was better in AMF+R (830.6g) treatment. However, Root dry weight was higher (69.6g) in AMF+R+F treatment. Maize yield/plot and per hectare was higher for intercropping treatments followed by AMF+F and AMF+R respectively. For all control treatment was recorded the lowest values. Treatments on the Effect of the Suitability of In-field Rainwater Harvesting Technique with Respect to the Width of its Runoff Strips showed Application of Tide-Ride is the best technique to hold water in soil followed by IRWHI. The lower values were recorded for IRWH1.5 and the conventional broadcast treatment. This tells us the broader the width of runoff the least rain water retained in soil. Besides, better root colonization and spore density was recorded for intercropping followed by Sole AMF treatment, while mycorrhizal dependency and maize tissue nutrient uptake was much better in AMF+R treatment. However, in almost all cases the control treatment was inferior. Overall, results of this study suggest that mycorrhizal and rhizobium inoculation and application of infield rain water harvesting techniques enhances nutrient uptake and maximizes maize biomass under low soil moisture conditions. Mycorrhizal plants produced higher biomass, with greater tissue nutrient content than the control plants. These results indicate that establishing efficacious AMF and rhizobium with maize could be an efficient alternative for growers in drought prone areas than relying on fertilizer application and its associated costs and environmental concerns.

Key words: Arbuscular mycorrhizal fungi, in-field rain water harvesting, inoculation, Intercropping, moisture stress, productivity, Rhizobium, yield

1. INTRODUCTION

1.1 Background Information

Water is one of the natural factors that most restricts plant growth in agriculture. Long-term lack of irrigation or precipitation depletes soil moisture and results in a condition known as agricultural drought. Therefore, according to Amiri *et al*. (2015), water stress (WS) is a serious abiotic stressor that has an adverse effect on plant growth and development worldwide. Recent climate change has made water stress more severe, which poses a major challenge to global food security (Behrooz *et al*., 2019). Drought stress is the most significant threat to field crops because it has a direct impact on crop yield and the global economy. Drought stress has a negative impact on various processes, including Seed germination, growth, and final productivity. For plants to thrive, seeds must germinate (El-Badri *et al*., 2021). Furthermore, WS disturbs the photosynthetic process, lowers photosynthesis, and depletes plant water levels, all of which are detrimental to plant growth (Hellal *et al*., 2018).

Additionally, drought stress prevents plants from photosynthesis by causing stomata to close and cell turgor to decrease (Jaleel *et al.*, 2007). One of the most detrimental impacts of WS is the production of reactive oxygen species (ROS), which can damage proteins, membranes, and DNA (Sultan *et al*., 2021). According to Franzini *et al.* (2013), inoculating seeds with Rhizobium has been demonstrated to increase plants' ability to withstand environmental stress. A combination of reduced reactive oxygen species (ROS) production, improved leaf hydration status, facilitated water uptake, reduced ionic imbalance, and improved nutrient acquisition is probably responsible for this increased resilience.

Over 80% of terrestrial plant species have symbiotic relationships with arbuscular mycorrhizal fungus (AMF), one of the most widely spread fungi in the world (Behrooz *et al.*, 2019). Plant development, nitrogen uptake, soil quality, and stress resistance are all enhanced by the symbiotic interaction that develops between plants and AMF (Bi *et al*., 2019). The host plant's resistance to drought stress was significantly increased by the symbiotic interaction between AMF and the plant (Hashem *et al*., 2019). AMF controls WS in plants through a multifaceted process that involves several metabolic pathways and metabolites (Aalipour *et al*., 2020; Huang *et al*., 2020).

AMF improves plant water use efficiency and gas exchange capabilities, increases seedling survival, facilitates water uptake and transportation in the host plant, alters root morphology, regulates hormone levels, and reduces ROS production (Amiri *et al.*, 2015), all of which mitigate the adverse effects of WS. Moreover, AMF generates glomalin, also known as glomalin-related soil protein (GRSP), which acts as a glue to promote the physical entanglement of extraradical hyphae, improving the soil's capacity to retain water and steadying its structure (Santander *et al*., 2017; Gupta, 2020).

Plant growth requires nitrogen (N), according to Nishida and Suzaki (2018). However, only 40–45% of adequately applied nitrogenous fertilizers satisfy plant requirements; therefore, this issue must be resolved to lessen the negative environmental impact (Chien *et al.,* 2016). The overuse of fertilizers raises greenhouse gas (GHG) emissions, especially nitrous oxide (N_2O), which is a major global concern (Abeydeera *et al*., 2019). Worldwide, a number of programs are being implemented to improve the nitrogen consumption efficiency (NUE) of plants. Among these efforts, using microbes has been found to be an excellent technique to boost NUE. AMF can significantly improve the efficiency of N and other nutrients in field crops by increasing the surface area of different microorganisms.

One sustainable crop production method that can empower people in remote areas and help them combat food insecurity is the in-field rainwater harvesting (IRWH) approach (Botha *et al.*, 2003). Hensley *et al*. (2000) and Botha *et al*. (2003) reported a notable improvement in the yield of maize, sunflower, and sorghum cultivated with the IRWH approach based on experimental data from South Africa. Utilizing suitable crop production technology could improvement agricultural productivity in order to mitigate the severe issue of food scarcity and to benefit from Ethiopia's extensive dry land, which makes up over 66% of the country's total land area (Worku Adefires, 2011). Therefore, this study aims to evaluate the effects of mycorrhiza, Rhizobium inoculation, and in-field rainwater harvesting (IRWH) technique on the growth and yield improvement of maize varieties under field conditions.

1.2 Statement of the Problem

The maize (Zea mays) crop was brought to Ethiopia in the sixteenth and seventeenth centuries (McCann, 2005), and it was first introduced to West Africa in the early sixteenth century (FAO, 1992). Six percent of the world's maize crop is produced in Africa, and the majority of it is consumed by humans (Shiferaw Bekele *et al.*,2011). Because maize is as essential in this subregion as rice and wheat are in Asia, governments in East and South Africa have made it their top goal to produce more of the grain (Tallury and Goodman, 2000). Among the major cereals, maize has the lowest cost of calories and protein, making it the primary food security for Ethiopian households. Four main cereals—wheat, sorghum, teff, and maize—account for 1,858 of the daily calories consumed by Ethiopians on average (Shahidur *et al.*, 2010).

In Ethiopia, smallholder farmers cultivate maize mostly. In terms of the quantity of farmers cultivating it as well as crop yield, it is likewise the most significant crop (Shahidur *et al.*, 2010). The majority producers and consumers of maize in Ethiopia are small-scale farmers, who make up around 80% of the country's population (Dawit *et al.*, 2008). Therefore, maize production in 2007–08 was 4.2 million tons, which was 40% more than teff, 56% more than sorghum, and 75% more than wheat production (Shahidur *et al.*, 2010). However, the increase of the maize-producing area and the involvement of numerous smallholders in the crop allowed for this high yield to be attained. Therefore, increases in production and efficiency will lessen the encroachment of population into marginal areas.

Raising productivity through increased input and resource utilization will result in a higher yield and higher return, allowing society to transcend poverty and malnutrition in light of the rapid population growth and the boundaries of available land (Mohammed, 2002). Thus, increases in productivity will prevent people from encroaching on marginal agricultural land (Essa *et al*., 2011). However, the productivity of the agriculture sector is among the lowest and is even trending downward, which is causing a reduction in the amount of cereal consumed per person (Jema, 2008). The lower maize productivity trend in the drought prone Boricha woreda is the current issue of investigation for the way out.

In this research area, why has the productivity of maize production remained low? Drought, global warming, and environmental degradation brought on by anthropogenic activities worldwide, especially in Ethiopia, could be contributing factors to the low yield of the maize crop. Drought has often threatened maize output in Yirba Duwancho, the research area. However, there were years without a sustainable solution discussed.

Sustainable maize production has not been the subject of previous research in the area of inquiry. There was no biotechnological and environment friendly measures taken to conserve soil moisture and increase maize output during damaging drought/low moisture periods. Furthermore, no research has attempted to use biofertilizers, which could raise sustainable maize output while preserving environmental resilience. Adoption of technology and varieties of maize are the subjects of the majority of current research. Therefore, the research region may be able to adapt and use biofertilizers like Rhizobium and arbuscular mycorrhizal fungi with or without combined application of in-field rain water harvesting techniques for the sustainable production of maize. Therefore, the main objective of this study was to investigate the synergistic role of arbuscular mycorrhizal fungi, rhizobium inoculation, and in-field rainwater harvesting techniques in growth and yield improvement of maize under field conditions.

1.3 Objectives

1.3.1 General Objective

The general objective of this research is to investigate the synergistic role of arbuscular mycorrhizal fungi, rhizobium co-inoculation, and in-field rainwater harvesting techniques in growth and yield improvement of maize in yirba duwancho district, sidama regional state, Ethiopia**.**

1.3.2 Specific objectives

1) To evaluate the influence of sole AMF, rhizobium co-inoculation, and combined application of inorganic fertilizer on growth and biomass yield of maize plants.
2) To evaluate the influence of AMF and Rhizobium co-inoculation on nutrient uptake of maize plants.
3) To compare the AMF and Rhizobia inoculated treatments with maize-haricot bean intercropping.
4) To investigate the rate of root colonization and spore density of maize plants inoculated with AMF, Rhizobia, and NPSB.
5) To evaluate the suitability of in-field rainwater harvesting technique with respect to the width of its runoff strips.

1.3.3. Research questions

1) What is the influence of sole AMF inoculation, AMF and rhizobium inoculation, and combined application of inorganic fertilizer on growth and biomass yield of maize plants?

2) What is the influence of AMF and Rhizobium inoculation on the nutrient uptake of maize plants?

3) What is the difference in between AMF and Rhizobia inoculated treatments and Maize-Haricot bean intercropping?

4) What is the rate of root colonization and spore density of maize plants inoculated with AMF, Rhizobia and NPSB?

5) How suitability is the in-field rainwater harvesting techniques with respect to the width of its runoff strips?

1.4 Significance of the study

In terms of productivity and cultivated area, Maize (*Zea mays* L.) is one of the most significant cereal crops in agricultural ecosystems. Due to the industrial use of maize-byproducts, the production of biofuels, and the need to supply food for the world's expanding population, there is an increasing demand for maize, and this trend is expected to continue. Therefore, in order to increase sustainable maize productivity, a novel biotechnology-strategy is needed. Utilizing low-cost agricultural inputs and bio-inoculants, such as arbuscular mycorrhizal fungi, as a biofertilizer, is one of these techniques. Many aspects of plant life are aided by arbuscular mycorrhizal fungi, including improved nutrition, growth, stress tolerance, and disease resistance. AMF also plays an important role in soil structural stability and micronutrient concentration Enhancement. As a result, the findings of this study will provide new information to the agricultural community on methods of sustainable maize production while maintaining proper environmental resilience. The findings may also be useful for researchers, agricultural extension offices, and the regional and national agricultural communities.

2. LITERATURE REVIEW

2.1 Effect of water stress on plants

Low-moisture-contents have a significant impact on Maize productivity, especially in semi-desert and desert regions as well as Mid-land areas, that are vulnerable to Drought. Due to physiological damage and metabolic alterations, this impairs plant processes, which in turn impacts crop output and yield quality. Drought produces tissue-dryness and osmotic stress because there is less or no water available in the root zone, which reduces the amount of water absorbed by the plant roots. Numerous Alterations in Gene expression are triggered by tissue-water-deficiency-stress. Consequently, a large number of metabolites build up within the cell, raising its water potential and preventing roots from taking up water. One of the main hormones that control signaling pathways for the synthesis of metabolites and gene expression in physiological processes is abscisic acid (ABA), which builds up in response to osmotic stress.

Under conditions of water stress, the electron transport mechanism of cell organelles is compromised, and electrons from the plasma membrane, peroxisomes, mitochondria, and chloroplasts overflow into the cell (Bhattacharjee, 2019). Overproduction of reactive oxygen species (ROS) such as singlet oxygen ($^1O_2$), hydrogen peroxide (H_2O_2), hydroxyl radical ($OH^{\cdot}$), free radical superoxide anion ($O2^{-}$), and malondialdehyde (MDA) is caused by this imbalance in electron transport. ROS buildup results in oxidative stress, which in turn disturbs regular metabolism through oxidative damage, including protein oxidation, lipid peroxidation, and damage to nucleic acids, which may ultimately cause cell death (Kusuvaran *et al.,* 2016; Sharma *et al*., 2012).

In order to stop water loss through transpiration, plants respond to water stress by closing their stomata. According to Okabe *et al*. (2014), stomata closure lowers CO_2 influx and negatively affects plants' ability to photosynthesize, which in turn affects plant growth and production. Reduced soil moisture during a drought also limits the flow of nutrients in the soil matrix and, consequently, the roots' ability to absorb them. Furthermore, because of reduced transpiration rate, changed membrane permeability, and malfunctioning membrane-active transporters, water stress impedes the transfer of mineral nutrients from the root surface to shoots (da Silva *et al.*, 2011).

However, plant genetic potential, development stage, drought intensity, and duration all affect how detrimental a drought is to plant growth and yield (Aroca and Ruiz-Lozano, 2012; Stagnari *et al.*, 2016). Furthermore, studies have demonstrated the impact of plant-associated microorganisms, such as arbuscular mycorrhizal fungi (AMF), on a plant's ability to efficiently allocate water from the soil when there is a water deficit. Furthermore, AMF influences multiple physiological processes that increase plant tolerance to drought stress (Zou *et al.*, 2018; Zhang *et al.*, 2018a). The potential of AMF and rhizobium to boost agricultural output during drought conditions was examined in this study through a discussion of the different defense mechanisms used by rhizobium-plant and AMF-plant symbiosis.

2.2 Arbuscular mycorrhizal fungi (AMF)

Recognized as one of the most significant mutualistic symbioses on Earth, the symbiosis between AMF (phylum Glomeromycota) and the roots of terrestrial plants extends back 450 million years. Remarkably, almost 80% of plant species are able to coexist peacefully with AMF. Smith and David (2010) and Smith *et al.* (2009) have noted that the AMF colonization density is contingent upon AMF taxa, plant preference for AMF species, and the environments in which the symbionts have developed. Mycorrhizae are fungus and plant roots that work together symbiotically. The hyphae of the AMF, which are tiny, tubular filaments that pierce cell walls and surround themselves in the cell membrane of cortical cells of plant roots, are what make it an endomycorrhiza. There are two stages of colonization in a well-established AMF and plant symbiosis: the internal phase and the exterior phase. Mycelium, a mass of hyphae, is formed by fungi during the internal phase, when they colonize the root cortical cells. Oval and branching structures known as vesicles and arbuscules, respectively, are formed by mycelium. For AMF, vesicles serve as food and lipid storage organs. The site of the nutrition exchange between the fungus and the host is an extremely branching arbuscule fashioned like a tree. The fungus grows heavily branched extraradical hyphae (ERH) in the soil during the external phase. The fungal structure's hyphae, which have a diameter of around 2 to 5 µm and are longer than plant roots, allow them to penetrate deeper into soil micropores than plant roots can (Smith and David, 2010).

AMF rely on host plants for nourishment throughout their lives, including lipids and carbohydrates (Parihar *et al.*, 2020). Up exchange, AMF increases the host's capacity to take up water and nutrients from the soil by expanding the root-absorbing area and making plants more resilient to unfavorable environmental circumstances (Diagne, 2020). Numerous investigations have confirmed that, even though water stress has a detrimental effect on AMF colonization, AMF enhances plant growth, production, and quality while also improving plant resistance to drought stress (Ouledali *et al.*, 2018; Meddich *et al.*, 2015). Nonetheless, AMF demonstrates functional diversity because of the plant mycorrhizal dependence, plant preference for individual AMF, the environment, and functional specialization among AMF (Thirkell *et al.*, 2020).

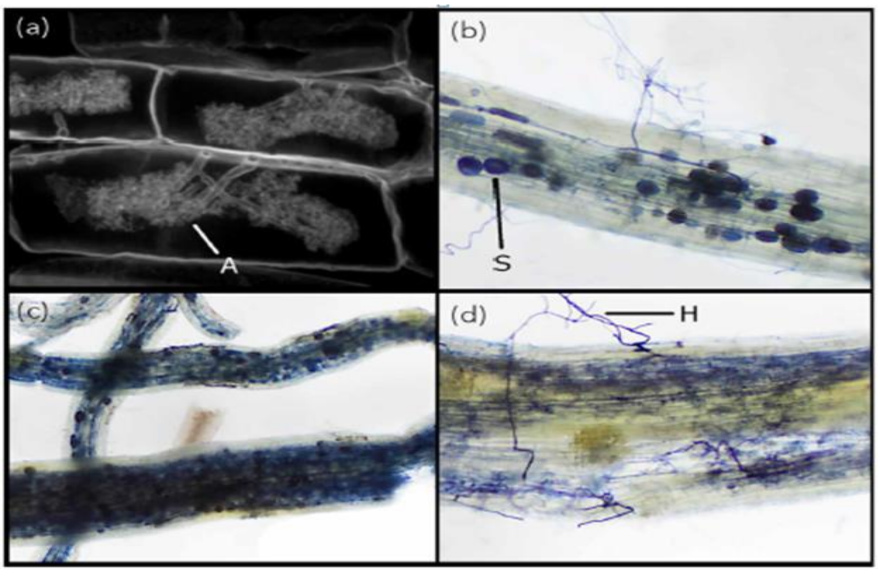


Figure 1 a) Mycorrhizal arbuscules inside Pisum sativum root cell, (b-d) colonized maize roots with many intraradical spores and extrarardical hyphae; A= arbuscules; S=Spore; H=hyphae (source, Peterson and Missicotte, 2004).

2.3 AMF mediated water stress tolerance in plants

Because AMF improves plant performance and soil health, it increases crop productivity and sustains ecosystems. By enhancing soil health, changing the physiological, morphological, and biochemical traits of the plants, as well as the physiochemical features of the rhizosphere, this symbiosis aids plants in adapting to drought stress.

2.4 AMF-mediated changes in soil quality

Good soil quality is indicated by features such as aggregate stability, soil microbial diversity, water-holding capacity, and good soil structure (Maikhuri and Rao, 2012). The process of arbuscular mycorrhization is essential for enhancing soil quality. By applying physical stress, reorienting clay particles, and preserving air-filed soil porosity, the extraradical hypha (ERH) of the AMF binds, holds, and compresses the soil particles. Soil biomass is increased by both the ERH itself and its exudates. The main exudates generated by AMF are glomalin and glomalin-related soil proteins. Glomalin is a heat- and water-stable glycoprotein that is hydrophobic and/or the rhizosphere's physiochemical characteristics. According to Rilling and Mummey (2006), the hydrophilic fungal wall can stick to the hydrophobic soil surface once hydrophobic GRPS has coated it. Enhancing soil aggregate stability, it functions as a glue to bind soil particles together (Cornejo *et al*., 2008a; Rilling and Mummey, 2006). A larger capacity to keep water in the soil (Auge, 2001), store nutrients (Rilling and Daniel, 2006), and allow root penetration are all attributed to improved soil structure and higher organic matter buildup. Through AMF induced root exudates, AMF symbiosis also modifies the diversity and organization of rhizospheric microbiota (Vázquez *et al*., 2000).

There is a direct correlation between soil quality/health and plant growth and productivity as soil plays vital functions in plant growth. AMF improves soil quality by increasing water-stable soil aggregates, adding biomass, and reorienting the soil aggregates. Therefore, AMF indicates the potential to improve plant health and productivity via improving soil quality (Maikhuri and Rao, 2012).

2.5 AMF mediated improved nutrient and water status of plants

The AMF symbiosis promotes plant water and nutrient status under water scarcity situations by enhancing water and nutrient absorption (Barros *et al*., 2018). Because ERH increases the surface area of the AMF plants, they are able to overcome the water and nutrient depletion zone in the rhizosphere and absorb more water and nutrients (Wu *et al*., 2013). Moreover, depending on the size of the soil pores, mycorrhizae can alter the hyphal diameter, enabling them to enter pores that are closed off to plant roots because of their significantly bigger diameter (Drew *et al*., 2003). Apart from ERH, AM colonization results in an increase in the length and density of root hair by generating and elongating lateral roots, which in turn increases the surface area and volume of the host root. Consequently, the host's increased digging in the soil (Zou *et al*., 2017).

It's interesting to note that in this symbiosis, some transporters absorb and transfer both organic and inorganic nutrient forms from the soil to the plant (Kikuci *et al.*, 2016). AMF symbiosis promotes the uptake of nutrients, particularly those that are less mobile in the soil like magnesium, potassium, and phosphorus. Furthermore, AMF improves the status of plant nitrogen, a highly mobile nutrient in the soil (Garg and Bhandari, 2016). Moreover, the ERH turnover raises the availability of plant minerals and serves as a source of minerals (Riling *et al*., 2001). However, a variety of responses to nutrient uptake, including positive, negative, and no effect, are seen in combinations of AMF species, plant (inter/intra-species), and environment (El Amerany *et al*., 2020).

According to Satander *et al*. (2017), AM symbiosis increases plants' water use efficiency, which is determined by dividing their net photosynthetic rate by their leaf transpiration rate. Furthermore, increased hyphal and root water absorption rates are caused by upregulating the host and fungal hyphae plasma membrane intrinsic proteins, aquaporin (AQP), gene expressions (Li *et al*., 2013). These aquaporin proteins function as water channels to control water flow and are crucial for root cell osmoregulation. Above all, during water shortage conditions in AM plants, hyphal and root water absorption is faster than in adequate water situations because less resistant channels for water radial flow across the cortex are activated (Zhang *et al*., 2018a; Quiroga *et al*.,2017).

Reduced hyphal water redistribution is another element contributing to the better water status of AM plants. The hydrophobic sheath of glomalin on the AM hyphae protects nutrients and water loss while transporting from the hyphal tip to the plant and vice versa (Zou *et al.*, 2018). Increased water status of AMF plants also aids plant productivity by modulating molecular responses under water-scarce conditions, such as oxidative damage mitigation.

2.6 The Role of AMF in Mitigating Oxidative damage

According to Zou *et al*. (2021) oxidative damage is caused by reactive oxygen species (ROS) that are produced under drought stress and are referred to as oxidative burst. In low concentrations, ROS functions as a signaling molecule to initiate plant responses to drought and is the first reaction of plants to water stress. According to Miller *et al.* (2010), oxidative damage to the host occurs when the concentration of ROS beyond a certain threshold. Since ROS plays a variety of functions, it's important to maintain its level below what could lead to oxidative damage and to prevent its total eradication (Zou *et al*., 2021).

AM plants have an oxidative burst that is mitigated by increased enzymatic and no enzymatic antioxidants. Using their reducing properties, direct ROS scavenging abilities, or signaling events to modulate cellular ROS levels, antioxidants regulate defense mechanisms and shield plants from oxidative damage. According to studies conducted by Zou *et al*. (2015), Bahadur *et al*. (2019), mycorrhizal plants produce less H_2O_2, less O_2, and less MDA value than non-mycorrhizal plants. Additionally, the generation of MDA value is also lower in mycorrhizal plants. Zou *et al.* (2021) reported damage.

Fatty acid (FA) and polyamine (PAS) synthesis are both increased by mycorrhization. Under stressful circumstances, PAs and FAs alter antioxidant systems. For instance, higher PAs lessen the buildup of H_2O_2 and the degradation of the electron supply system. Plant cell membrane integrity, stability, and function are significantly regulated by PAs and FAs. Furthermore, higher PAs during mycorrhization enhance the growth of the host roots and N assimilation, strengthening the host's resistance to drought stress (Wu *et al*., 2013).

According to Zou *et al.* (2021), the AMF has the potential to reduce oxidative damage to root cortical cells that do not contain arbuscules by partially limiting oxidative burst to these cells.

However, numerous studies demonstrate that the AM root also causes the production of ROS, particularly in the root cortical cells that contain mycorrhizal. Due to the dynamic nature of ROS levels during fungal colonization, this phenomenon is essential to the process. Carotenoids, SOD, and CAT rapidly remove the H_2O_2 produced in mycorrhizal-containing root cortical cells, which ensures the first fungal colonization (Segal and Wilson, 2018).

2.7 AMF and Phytohormones

Plant hormones known as phytohormones are essential to the growth of plants. Additionally, they contribute to the growth of the AMF symbiosis with plant roots (Ludwig-Müller, 2010). Strigolactones (SLs) are able to create the necessary signals for AMF spore germination and the start of the host-AMF infection process. Additionally, SLs are essential for a number of symbiotic growth processes, including hyphal branching, shoot branching, and root development (Mostofa *et al.*, 2018). Cytokinins (CK) and jasmonic acids (JA) also influence AMF colonization. At low concentrations, JA promotes AMF colonization and development, while at high concentrations, it inhibits it. Abscisic acid (ABA) levels rise in response to increases in JA, whereas ABA levels fall in response to decreases in JA (de Ollas *et al*., 2016). Plant phytohormone production is altered by water deficiency stress. According to Oliudeli *et al.* (2019), ABA levels rise while SLs levels fall during stressful situations (Ruiz-Lozano *et al.*, 2016). Because ABA builds up quickly and stimulates plant responses to stress, it is referred to as the stress hormone. For the majority of plants, ABA modulates leaf development and stomatal closure to minimize transpiration-related water loss. Leaf hydraulic conductivity is lowered by increased ABA because it inhibits AQP activity through the ABA-dependent signaling pathway.

2.8 Osmotic adjustment by AMF in Plants

The most important cellular reaction to reduced osmotic potential in plants under water stress is likely osmotic adjustment (OA), which is achieved by raising cellular solute concentration. There are two categories of solutes: inorganic solutes (Ca^{2+}, K^{+}, Mg^{2+}) and organic solutes (aspartic acid, protein, sugars, proline, and glycine beta) (Wu *et al.*, 2013). A higher concentration of solutes preserves the water potential of plants, which helps them avoid dehydration (Kiani *et al.*, 2007) and absorb more water from the soil when growing crops (Chimenti *et al.*, 2006). Under water stress, the OA maintains the stability of macromolecular structures and subcellular membranes.

OA under water stress is improved by AM colonization, according to numerous researches (Wu *et al.*, 2013). Under drought stress, the osmotic pressure of the vacuole and AM colonization increase the absorption of K^{+} ions, which are crucial for cell turgor (Evelin *et al.*, 2012). Higher net accumulation of proline, non-structural carbohydrates, Ca^{2+}, K^{+}, sucrose, and fructose in roots and leaves, and glucose in plant roots has been detected in AM plants compared to non-AM plants under water stress (Wu *et al.*, 2013). Proline, one of the main osmoprotectants, was found to be less concentrated in certain AM under water stress than in non-mycorrhizal plants. It could be as a result of the symbiosis creating better water conditions (Wu *et al.*, 2013). Thus, by preserving OA, mycorrhization aids in yield maintenance.

2.9 AMF mediated crop Photosynthesis

Due to stomatal closure and membrane damage, drought inhibits photosynthesis, which in turn restricts crop development (Farooq *et al.*, 2012). Under water stress, AM colonization has demonstrated an increase in plant photosynthesis. Mycorrhizal plants benefit from enhanced photosynthesis due to both stomatal and non-stomatal causes. Increased water content protects guard cell turgidity, which is necessary for the opening and closing of stomata. Therefore, greater water usage efficiency of AM plants maintains higher tissue water status and better stomatal conductance. Furthermore, in many situations, AMF symbiosis also increases the number of stomata (Chitarra *et al.*, 2016). Transpiration, CO_2 intake, and assimilation are all improved by increased stomatal conductance (Auge *et al.*, 2015; Yang *et al.*, 2014).

Enhanced levels of N, Mg, and P in AM plants also support photosynthesis. P is an essential part of ATP, the "energy unit" of the plant cell, whereas N and Mg are essential parts of chlorophyll. In the photosynthetic cycle, ATP transmits energy while chlorophyll absorbs the sunlight needed for photosynthesis (Atkin *et al.*, 2000). Mycorrhizal plants store antioxidants called osmolytes, which shield the photosynthetic machinery from oxidative damage. For instance, by scavenging singlet oxygen, the synthesis of carotenoids (antioxidants) shields the photosynthetic machinery against deterioration (Satander *et al.*, 2017). The carbon balance and nutrient uptake efficiency of the plant are enhanced by stimulated photosynthesis in symbiosis (Barros *et al.*, 2018).

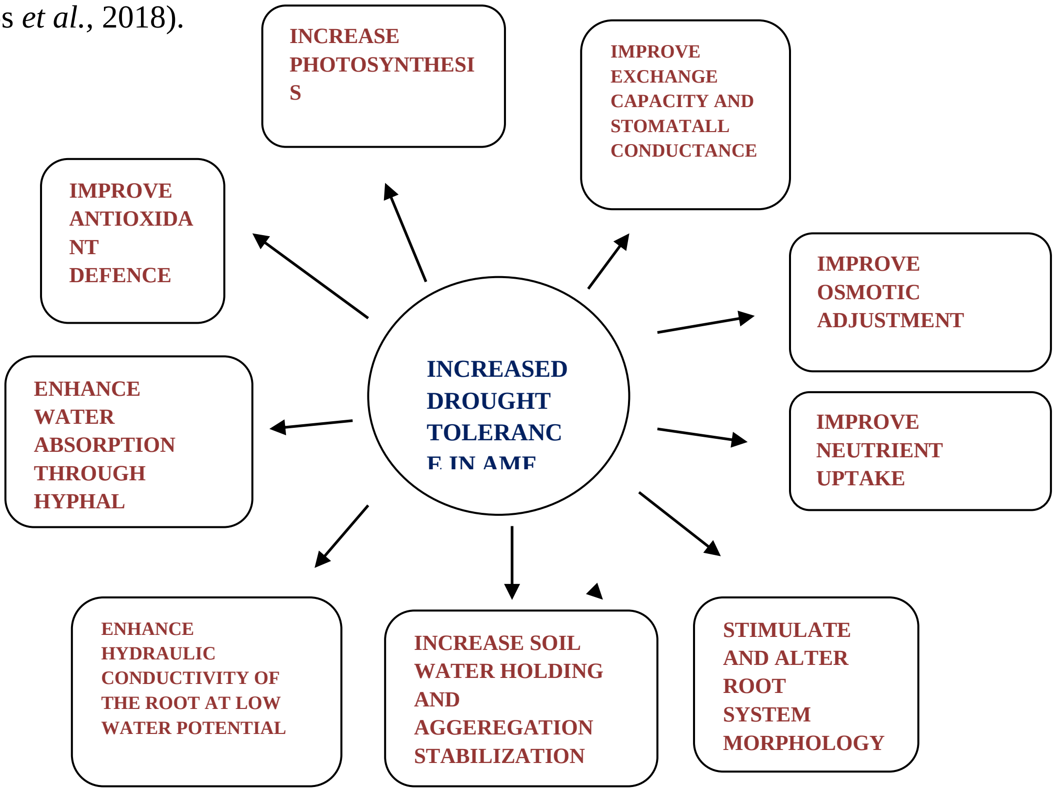


Figure 2. Mechanisms involved in increasing drought tolerance in AMF associated plants. *(Bahadur et al., 2019)*

2.10. Characteristics of Rhizobia

The term "symbiotic nitrogen fixation" refers to the process by which rhizobia, a diverse group of soil-dwelling bacteria, convert atmospheric nitrogen into a form that plants can use in exchange for a source of carbon from their plant host. Rhizobia can form symbiotic relationships with specific plant species, mainly legumes, leading to natural nitrogen fixation (Ledermann *et al.*, 2021).

Rhizobia are Proteobacteria-phylum members that are Gram-negative bacteria. They fall under the subclasses of Betaproteobacteria and Alphaproteobacteria specifically (Helene *et al.*, 2022; Delajudie *et al.*, 2019). Rhizobia have an unknown number of species because new ones are always being found and identified. There are more than 150 recognized species in the genus Rhizobium alone, and there are many more species in the other genera in the Rhizobiaceae family. Furthermore, numerous unidentified and uncultivated species have been found in various settings (Chen *et al.*, 2021).

Many bacterial genera, including Bradyrhizobium, Azorhizobium, Mesorhizobium, Ensifer (Sinorhizobium), Neorhizobium, Pararhizobium, and Allorhizobium (Jaiswal *et al.*, 2021), are included in the Rhizobiaceae family and are distinguished by their capacity to create intracellular, N_2-fixing infections in a wide range of plant hosts. This characteristic is complex and frequently coevolved closely with the particular plant hosts that it inhabits (Wardell *et al.*, 2022). Rhizobia can also form non-specific associative relationships with other plant roots (non-legumes) without developing nodules. These associative interactions between plant roots and bacteria are very important because many crops show increased yields after inoculation (Mehboob *et al.*, 2009).

It has been demonstrated that rhizobia promote root growth, shield plants from diseases found in the soil, ***increase stress tolerance, and create systemic resistance***. Mechanisms include mineral solubilization and the synthesis of plant growth hormones like auxin, gibberellin, and cytokinin are used to accomplish this. In addition to their capacity to fix nitrogen dioxide (N_2) in legumes, rhizobia function as plant growth-promoting rhizobacteria (PGPR) and can lower the susceptibility to disease. The production of phytohormones, the reduction of ethylene levels in roots through ACC deaminase, and the release of compounds that support ***induced systemic tolerance (IST)*** are some of the mechanisms by which rhizobia manage biotic and abiotic stresses that are the subject of increasing amounts of research (Jaiswal *et al*., 2021).

Though rhizobia must compete with a variety of bacteria for root colonization and with other suitable rhizobial strains for nodulation, host plants can influence the composition of the root microbiome. The complex characteristic of competitiveness is influenced by a number of biotic and abiotic factors, including host-symbiont association, strain- or plant-intrinsic factors, the production of exopolysaccharide, and the ability of rhizobia to catabolize a variety of substrates (such as myo-inositol, glycerol, arabinose, homoserine, or erythritol) (Ledermann *et al.,* 2021).

2.11 The In-field Rain water Harvesting (IRWH) technique

Rainwater is typically used most extensively in agriculture. Water scarcity, however, has an impact on rain-fed agriculture and directly jeopardizes the livelihood of millions of people, especially in emerging nations and Sub-Saharan Africa. For instance, almost 70% of the rainfall in South Africa is utilized to generate food, natural fibers, and forestry goods, employing a sizable population in a productive manner (Botha *et al.,* 2003). According to FAO (2000), rainfed agriculture provides 60% of the world's food. According to Worku (2006), over 80% of Ethiopians are small-scale farmers, and over 95% of the country's crops are grown using rainfed methods. The country’s economy depends greatly on this sector which provides about 90% of the GDP (Worku, 2006). The amount and distribution of the rainfall is generally unreliable for sustainable crop production in the arid and semi-arid regions. These areas also experience high runoff and evaporation losses which aggravate the problem of water stress in crop production.

Where water is scarce, the need for developing rainwater management skills to improve water-use efficiency is increased. Population growth necessitates an increase in food supplies, requiring the use of marginal land for food production. Water harvesting can address this problem by increasing the water available to crops under rain-fed conditions, and thereby increasing yields. Ethiopia is one of the most seriously affected countries by the unsatisfactory level of food security and sustainability. In South Africa, and in other developing countries, levels and incidence of poverty tend to be disproportionately high amongst the rural population. The majorities of the poorest rural households reside in arid and semi-arid regions, depend on rain-fed agriculture, and frequently cultivate on marginal or delicate soils. Lack of sufficient water in arid regions is a significant barrier to efforts to expand other business ventures and boost agricultural output. Nonetheless, a number of agricultural scientists concur that it is feasible to boost and maintain agricultural output in semi-arid regions by utilizing suitable production methods, particularly those that promote the preservation of soil and water resources (Hatibu, 2002). Kronen (1994) emphasizes the necessity of developing water harvesting and water conservation strategies in relation to smallholder agriculture demands in the semi-arid parts of the Southern African Development Community (SADC).

Rainfall distribution in the arid and semi-arid regions of Ethiopia is erratic and low in amount resulting in soil water deficits at some critical stages of crop growth (MoA, 2000). This leads to lower crop yields and sometimes total crop failure. Hence, crop variety selection and plant breeding alone become unsuccessful strategies for the achievement of optimum crop production and sustainability in the arid and semi-arid regions (Worku, 2006). It is, therefore, necessary to seek for suitable water conservation techniques that could combat the low soil water storage problem and improve rainwater productivity (RWP). These strategies are particularly important for critical crop growth stages, as well as for the whole growing period.

Maize (*Zea mays* L.) is one of the food crops grown in the Sidama region. It is estimated that about 54% of maize in Boricha woreda of Sidama region is grown in intercrop pattern. However, drought causes a great deal of instability and uncertainty in crop production in this region. Therefore, improved resource management system that allows effective conservation and utilization of the meager rainfall that ensures sustainable production is a requirement.

According to Reddy and Georgis (1993), the most efficient and cheapest way of conserving rainfall is to hold it *in-situ*. There are wide ranges of *in-situ* water harvesting techniques known throughout the arid and semi-arid regions of the world (Critchley and Reij, 1989; FAO, 1994). One of such techniques is the in-field rainwater harvesting (IRWH) technique. According to Biazin *et al*., (2012), in-field rainwater harvesting is defined as the process of concentrating precipitation through runoff and storing it for beneficial use. The IRWH systems are micro-catchments using sheet flow from short slopes within the cultivated fields. The systems maximize infiltration of rainfall by concentrating the runoff from in-field strips (micro-catchments) to a cultivated crop. The IRWH technique reduces runoff from field to zero by converting it to stored soil water, and hence lead to increased yields (Hensley *et al.*, 2000). The technique is simple because it can be done with locally available tools and easy to farmers to perform.

In-field rainwater harvesting technique is a sustainable crop production tool that has the ability to empower people in rural villages and enable them to fight food insecurity (Botha *et al.*, 2003). From experimental data in South Africa, Hensley *et al.* (2000) and Botha *et al.* (2003) reported a significant yield increase of maize, sunflower and sorghum grown using the IRWH technique. To alleviate the serious problem of food scarcity and to get benefit from the vast area of the dry lands of Ethiopia, which accounts for more than 66% of the total land mass (Kidane *et al.*, 2001), crop yield should be increased by using appropriate crop production technologies.

3. MATERIALS AND METHODS

3.1 Description of the study area

The study was conducted in Boricha woreda, **yirba duwancho village** of Sidama regional state with geographical coordinates of 6°55′538″N and 30°25′771″E with an altitude of 1996 meters above sea level. Geographically, it shares borders with Loka Abaya Woreda to the south, the Wolayita Zone to the west, the Oromiya region to the northwest, Hawassa Zuria Woreda to the northeast, Shebedino Woreda to the east, and Dale Woreda to the southeast. Comprising 39 Kebeles, three of which are urban and the remaining ones are rural, it is estimated to be 588.05 square kilometers in total size. It reaches from the lowest point, 1320 meters above sea level, to 2080 meters above sea level, northeast of the mouth of a Bilate River branch (Bechaye, 2011). Maize, haricot beans, coffee, horticultural crops, and teff are the main crops in terms of coverage (CSA, 2007). The temperature of the woreda ranged from 18^0c – 32^0c annually. The woreda is also found under the Great Rift Valley region. The soil type of the woreda mostly comprises 80 percent sandy loom black soil and 20 percent clay soil. Soil for our study site, Yirba Duwancho, is Redish with clay-loam texture.

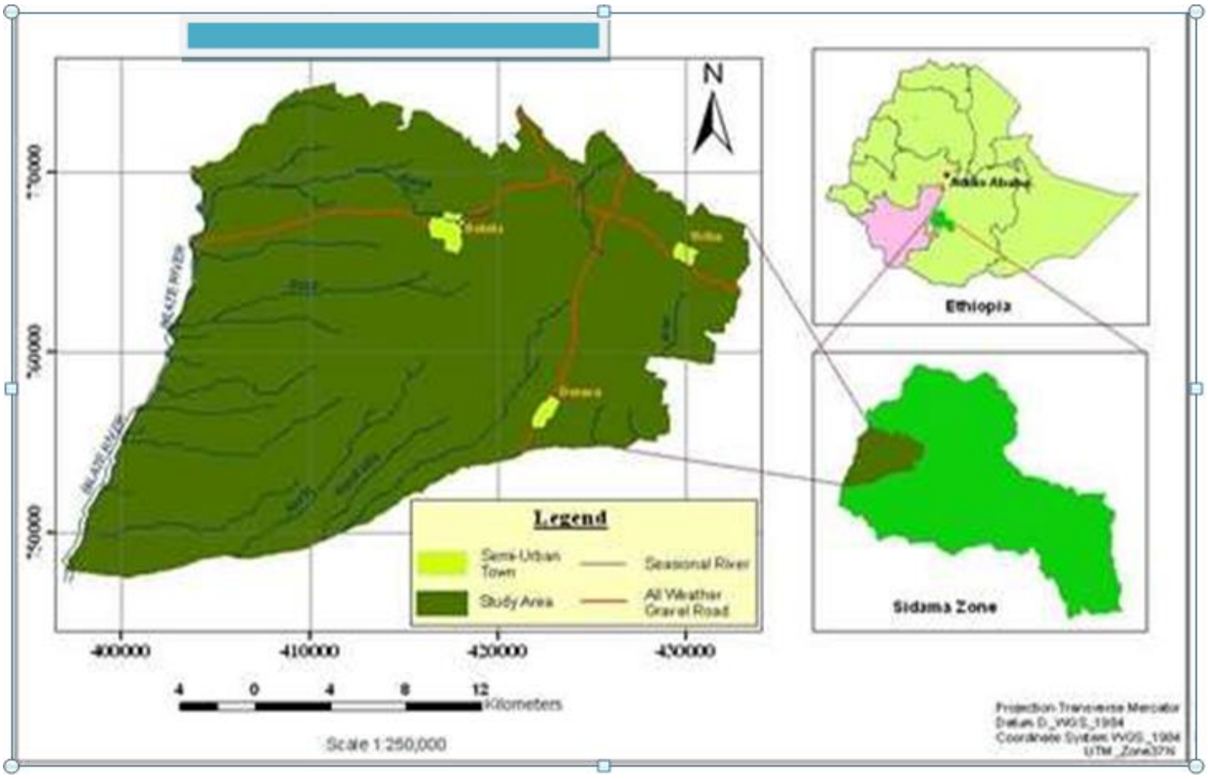


Figure 3. Map of Boricha Woreda

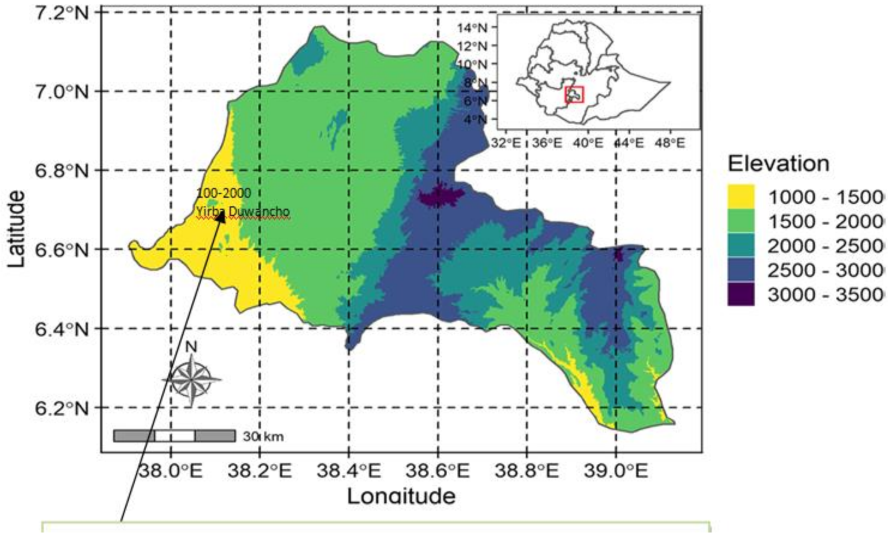


Figure 4. Map of Yirba Duwancho

3.2 Metrological data collection

Secondary meteorological data of rainfall and temperature of the experimental sites were collected from a nearby meteorological station and during the cropping seasons in Yirbas'

Duwancho village. Data on days to emergence, flowering, and maturity of maize was collected when 50% of the plants in a plot reached the respective 50% phenological stages.

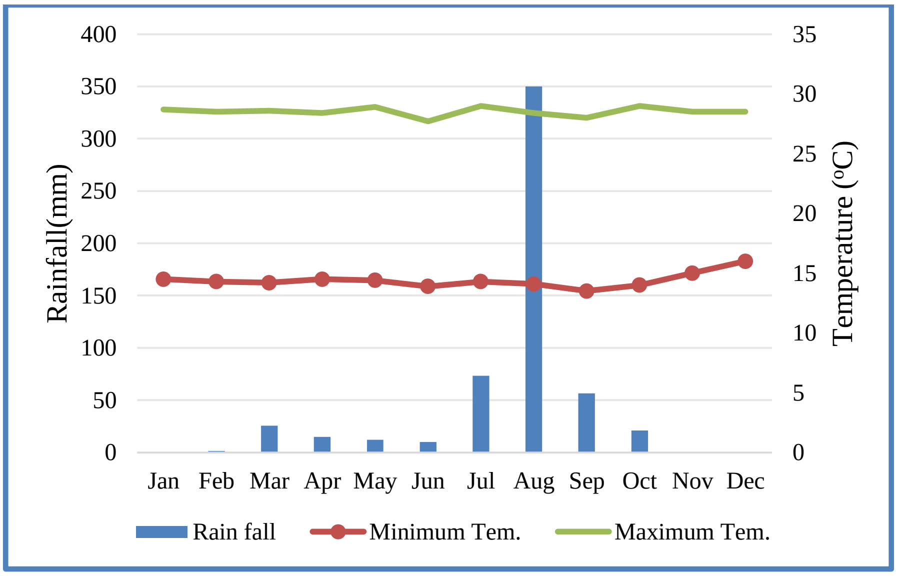


Figure 5. 10 Years Annual Average Rainfall, Maximum and Minimum Temperature

3.3 Biological material

The maize seed variety Ethio.BH.140 was obtained from the Southern Agricultural Research Centre for use in the experiment. A consortium of *arbuscular* mycorrhizal fungus (AMF) isolated (*Gigaspora rosea and Rhizophugus clarus*), from crops and grasslands was obtained from the Hawassa University biology department and used as a bioinoculant. Furthermore, the commercial Rhizobial inoculants isolate from haricot bean was obtained from Menagesha Biotechnology Institute (MBI), and blended chemical fertilizer in the form of NPSB was bought from Hawassa agricultural inputs shop.

3.4 Soil sample collection

1 kg of soil sample from a depth of 0 to 20 cm was collected from four locations in the field to saw maize. Following collection, soil samples were dried at room temperature. Then the samples were pooled and preserved in polyethylene bags until analysis. Finally, before the

experiment, roughly 250 gm of soil was collected and prepared for the analysis of physicochemical properties. The dry soil samples were ground using mortar and pistil and passed through a 2 mm porous sieve, and then the soil physicochemical parameters were analyzed using standard procedures.

3.5 Experimental design, AMF and Rhizobium inoculation treatments

The field experiment was organized in a randomized complete block design (RCBD) (Tables 1 and 2), and the experiment was started in March of 2016 E.C. in the farmers training center (FTC) of Yirba Duwancho village of Boricha district. The experimental design is shown in Tables 1and 2 below.

Table 1. Treatments

Treatments	Description	Replications
T1	AMF(arbuscular mycorrhizal fungi)	3
T2	Rhizobium ®	
T3	NPSB(blended fertilizer)	
T4	AMF +Rhizobium	
T5	AMF+NPSB	
T6	AMF+Rhizobium+NPSB	
T7	Maize-Haricot bean intercropping	
T8	Control	

3.5.1 Experimental design

The experimental design was laid in a randomized complete block design (RCBD) as shown below to study the effect of bio-inoculants and fertilizer application on maize production in rain-prone Boricha district at Yirba Duwancho Farmers Training Center (FTC).

Table 2. Experimental design for inoculation

RBCD							
C	**AMF+R+F**	**Inter**	**AMF+R**	**AMF**	**R**	**AMF+F**	**F**
AMF	**F**	**R**	**AMF+F**	**Inter**	**AMF+R**	**C**	**AMF+R+F**
AMF+R	**AMF**	**F**	**AMF+R+F**	**R**	**C**	**Inter**	**AMF+F**

Key: *AMF-arbuscular mycorrhizal fungi, R-Rhizobium, F-blended fertilizer (N-nitrogen, P-phosphorus, S-sulfur, and b-boron), Inter-intercropping, C-control*

3.5.2 Data Collection

Plant height, shoot and root wet weight, shoot and root dry weight, leaf area index, and stem diameter were all measured using appropriate methods. Plant height was measured one inch above the soil surface to the tip of the juvenile shoot and measured in centimeters (cm). The sliding micrometer was used to measure the stem diameter (mm). Shoots and roots were separated, washed with tap water to remove adherent debris, dried in the glasshouse, and then weighed periodically using a digital scale until constant weight was achieved. At harvest, the leaf area index (LAI = L x W x 0.75) was measured using a standard meter according to Pal and Murari (1985) and multiplied by a correction factor.

3.6. AMF and rhizobium inoculation and experimental procedures on soil-water holding capacity using in-field rain water harvesting techniques.

AMF inoculum production was carried out in association with the host plant *Sorghum bicolor* in pot culture. Consortia of AMF morphospecies isolated from crop and grasslands by wet sieving and decanting technique according to Gredman and Nicolson, 1963 were multiplied in the roots of Sorghum (*Sorghum bicolor)* plants.

The plants were inoculated and allowed to grow for three months, after which the roots were persevered, and the substrate containing root fragments, mycelium, and spores was collected, air dried, and used as a crude inoculum. The trials were divided into four steps: (1) Healthy seeds of maize (*Zea mays)* Ethio.BH.140 were selected, and 2 seeds were sown in a hole in which 25 g of AMF inoculum was previously added. As mentioned above, fresh rhizobium isolate was obtained from Menagesha Biotechnology Institute (MBI), Addis Ababa. The purpose of this trial is to evaluate the potential of rhizobia in the provision of fixed nitrogen to the nearby maize plant. (2) Blended inorganic chemical fertilizer was also applied in corresponding treatments in triplicate plots. (3) The third trial was an assessment of uninoculated maize-haricot bean intercropping. The purpose of this trial is to compare the output of uninoculated maize-haricot bean intercropping on growth parameters under test.

(4) The 4th experiment was to study the capacity of the field soil moisture holding capacity. This study focused on the in-field rainwater harvesting capacity of the field soil in the Yirba

Duwancho farmers' training center (FTC), where the inoculation study has been done. This is to verify whether plant productivity in inoculated trials has really been benefited from the inoculation of AMF and rhizobium. In light of this, the expectation that, particularly AMF inoculation, increases soil-water holding capacity and supports sustainable productivity of maize in drought-prone fields of the study site is expected to be verified. In this study, therefore, in-field rainwater harvesting techniques with respect to the width of their runoff strips were studied.

In this study the same maize variety mentioned above was used. The treatment was comprised of four *in-situ* water harvesting techniques. The four water harvesting treatments were:

i. In-field Rainwater harvesting with 1m wide runoff strip (IRWH1),
ii. In-field Rainwater harvesting with 1.5 m wide runoff strip (IRWH1.5),
iii. Closed-end tied ridge (TR), and
iv. Conventional (flatbed) tillage (CT).

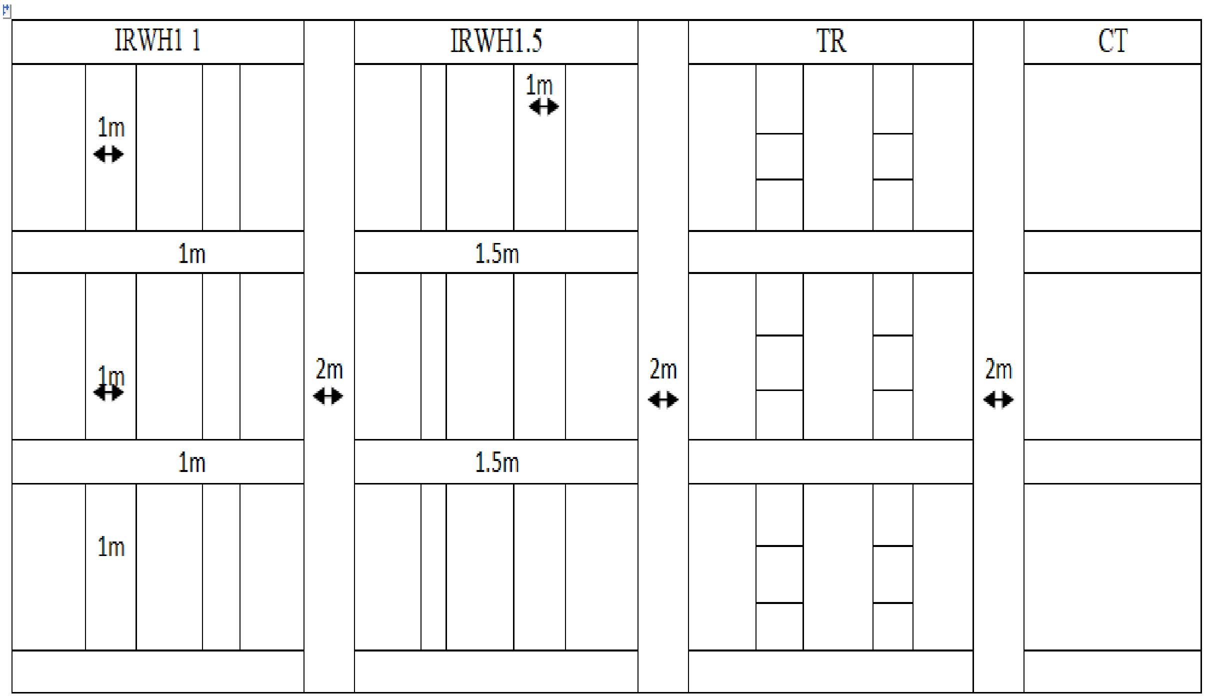
The treatments were laid out in a randomized complete block design (RCBD) as above, with three replications randomly assigned to each of the replications. The spacing between plots and blocks was 1 and 2 m, respectively. Plot sizes of 2 x 3 m were used for the IRWH1, IRWH1.5, tied ridge and conventional tillage treatments. A basin, 1 m wide and 0.30 m deep, was prepared to store the water coming from the respective runoff strips in the maize field. To ensure uniform distribution of water throughout the length of the IRWH and TR treatments' fields, the basins of the IRWH treatments and the furrows of the TR were tied in the middle along the length of the basins and ridges, respectively. The respective runoff strips of the IRWH treatments were compacted by human feet to discourage infiltration of water into the runoff strip fields and thereby encourage runoff.

The spacing used between rows and plants was 50 cm x 20 cm. in the IRWH and tied ridge treatments, while seeds were broadcast in the conventional tillage treatment.

Maize seeds were planted on March 2, 2016 and grown through April, May, June, and July of the year. A seed of maize was planted in the basin by preparing 6 rows within a basin by leaving 1 m at each border for IRWH treatments. For TR treatment, 6 rows were also prepared within a tied ridge with a spacing of 50 cm between rows. In the case of IRWH treatments, the 6 rows of crop, which are in the basin, were watered by the water and harvested from the respective runoff strip area. The recommended seed rate was used according to MoARD (2006) and MoARD (2007). Recommended rates of blended inorganic chemical fertilizers in the form of NPSB were used. Thinning was done after emergence to have optimum plant population per plot. All the plots were weeded manually during the cropping season.

Each plot had 6 rows except the conventional tillage plots. Data were collected from the middle 4 rows out of 6 rows of plant population per plot by excluding the border 2 plants at each end of rows. The layout for in-field rain water harvesting is shown in the table below.

Table 3. In-field rainwater harvesting technique to test soil moisture-holding capacity of the soil



3.7 Yield and Yield Components of Maize

Plant height was measured as the total length of 5 randomly taken plants per net plot area at 90% physiological maturity from the base of the stem to the head. Grain yield per net harvest plot area was recorded as the total grain weight obtained from the net plot area after adjusting the yield to 12.5% moisture content by using a seed moisture tester, then converted to grain yield per m^2. Grain yield per total net plot area allocated was obtained by considering the total net plot area allocated for each treatment (i.e., including the runoff strip areas in the case of IRWH treatments) and adjusting the yield to 12.5% moisture content, then converted to grain yield per hectare. This is used to explain the productivity of the treatments vis-à-vis the total area allocated for the treatments.

Grain yield per plant was determined by taking the average grain weight of 5 randomly taken plants at maturity from the net plot area. Thousand grain weights were determined by taking 1000 sample grains randomly from the harvested grain. Above-ground biomass was determined after sun drying the total above-ground biomass from the net plot area after harvest until the constant weight was reached. Leaf area was obtained by using 5 randomly taken sample plants per net plot area at 50% flowering. The length of the leaf was measured from the base up to the tip, while its maximum width was measured as its width. Then leaf area was obtained using the method described by Pal and Murari (1985) as the leaf area index (LAI= L x W x 0.75) calculated for the 5 randomly taken sample plants in each net plot for all treatments both in AMF and rhizobium inoculation and in-field rainwater harvesting techniques.

3.8. Spores extraction

To investigate the spore density in the field experiments, 500 gm soil samples were taken from each treatment after field experiments 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. The suspension was then sieved with sieves having a mesh size of 500 µm, 105 µm, and 50 micrometers, following the wet sieving and decanting method (Brundrett *et al*., 1994). The last (50 µm) sample was transferred to four 250 ml centrifuge tubes and centrifuged at 2000 rpm for five minutes, then it was suspended in a 60% sucrose solution and thoroughly mixed and centrifuged at 2000 rpm for a minute, and spores were rinsed with tap water and transferred to petri dishes, and the spores of the sample were observed under a stereomicroscope according to INVAM (2006).

3.9. Mycorrhizal colonization

About 0.5 mg of roots from each sample were thoroughly cleaned with tap water and cleared with a 10% KOH solution in a water bath at 90^oC for 1 hour, acidify in 1%HCL for 1 hour, stained with 0.05% trypan blue in a nitric acid solution for 1 hour, and distained using an acidified glycerol solution. The root samples were then left overnight in the acidified glycerol distaining solution (1:1:1; nitric acid, glycerol, and water) in a dark room to remove coloration from root cells. After rinsing in tap water, only fine roots were cut into segments of about 1 cm long. Finally, roots were mounted on microscopic slides and covered with a cover slip. Fungal colonization was rated using the magnified intersection method of McGonagall *et al.* (1990) as arbuscular and vesicular colonization. Rating was done after examining 100-150 intersections per sample.

3.10 Mycorrhizal dependency

Mycorrhizal dependency (MD) of maize 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 (control).

3.11. Nutrient Content

Plant tissue analyses were undertaken at Hawassa University in the College of Agriculture following standard procedures. The concentration of nitrogen in the samples was determined using the Kijeldihal acid digestion method. The P content in the plant tissues was analyzed by the vanadomolybdate method after the wet digestion followed by photometry (Cavell, 1955).The available boron content of the soil was determined by the mono-calcium biphosphate [Ca $(H_2PO4)_2$] extraction method. The extractable B was estimated calorimetrically by a spectrophotometer at 540 nm wavelength.

3.12. Statistical analysis

Statistical analysis for comparison of all growth parameters (plant height, shoot and root wet weight, shoot and root dry weight, leaf area index, stem diameter) among treatments and controls was carried out using the SPSS software package (version 26.0). 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).

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. The soil's pH is 6.2 at a depth of 0–20 cm, which is ideal for maize growing. The soil's electrical conductivity (Ec), N, P, Ca, Mg, K, and organic carbon (OC) concentrations were 0.15 (µS/cm)., 0.26%, 9 mg/kg , 65%, 9.25, 0.10 mg/kg, and 2.47%, respectively. The soil has a clay-like texture. The level of all nutrients in the experimental soil was found to be optimal for maize growth.

4.1.2 Effects of AMF, AMF+F, AMF+R, AMF+F+R, F, R, control and maize- haricot bean intercropping in growth and productivity of maize plant in the field

The growth parameters of the various treatments on the maize plant are displayed in Table 4. The analysis of variance revealed an insignificant difference between F alone and AMF+R combination treatments on plant height at $p > 0.05$. When comparing the other treatments with the intercropping of maize and haricot beans, the maximum mean on plant height was recorded from the uninoculated maize-haricot bean intercropping (140.6 cm), while the minimum mean was recorded from the control (53.6 cm) (Table 4). And also results showed that the AMF plants had the highest plant height compared to the control plants (71 cm and 53.6 cm, respectively).

For stem diameter, the maize-haricot bean intercropping (1327mm) produced the highest mean value, and the control plants (16.3mm) produced the lowest mean value. In the case of leaf area index, when comparing the AMF and Rhizobium inoculation with maize-haricot bean intercropping, the maximum mean value was recorded from the R alone (1853cm^2), while the minimum mean value was recorded from uninoculated maize-haricot bean intercropping(30.2

cm^2). The AMF+R (830.6g) produced the highest mean values for shoot dry weight. Root dry weight better in AMF+R+F (69.6g). The minimum mean values for shoot dry weight, and root dry weight were obtained from the control group.

As can be seen in Figure 6 below, Maize yield/plot and per hectare was higher for intercropping maize-haricot bean treatments, followed by AMF+F and AMF+R, whereas control plants produced the lowest recorded yield value. In terms of 100 seed weight/plot, the two groups with the highest yields were AMF+R and AMF+F (36.57 kg and 36.37 kg, respectively), whereas the control group reported the lowest yield (24.6 kg) (Figure 6).

Table 3. Effect of AMF only, AMF+F, AMF+R, AMF+R+F, F, R, Control, and Intercropping on maize plant

Treatments	**H(cm)**	**SD(mm)**	**LA(cm^2)**	**SWW(kg)**	**SDW(g)**	**RWW(Kg)**	**RDW(g)**
AMF	71.0 ± 13.1^{cde}	20.0 ± 1.4^{cd}	710.6 ± 88.9^{a}	$0.9\pm\mathbf{0}.2^{d}$	115.8 ± 52.0^{b}	$0.1\pm\mathbf{0}.0^{bc}$	27.9 ± 2.3^{ab}
R	63.6 ± 7.1^{de}	18.5 ± 1.7^{cd}	1853.0 ± 1289.5^{a}	0.9 ± 0.16^{cd}	205.5 ± 15.0^{ab}	0.1 ± 0.0^{bc}	26.2 ± 4.4^{ab}
F	90.1 ± 3.2^{bcd}	22.8 ± 1.4^{bc}	759.4 ± 44.8^{a}	1.0 ± 0.1^{cd}	234.9 ± 22.2^{ab}	0.1 ± 0.0^{bc}	43.2 ± 0.7^{ab}
AMF+R	86.9 ± 12.7^{bcd}	86.9 ± 12.8^{cd}	686.6 ± 75.5^{a}	0.9 ± 0.1^{d}	830.6 ± 651.7^{a}	0.1 ± 0.0^{bc}	31.8 ± 7.7^{a}
AMF+F	113.5 ± 8.4^{ab}	26.8 ± 2.2^{ab}	960.4 ± 45.8^{a}	1.6 ± 0.2^{b}	340.3 ± 34.6^{ab}	0.3 ± 0.0^{a}	45.7 ± 7.3^{ab}
AMF+R+F	93.3 ± 9.4^{bc}	20.7 ± 1.4^{cd}	738.8 ± 82.9^{a}	1.4 ± 0.2^{bc}	337.8 ± 49.0^{ab}	0.2 ± 0.2^{b}	69.6 ± 40.3^{ab}
INTERCROPPING	140.6 ± 5.1^{a}	1327.0 ± 135.9^{a}	30.2 ± 0.5^{a}	2.4 ± 0.2^{a}	413.6 ± 44.6^{ab}	0.2 ± 0.0^{b}	52.5 ± 12.1^{ab}
CONTROL	53.6 ± 9.5^{e}	16.3 ± 2.3^{cd}	512.7 ± 40.3^{a}	0.7 ± 0.1^{d}	186.9 ± 12.9^{ab}	0.1 ± 0.0^{c}	20.4 ± 1.23^{ab}

Key: *H=height, LA=leaf area, SD=stem diameter, SWW=shoot wet weight, SDW= shoot dry weight, RWW=root wet weight, RDW=root 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.*

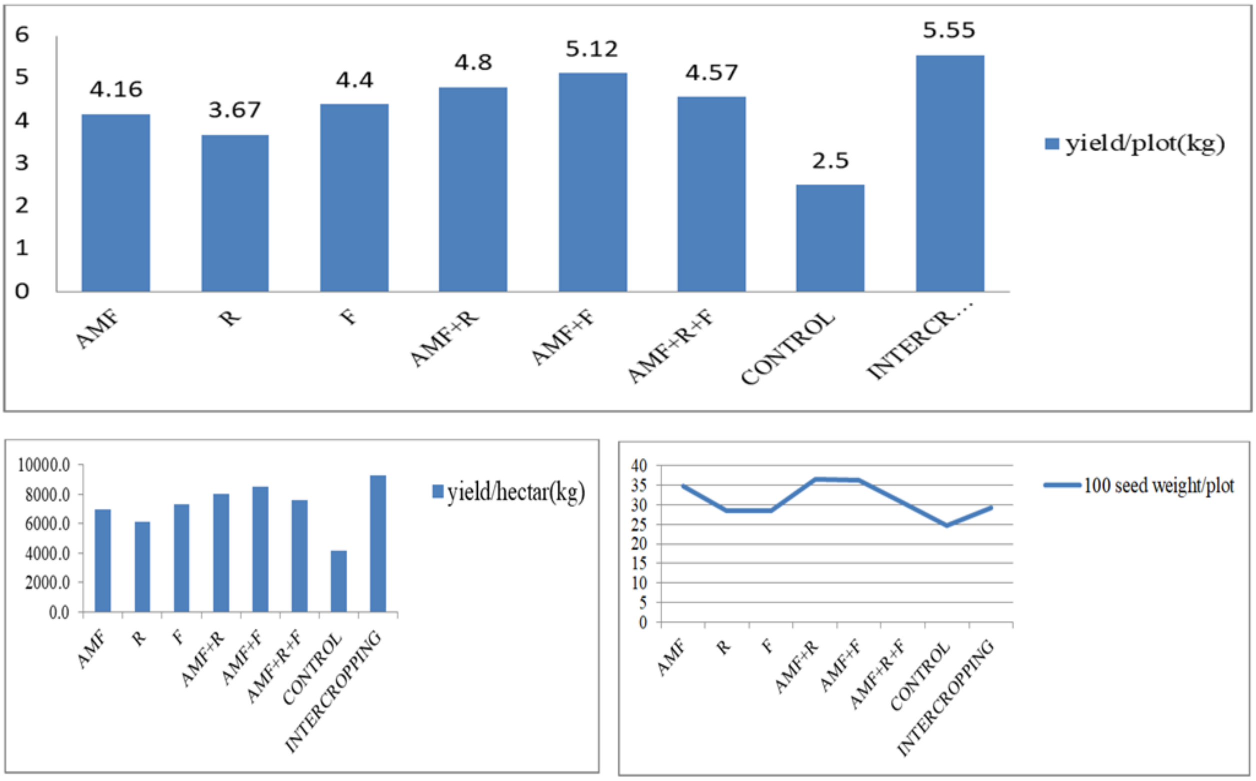


Figure 6. Effect of AMF, AMF+F, AMF+R, AMF+R+F, F, R, Control, and Intercropping on maize plant (yield/plot (kg), yield/hectar (kg) and 100 seed weight/plot)

4.1.3 Effect of the Suitability of In-field Rainwater Harvesting (IRWH) Technique with Respect to the Width of its Runoff Strips

The effects of treatments on in-field rainfall harvesting techniques in different growth parameters were shown in Table 5 and Figure 7. The results obtained showed non-significant differences between all treatments ($p > 0.05$) except in stem diameter. There was a significant difference between conventional tillage and IRWH1 treatments ($p<0.05$) in stem diameter (Table 5). In terms of plant height, the highest mean was measured from tied ridge (7.7 cm) and the lowest mean from IRWH1.5 (5.7 cm).

In terms of leaf area index, the highest mean was measured from tied ridge (745.3 cm^2) and the lowest mean from the conventional tillage (624.7 cm^2) (Table 5). In stem diameter, the highest mean recorded from IRWH1 (12.3 mm) and the lowest mean recorded from the conventional tillage (8.3 mm). The tallest plant was recorded from shoot wet weight in IRWH1 (1.10 kg), shoot dry weight in IRWH1 (265 g), root dry weight in IRWH1 (47.67 g), and the lowest value of shoot wet weight and shoot dry weight is recorded from tied ridge (Table 5).

As shown in Figure 7 below, Maize yield/plot and per hectare, and 100 seed weight/plot, was higher for tied ridge and lower for conventional tillage.

Table 4. Effect of IRWH1, IRWH1.5, Conventional tillage (CT), and Tied ridge (TR) on growth parameters and biomass yield of maize plant

Treatment	**H(cm)**	**LA(cm^{2})**	**SD(mm)**	**SWW(kg)**	**SDW(g)**	**RWW(kg)**	**RDW(g)**
CT	7.0±1.2^{a}	624.7±12.3^{a}	8.3±.3^{b}	1.0±0.1^{a}	264.0±38.1^{a}	0.10±0.0^{a}	29.7±2.6^{a}
IRWH1	6.0±2.5^{a}	680.7±62.1^{a}	12.3±0.7^{a}	1.1±0.2^{a}	265.0±41.5^{a}	0.07±0.0^{a}	47.7±13.7^{a}
IRWH1.5	5.7±2.3^{a}	681.0±108.9^{a}	8.7±0.7^{b}	1.0±0.2^{a}	262.0±65.2^{a}	0.07±0.0^{a}	32.7±8.1^{a}
TR	7.7±1.3^{a}	745.3±17.5^{a}	10.0±0.6^{b}	0.8±0.1^{a}	190.3±22.9^{a}	0.10±0.0^{a}	33.7±3.8^{a}

Key: *H=height, LA=leaf area, SD=stem diameter, SWW=shoot wet weight, SDW= shoot dry weight, RWW=root wet weight, RDW=root 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.*

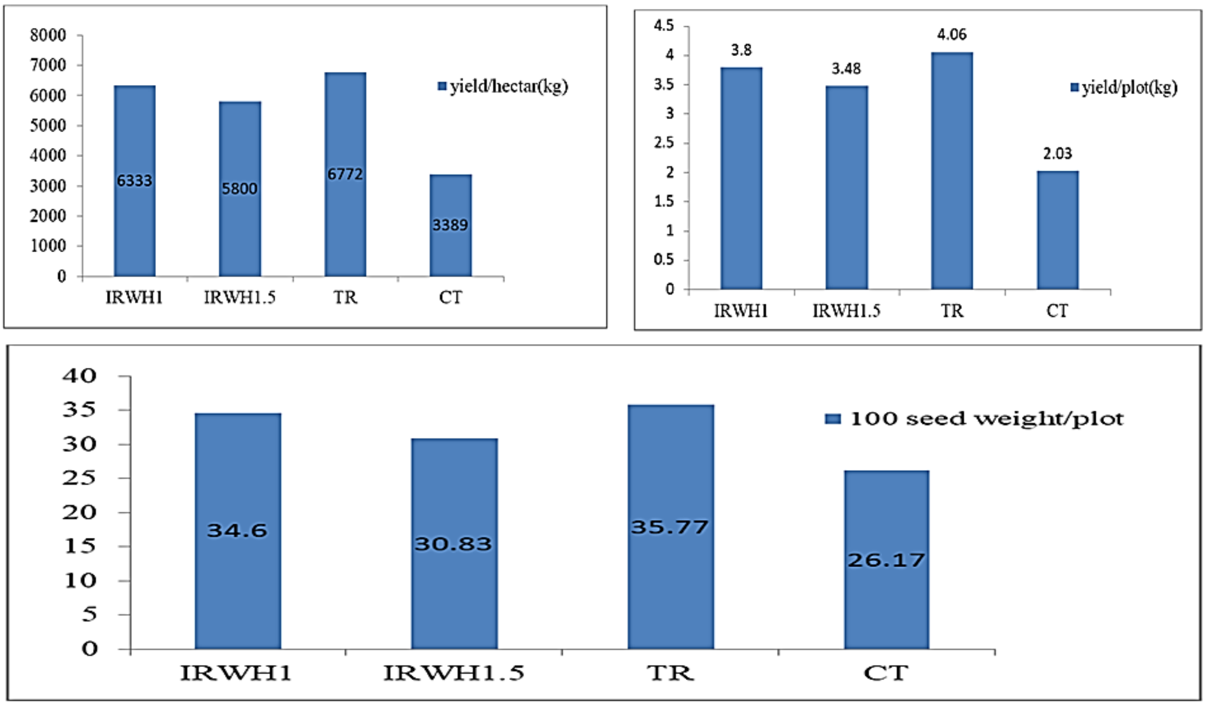


Figure 7. Effect of In-field Rainwater Harvesting Technique on maize plant [yield/hectar (kg), yield/plot (kg) and 100 seed weight/plot)]

4.1.4 Root Colonization and Spore Density

The symbiotic relationship between arbuscular mycorrhizal fungi (AMF) and plants is characterized by the percentage of roots that are colonized by AMF. The results showed that uninoculated maize-haricot bean intercropping had the highest value (84%), and the sole fertilizer had the lowest value (56%). While plant inoculation with AMF species alone resulted in more vesicles and arbiscules than AMF with rhizobium, combination inoculation of AMF and rhizobium resulted in very low colonization (Table 6). The result obtained showed ($p > 0.05$) that there was no significant difference between AC and VC between AMF+F and AMF+F+R. And also, there was an insignificant difference between VC in control and intercropping (Table 6).

Regarding spore density, the pattern of spore count indicates that the AMF alone inoculation produced a comparatively higher number of spores (mean spore density of 416.5 spores 100 g-1 soil), which was followed by the AMF+R inoculation (mean spore density of 337.6 spores 100 g-1 soil) and intercropping inoculation (mean spore density of 329.6 spores 100 g-1 soil). The fertilizer alone group showed a lowest spore density (162.1 spores 100 g-1 soil) (Table 6).

Table 5. Root Colonization and Spore Density of AMF and Rhizobium inoculation under Maize plant

Treatment	AC%	VC%	RLC%	SD/100 g^{-1} dry soil
AMF	12.0 ± 1.5^{c}	14.3 ± 2.2^{b}	73.7 ± 3.5^{b}	416.5 ± 72.2^{a}
R	22.7 ± 1.3^{a}	27.3 ± 6.4^{a}	65.5 ± 4.1^{cd}	232.5 ± 17.0^{bc}
F	14.7 ± 0.3^{bc}	17.7 ± 1.5^{ab}	56.7 ± 0.9^{e}	162.1 ± 14.7^{c}
AMF+R	5.7 ± 1.5^{d}	14.3 ± 4.2^{b}	$59.2 \pm .7^{de}$	337.6 ± 33.0^{ab}
AMF+F	15.7 ± 1.8^{bc}	23.3 ± 4.1^{ab}	73.2 ± 2.9^{bc}	283.7 ± 68.4^{bc}
AMF+F+R	15.7 ± 1.2^{bc}	26.0 ± 1.2^{ab}	69.3 ± 2.3^{bc}	294.9 ± 9.9^{ab}
C	18.0 ± 3.5^{ab}	22.0 ± 5.6^{ab}	66.1 ± 1.8^{bcd}	264.0 ± 27.7^{bc}
Inter-cropping	16.7 ± 2.2^{bc}	26.0 ± 3.6^{ab}	84.2 ± 2.5^{a}	329.6 ± 31.8^{ab}

Key: *AC- arbuscules, VC- vesicle, RLC- root length colonization, and SD- spore density. Mean values followed by Similar letters in columns show not significant difference between groups at $p<0.05$.*

4.1.5 Mycorrhizal Dependency (MD %) of Maize plant on field experiment

The treatments' mycorrhizal dependence is shown in figure 8 below. Although mycorrhizal associations support over 85% of plant species worldwide, the degree to which these associations support a given plant species depends on the mycorrhizal species that are engaged in the association (Brundrett *et al*., 2004). The study found that the AMF+R (77.5%) treatment had the highest mycorrhizal reliance when consortia AMF morphospecies were used. AMF+F treatment comes next, with a documented dependence rate of 45.07%. The following dependency value of 44.6% was also noted for the third treatment, AMF+R+F (Figure 8).

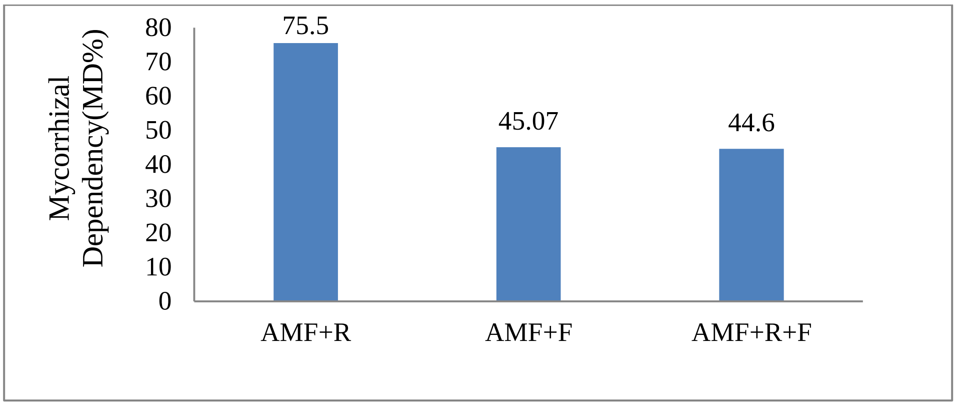


Figure 8. Mycorrhizal Dependency (MD %)

4.1.6 Nutrient content in plants

Table 7 shows the total N, P, Ca, Mg, K, S and B accumulation in maize above ground tissue at the end of the study. Total N, P, Ca, Mg, K, S and B accumulation in shoot dry matter differed considerably between treatments and controls. The AMF+R treatments had the highest nitrogen (0.26%) and phosphorus (0.65%) concentrations. The next highest results (0.22% N and 0.62% P) were reported for sole AMF inoculated treatments. Calcium levels are highest (3.9%) and lowest (2.25%) in AMF+R inoculated and control treatments, respectively. The magnesium level varied from 1.22% in sole AMF to 1.0% in the control treatment. The highest Sulfur uptake (0.51%) was recorded for AMF+R treatment, while the lowest uptake (0.9%) was recorded for the control. Boron was better utilized (0.57%) by AMF+R treatment as the case in sulfur and the lowest (0.21%) uptake was recorded for the control. The potassium concentration ranged from 2.93% in the sole AMF inoculation to 1.81% in the control.

Table 6. Plant tissue nutrient uptake after experiment

Treatments	N%	P%	Ca%	Mg%	K%	S%	B%
AMF	0.22	0.62	3.4	1.22	2.93	0.41	0.55
R	0.20	0.55	3.0	1.08	2.20	0.22	0.45
F	0.18	0.56	3.05	1.15	2.50	0.12	0.35
AMF+R	0.26	0.65	3.90	1.18	2.65	0.51	0.57
AMF+F	0.16	0.60	3.12	1.13	2.24	0.35	0.44
AMF+R+F	0.20	0.50	3.11	1.11	2.17	0.30	0.36
Control	0.14	0.48	2.25	1.0	1.81	0.9	0.21

Key: ***AMF- arbiscular mycorrhizal fungi, R- rhizobium, F-fertilizer***

4.2 Discussion

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

In this study, the effects of arbuscular mycorrhizal fungi on the growth and yield of maize plants in the drought-prone Boricha woreda of Sidama regional state was investigated. According to Bahram *et al*. (2020), plant nutrients are necessary for a number of basic ecological processes, such as photosynthesis, plant growth and competition, virus infection, decomposition, and associated biogeochemical cycling. According to Etsami *et al*. (2021), the extra-radical mycelium of AMFs can help plants absorb nutrients from the soil by increasing the root surface.

In comparison to the control plants, we discovered that the AMF-treated plants were taller. According to Koide and Mosse (2004), Cho *et al.* (2009), Begum *et al*. (2019), and others, the application of AMF can boost the intake of nutrients and water that the plant body utilizes for metabolic activities, which in turn increases the growth of the plant's height.

Large-scale field maize production has made use of AMF, indicating its considerable potential to boost crop yield (Sabia *et al*., 2015). Our research revealed that, in comparison to the control treatment, the yield of treated maize plants increased.

4.2.2 Effect of the combination of AMF and Rhizobium inoculation on the growth of maize plants

Nitrogen-fixing Bacteria and AMF give plants vital soil-nutrients, and Co-inoculation is thought to have the greatest synergistic effects. AMFs Interactions with nodulating rhizobial bacteria have been shown to have a favorable impact in a number of trials (Wu *et al*., 2019).

The results of this study showed that the Maize plant inoculated with Rhizobium and arbuscular mycorrhizal fungus had a considerably higher dry biomass, leaf area and seed yield than the control. These findings are consistent with research by Parvathi *et al*. (1985) and Alam (2006), who found that inoculating plants with AMF improves their nutrition and increases their leaf count more significantly. According to studies conducted in recent decades on many facets of root symbiosis, the dual interaction between Rhizobium and AM-fungi has enhanced growth, nodulation, and yield (Talaat and Abdallah, 2008).

The synergistic effects of applying Rhizobium and AM-fungi together improve plant development more than single inoculation, according to the same findings published by Mortimer *et al*. (2008).

According to the current research, AMF demonstrated noticeably better growth qualities when combined with Rhizobium or NPSB-Fertilizer as compared to the yield and yield attributes of the other bioinoculants and NPSB-Fertilizer alone.

4.2.3 Effect of inter-cropping

Intercropping had a major impact on maize output in the current study. Because of the significant differences in their root systems, intercropping legumes and cereals enhances transpiration and lowers water loss from the soil through deep percolation or evaporation (Carlson 2008). Their unique roots and growth patterns, varying nutrient needs, and varying crop lengths, among other factors, usually enhance their ability to emerge in challenging conditions (Layek *et al.*, 2018). In Yirba Duwancho village, Boricha district, haricot bean intercropping with maize under moisture stress showed more efficient soil utilization. As a result, it illustrates how farmers would apply smallholder agronomic practices to intercrop maize and legumes (haricot bean) in order to maximize their land utilization.

4.2.4 Effect of the Suitability of In-field Rainwater Harvesting Technique on the growth of maize plant

With the exception of stem diameter, all treatments were not significantly different from one another in terms of biomass yield or growth parameters, as shown in Table 5. The findings revealed a significant difference in stem diameter at ($P<0.05$) between conventional tillage and IRWH 1. However, water harvesting technique was superior in plant height; the values of the techniques can be put in a descending order as Tide-ridge, conventional tillage, IRWH1, and IRWH1.5 in maize plant.

When compared to conventional tillage, the results demonstrated that Tied Ridge was more successful at holding onto water since the ridges were made of maize residue, which can increase the amount of water in the soil root zone during the cropping period. Tied-ridging, open-ridging, and sub-soiling increased soil water content at the root zone during the cropping period by 24%, 15%, and 3%, respectively, when compared to traditional tillage, according to research on in-situ water collecting techniques conducted in northern Ethiopia (McHugh *et al.*, 2007).

From the (figure-7) seen, the yield of maize was significantly increased ($p<0.05$) in tied ridge followed by IRWH1. These results were consistent with those of Ahmed *et al.* (2018), who found that in-situ water gathering methods enhanced maize yields and improved plant height. When comparing in-field rainwater harvesting techniques with Arbuscular mycorrhizal fungi and rhizobium inoculation and maize-haricot bean intercropping on soil moisture holding capacity and rate of productivity in the same land-use system and similar climatic conditions, maize productivity was higher in intercropping, followed by AMF+F treatment and the tide-ridge, respectively. Even though the trials were carried out separately in various plots of the same land use in this case, better results would have been achieved if the inoculation test had been performed in conjunction with in-field rainwater harvesting techniques in smallholder farms within the same research area.

4.2.5 Mycorrhizal colonization and spore density

In field studies, Maize plants inoculated with different treatments were shown to be colonized with AMF, but more effective in Maize-haricot bean intercropping followed by AMF than the F alone treatments. Research also supported this; Patterson *et al*. (1990) found that plants inoculated with AM-Fungus individually and dual inoculation only showed good results for AM-fungal Colonization in Roots. According to (Kuila and Ghosh, (2022), *higher*-level nitrogen-*fertilizer*-application reduces AM-Colonization in plants.

Higher spore densities are found in arbuscular mycorrhizal fungi, while lower spore densities have been linked to fertilizer treatment; this is typically correlated with a reduced rate of spore formation (Egerton-Warburton *et al*., 2002; Bhadalung *et al*., 2005; Zhang *et al*., 2016, Debebe Yalembrham., 2019).

4.2.6 Mycorrhizal Dependency (MD %)

More than 80% of plant species in the environment depend on mycorrhizal connections; the strength of these connections varies by species. In this study, the maize plant showed varying degrees of dependency. The treatments with the highest MD Values (75.5) were AMF+R, after co-inoculations such as AMF+F (45.07%) and AMF+R+F (44.67%). This conclusion was further supported by Arumugam *et al*. (2002), who showed that rhizobia plus AMF coinoculation increased mycorrhizal dependence more than AMF inoculation alone.

4.2.7 Nutrient uptake

The results demonstrated that inoculation with Rhizobium and mycorrhizal fungi increases the amount of nitrogen and phosphorus in plants. The highest levels of N and P were found in the maize plant under the AMF+R treatment (0.26%N and 0.65%P). Concentration of phosphate in the soil solution is well below the critical level required for better crop production (Kiran *et al*., 2024). The increased P content may be a result of improved nodules, improved N utilization, and improved vegetative growth due to the applied manure. According to the results, the application of AMF (0.22% N and 0.62% P) to maize plants produced the significant next-highest postharvest N in the soil among the treatments used in (table 7). The results suggested that inoculation with AMF, and AMF+R, with recommended level of NPSB had positive effect on growth and P and N content in plant. According to Wu S. *et al.* (2023), this explanation is in line with the Notion that Inoculation with arbuscular mycorrhizal fungus enhances plant biomass and nitrogen- and phosphorus nutrients.

In comparison to control treatments, soil macronutrients significantly improved with microbial dual inoculation (AMF+R) and AMF alone. The current results are consistent with several studies that showed a significant increase in soil macronutrient contents (i.e., total N, P, K, and Ca) after dual inoculation of biofertilizers (Artursson and Jansson, 2006).

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The objective of the study was to examine the effects of inoculating maize plants with AMF alone, AMF and rhizobium, and a combination of inorganic fertilizer, uninoculated maize-haicot bean intercropping, and in-field rainwater harvesting techniques on the plants' growth and biomass yield. The plant development and yield were found to be greatly enhanced by the following techniques: Maize-haricot bean intercropping, fertilizers with the recommended level of NPSB application, mycorrhiza-rhizobia-plant interaction, and tied ridge followed by infield rainwater harvesting (IRWH1) techniques. This study clearly demonstrates that maize-haricot bean intercropping and dual-inoculation with AM fungi and Rhizobium biofertilizers are more effective in increasing growth, nutrition, and productivity of maize plants and biomass production of maize in Yirba Duwancho field trials as compared to other treatments and control ones.

In addition, it has been observed that Maize production in drought-stress-areas such as Yirba Duwancho can be improved with the use of infield rainwater harvesting techniques. These structures harvest water and increasing the water use efficiency of maize plants and improve growth and yields. Combining TR with IRWH proved to be one of the best options for smallholder farmers in Drought Stress in the field of Yirba Duwancho District of Sidama Regional State, Ethiopia.

5.2 Recommendation

According to current findings the following recommendations are forwarded:

- The applications of AMF and rhizobia and blended fertilizers amendments with recommended level of NPSB in field conditions showed that it is important to use those inoculants to improve growth and productivity of the maize plant. Therefore, applications of these inoculants are recommended for drought prone areas for maize production.
- The effect of Maize-Haricot bean intercropping showed best results of growth and productivity of maize plant as compared to other treatment. Therefore, for small holder farmer on drought stress areas Maize-Haricot bean intercropping were the most recommended.
- In-field rain water harvesting techniques are simple because it can be done with locally available tools and easy to farmers to perform and improve growth and productivity of maize plant. Therefore, the most recommended for farmers is tied ridge followed by IRWHI.
- In addition to improving yields, this method can significantly reduce crop losses due to pests, diseases, and extreme weather events, since it optimizes using natural resources, such as water and nutrients.
- Inoculations provide essential nutrients for crop production, such as by adding nitrogen, phosphorus, sulfur and Boron to the soil.
- Finally, as this study was limited to only one particular area, further study on the application of bio-inoculations, intercropping and in-field rain-water-harvesting techniques to improve Maize production in different drought-prone areas is recommended.

References

Aalipour, H., Nikbakht, A., Etemadi, N., Rejali, F., and Soleimani, M.,2020. Biochemical response and interactions between arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria during establishment and stimulating growth of Arizona cypress (Cupressusarizonica G.) under drought stress. *Sci. Hortic*. 261:108923.

Abeydeera, L. H. U. W., Mesthrige, J. W., and Samarasinghalage, T. I. 2019. Global research on carbon emissions: a scientometric review. *Sustainability* 11:3972.

Ahmed M. El Naim, Sabah M. Hamoda, Elshiekh A. Ibrahim, Moayad M. B. Zaied and Elsadig B. Ibrahim.,2018. Performance of in-situ rain water harvesting on yield of grain sorghum in gradud soil of north Kordofan.*Int. J. Agric. Forest*. 8(2): 77-82.

Alam, M.S., 2006. Role of arbuscular mycorrhizal (AM) fungi on growth and nutrient uptake of some legumes.

Alemayehu, N., 2013. Assessment of environmental-livestock interactions in crop-livestock systems of central Ethiopian highlands (*Doctoral dissertation, University of South Africa).*

Amiri, R., Nikbakht, A., and Etemadi, N.,2015.Alleviation of drought stress on rose geranium [Pelargonium graveolens (L.)Herit.]in terms of antioxidant activity and secondary metabolites by mycorrhizal inoculation. *Sci. Hortic*. 197: 373–38.

Aroca, R., and Ruiz-Lozano, J. M.,2012.Regulation of root water uptake under drought stress conditions. In *Plant responses to drought stress* (pp. 113-127). Springer, Berlin, Heidelberg.

Artursson, V. R.D. and, Jansson, J.K. 2006. Interactions between arbuscular mycorrhizal fungi and bacteria and their potential for stimulating plant growth. *Environ. Microbiol.,* 8, pp. 1-10

Arumugam, R., Rajasekhara, S. and Nagarajan, SM. 2002. The contribution of Arbuscular Mycorrhizal Fungi and Rhizobium inoculation on growth and chlorophyll content of Vigna unguiculata (L) Walp Var. Pusan 151. *J. Appl. Sci. Environ. Manage***.** 14:113-115.

Atkin, O. K., Millar, A. H., Gardeström, P., and Day, D. A.,2000. Photosynthesis, carbohydrate.

Augé, R. M., 2001. Water relations, drought and vesicular-arbuscular mycorrhizal symbiosis.*Mycorrhiza*, *11*(1), 3-42.

Augé, R. M., Toler, H. D., and Saxton, A. M.,2015. Arbuscular mycorrhizal symbiosis alters stomatal conductance of host plants more under drought than under amply watered conditions: a meta-analysis. *Mycorrhiza*, *25*(1), 13-24.

Bahadur, A., Batool, A., Nasir, F., Jiang, S., Mingsen, Q., Zhang, Q., and Feng, H., 2019. Mechanistic insights into arbuscular mycorrhizal fungi-mediated drought stress tolerance in plants. *International journal of molecular sciences*, *20*(17), 4199.

Bahram, M., Netherway, T., Hildebrand, F., Pritsch, K., Drenkhan, R., Loit, K., andTedersoo, L.,2020. Plant nutrient- acquisition strategies drive topsoil microbiome structure and function. *New Phytologist*, *227*(4), 1189-1199.

Barros, V., Frosi, G., Santos, M., Ramos, D. G., Falcão, H. M., and Santos, M. G., 2018. Arbuscular mycorrhizal fungi improve photosynthetic energy use efficiency and decrease foliar construction cost under recurrent water deficit in woody evergreen species. *Plant Physiology and Biochemistry*, *127*, 469-477.

Bechaye Tesfaye.,2011. The case of Boricha Woreda Sidama Zone. *Rural household food security situation anaylsis*: MSc Thesis. Addis Ababa University, Addis Ababa, Ethiopia. 109p.

Begum, N., Ahanger, M.A., Su, Y., Lei, Y., Mustafa, N.S.A., Ahmad, P. and Zhang, L.,2019. Improved drought tolerance by AMF inoculation in maize (Zea mays) involves physiological and biochemical implications. *Plants*, *8*(12), p.579.

Behrooz, A., Vahdati, K., Rejali, F., Lotfi, M., Sarikhani, S., and Leslie, C.,2019. Arbuscular mycorrhiza and plant growth-promoting bacteria alleviate drought stress in walnut. *Hortscience* 54, 1087–1092.

Bhadalung, N.N., Suwanarit, A., Dell, B., Nopamornbodi, O., Thamchaipenet, A. and Rungchuang, J.,2005. Effects of long-term NP-fertilization on abundance and diversity of arbuscular mycorrhizal fungi under a maize cropping system. *Plant and soil*, *270*, pp.371-382.

Bhattacharjee, S., 2019. ROS and oxidative stress: origin and implication. *In Reactive Oxygen Species in Plant Biology* (pp. 1-31).Springer, New Delhi.

Bi, Y., Xiao, L., and Sun, J., 2019. An arbuscular mycorrhizal fungus ameliorates plant growth and hormones after moderate root damage due to simulated coal mining subsidence: a microcosm study. *Environ. Sci. Pollut. Res*. 26, 11053–11061.

Biazin, B., Sterk, G., Temesgen, M., Abdulkedir, A. and Stroosnijder, L., 2012. Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa–a review. *Physics and Chemistry of the Earth, Parts A/B/C, 47,* pp.139-151.

Botha, J.J., Anderson, J.J., Macheli, M., van Rensburg, L.D. and Van Staden, P.P., 2003, April. Water conservation techniques on small plots in semi-arid areas to increase crop yields.In *Proceedings of Symposium/Workshop on Water Conservation Technologies for Sustainable Dryland Agriculture in Sub-Saharan Africa, Bloemfontein, South Africa* (Vol. 811, p. 127133).

Botha, J.J., Anderson, J.J., Macheli, M., van Rensburg, L.D. and Van Staden, P.P., 2003, April. Water conservation techniques on small plots in semi-arid areas to increase crop yields.In *Proceedings of Symposium/Workshop on Water Conservation Technologies for Sustainable Dryland Agriculture in Sub-Saharan Africa, Bloemfontein, South Africa* (Vol. 811, p. 127133).

Brundrett M., 2004. Diversity and classification of mycorrhizal associations. Biol Rev Camb Philos Soc.Aug; 79(3):473-95.

Brundrett, M., Melville, L. and Peterson, L., 1994.Practical Methods in Mycorrhiza Research.*Mycologue Publications, University of Guelph, Guelph, Ontario, Canada.*

Carlson, J.D., 2008. Intercropping with maize in sub-arid regions. *Community planning and analysis.Technical brief, April 16th, 6pp*.

Cavell, A.J., 1955. The Colorimetric Determination of Phosphorous in Plant Materials.*Journal of Science and Food Agriculture.*, 6, 479-480.

Chen, W.F.; Wang, E.T.; Ji, Z.J.; Zhang, J.J.,2021. Recent development and new insight of diversification and symbiosis specificity of legume rhizobia: *Mechanism and application*. J. Appl. Microbiol.131, 553–563.

Chien, S. H., Teixeira, L. A., Cantarella, H., Rehm, G. W., Grant, C. A., and Gearhart, M. M. .,2016. Agronomic effectiveness of granular nitrogen/phosphorus fertilizers containing elemental sulfur with and without ammonium sulfate: a review. *Agron. J.* 108, 1203–1213.

Chimenti, C. A., Marcantonio, M., and Hall, A. J.,2006. Divergent selection for osmotic adjustment results in improved drought tolerance in maize (Zea mays L.) in both early growth and flowering phases. *Field Crops Research*, *95*(2-3), 305-315.

Chitarra, W., Pagliarani, C., Maserti, B., Lumini, E., Siciliano, I., Cascone, P., andGuerrieri, E., 2016. Insights on the impact of arbuscular mycorrhizal symbiosis on tomato tolerance to water stress. *Plant Physiology*, *171*(2), 1009-1023.

Cho, E.J., Do Wee, C., Kim, H.L., Cheong, Y.H., Cho, J.S. and Sohn, B.K., 2009. Effects of AMF inoculation on growth of Panax ginseng CA Meyer seedlings and on soil structures in mycorrhizosphere. *Scientiahorticulturae*, *122*(4), pp.633-637.

Cornejo, P., Meier, S., Borie, G., Rillig, M. C., andBorie, F., 2008a. Glomalin-related soil protein in a Mediterranean ecosystem affected by a copper smelter and its contribution to Cu and Zn sequestration. *Science of the Total Environment*, *406*(1-2), 154-160.

Critchley, W.R.S. and C. Reij, 1989. Water harvesting for plant production: *Part 2 Case studies and conclusions from Sub-Saharan Africa.*

CSA., 2007. Central statistics authority of Federal republic of Ethiopia.

da Silva, E. C., Nogueira, R. J. M. C., da Silva, M. A., and de Albuquerque, M. B..2011. Drought stress and plant nutrition. *Plant stress*, *5*(1), 32-41.

Dawit Alemu, Mwangi W., Mandefro Nigussie and David J.S., 2008. The maize seed system in Ethiopia: Challenges and opportunities in drought prone areas, *African Journal of Agricultural Research* Vol. 3 (4), pp. 305-314.

de Ollas, C., and Dodd, I. C., 2016. Physiological impacts of ABA–JA interactions under water-limitation. *Plant molecular biology*, *91*(6), 641-650.

Debebe, Y., 2024. Combining rainwater harvesting and agroforestry system for enhancing crop yield and soil nutrients: *a holistic approach towards improved small-holder farming* (Doctoral dissertation).

DeLajudie, P.M.; Andrews, M.; Ardley, J.; Eardly, B.; Jumas-Bilak, E.; Kuzmanovi´ c, N.; Lassalle, F.; Lindström, K.; Mhamdi, R.; Martínez-Romero, E.; et al., 2019. Minimal standards for the description of new genera and species of rhizobia and agrobacteria.*Int. J. Syst. Evol. Microbiol*. 69, 1852–1863.

Diagne, N., Ngom, M., Djighaly, P. I., Fall, D., Hocher, V., and Svistoonoff, S., 2020. Roles of arbuscular mycorrhizal fungi on plant growth and performance: Importance in biotic and abiotic stressed regulation. *Diversity*, *12*(10), 370.

Drew, E. A., Murray, R. S., Smith, S. E., and Jakobsen, I., 2003. Beyond the rhizosphere: growth and function of arbuscular mycorrhizal external hyphae in sands of varying pore sizes. *Plant and Soil*, *251*(1), 105-114.

Egerton-Warburton, L.M., Allen, E.B. and Allen, M.F., 2002. Conservation of mycorrhizal fungal communities under elevated atmospheric CO2 and anthropogenic nitrogen deposition. *Microorganisms in plant conservation and biodiversity*, pp.19-43.

El Amerany, F., Rhazi, M., Wahbi, S., Taourirte, M., and Meddich, A., 2020. The effect of chitosan, arbuscular mycorrhizal fungi, and compost applied individually or in combination on growth, nutrient uptake, and stem anatomy of tomato. *ScientiaHorticulturae*, *261*, 109015.

El-Badri, A. M., Batool, M., Aa Mohamed, I., Wang, Z., Khatab, A., Sherif, A., et al.,2021. Antioxidative and metabolic contribution to salinity stress responses in two rapeseed cultivars during the early seedling stage. *Antioxidants* 10:1227.

Essa, C. Mussa, Gideon A. Obare, Ayalneh Bogale, and Franklin P. Simtowe., 2011. Resource use efficiency of smallholder crop production in the central highlands of Ethiopia.*JEL classification*: C21, C61, Q12.

Etesami, H., Jeong, B. R., and Glick, B. R., 2021.Contribution of arbuscular mycorrhizal fungi, phosphate–solubilizing bacteria, and silicon to P uptake by plant. *Frontiers in Plant Science*, *12*, 699618.

Evelin, H., Giri, B., andKapoor, R., 2012.Contribution of Glomusintraradices inoculation to nutrient acquisition and mitigation of ionic imbalance in NaCl-stressed Trigonellafoenum-graecum.*Mycorrhiza*, *22*(3), 203-217.

FAO (Food and Agriculture Organization of the United Nations), 1992. Maize in Human Nutrition.*FAO*, Rome, Italy.

FAO, 2000. Crops and drops. Making the best use of water for agriculture. *Food and Agriculture Organization (FAO) of the United Nations. Rome.*

FAO., 1994.Integrated management of striga for African farmers. Proceedings of the 3rd general workshop of Pan-Africa Striga Control Net-work (PASCON) Harare, Zimbabwe. *Food and Agriculture Organization of the United Nations, Rome*.

Farooq, M., Hussain, M., Wahid, A., and Siddique, K. H. M., 2012. Drought stress in plants: an overview. *Plant responses to drought stress*, 1-33.

Franzini, V. I., Azcón, R., Méndes, F. L., and Aroca, R., 2013. Different interaction among glomus and rhizobium species on Phaseolus vulgaris and Zea mays plant growth, physiology and symbiotic development under moderate drought stress conditions. *Plant Growth Regul*. 70, 265–273.

Garg, N., and Bhandari, P., 2016. Silicon nutrition and mycorrhizal inoculations improve growth, nutrient status, K+/Na+ ratio and yield of Cicerarietinum L. genotypes under salinity stress. *Plant Growth Regulation*, *78*(3), 371-387.

Gerdemann, J. W., and Nicolson, T. H., 1963. Spores of mycorrhizal Endogone species extracted from soil by wet sieving and decanting. *Transactions of the British Mycological society*, *46*(2), 235-244.

Gupta, M. M.,2020. "Arbuscular mycorrhizal fungi: the potential soil health indicators," *in Soil Health, eds B. Giri and A. Varma (Cham: Springe*r), 183–195.

Hashem, A., Kumar, A., Al-Dbass, A. M., Alqarawi, A. A., Al-Arjani, A. B. F., Singh, G., et al. .,2019. Arbuscular mycorrhizal fungi and biochar improves drought tolerance in chickpea. *Saudi J. Biol. Sci*. 26, 614–624.

Hatibu, N., 2002. Rainwater management: strategies for improving water availability and productivity in semi-arid and arid areas. *issues*, p.7.

Helene, L.C.F.; Klepa, M.S.; Hungria, M., 2022.New Insights into the Taxonomy of Bacteria in the Genomic Era and a Case Study with Rhizobia.*Int. J. Microbiol*. 4623713.

Hellal, F. A., El-Shabrawi, H. M., Abd El-Hady, M., Khatab, I. A., El-Sayed, S. A. A., and Abdelly, C.,2018. Influence of PEG induced drought stress on molecular and biochemical constituents and seedling growth of Egyptian barley cultivars. *J. Genet. Engr. Biotechnol.* 16, 203–212.

Hensley, M., Botha, J.J., Anderson, J.J., Van Staden, P.P. and Du Toit, A., 2000. *Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water* (No. 878/1, p. 00).WRC report.

Hensley, M., Botha, J.J., Anderson, J.J., Van Staden, P.P. and Du Toit, A., 2000. Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water .*WRC report* (No. 878/1, p. 00)

Huang, D., Ma, M., Wang, Q., Zhang, M., Jing, G., Li, C., et al.,2020. Arbuscular mycorrhizal fungi enhanced drought resistance in apple by regulating genes in the MAPK pathway. *Plant Physiol*. *Biochem.* 149, 245–255.

INVAM.,2006 (International Collection of Vesicular and Arbuscular Mycorrhizal Fungi). (http://invam.caf.wvu.edu).

Jaiswal, S.K.; Mohammed, M.; Ibny, F.Y.I.; Dakora, F.D., 2021. Rhizobia as a Source of Plant Growth-Promoting Molecules: Potential Applications and Possible Operational Mechanisms. *Front. Sustain. Food Syst*. 4, 619676.

Jaleel, C. A., Manivannan, P., Kishorekumar, A., Sankar, B., Gopi, R., Somasundaram, R., et al., 2007. Alterations in osmoregulation, antioxidant enzymes and indole alkaloid levels in Catharanthusroseus exposed to water deficit. *Coll. Surf. Biointer.* 59, 150–157.

Jema Haji.,2008. Economic efficiency and marketing performance of vegetable production in the Eastern and Central parts of Ethiopia.*Ph.D Thesis*.Swedish University of Agricultural Sciences, Uppsala, Sweden. 64P.

Kiani, S. P., Talia, P., Maury, P., Grieu, P., Heinz, R., Perrault, A., and Sarrafi, A.,2007. Genetic analysis of plant water status and osmotic adjustment in recombinant inbred lines of sunflower under two water treatments. *Plant Science*, *172*(4), 773-787.

Kidane, G., John, H.S., Della, E.M., Eliud, O. and Thomas, W., 2001. Agricultural Technology for the semi-arid Africa Horn. *Country Study. Ethiopia. Country report (revised) from INTSORMIL publication*, *3*, p.2.

Kikuchi, Y., Hijikata, N., Ohtomo, R., Handa, Y., Kawaguchi, M., Saito, K., and Ezawa, T., 2016. Aquaporin- mediated long- distance polyphosphate translocation directed towards the host in arbuscular mycorrhizal symbiosis: application of virus- induced gene silencing. *New Phytologist*, *211*(4), 1202-1208.

Kiran, A., Noshad, Q., Ajaib, M., Shahzad, A.N., Pervez, S., Lalarukh, I., Siddiqui, M.F. and Wakeel, A., 2024. Maize Root Architecture Response to Phosphorus Availability in Rooting Medium. *Pak. J. Bot*, *56*(3), pp.939-944.

Koide, R.T. and Mosse, B., 2004.A history of research on arbuscular mycorrhiza. *Mycorrhiza*, *14*, pp.145-163.

Kronen, M., 1994. Water harvesting and conservation techniques for smallholder crop production systems. *Soil and tillage research*, 32(1), pp.71-86.

Kuila, D. and Ghosh, S., 2022. Aspects, problems and utilization of Arbuscular Mycorrhizal (AM) application as bio-fertilizer in sustainable agriculture. *Current Research in Microbial Sciences*, *3*, p.100107.

Kusvuran, S., Kiran, S., and Ellialtioglu, S. S., 2016.Antioxidant enzyme activities and abiotic stress tolerance relationship in vegetable crops.*Abiotic and biotic stress in plants-recent advances and future perspectives [Internet]. 1st ed. Croatia: InTech*, 481-503.

Layek, J., Das, A., Mitran, T., Nath, C., Meena, R.S., Yadav, G.S., Shivakumar, B.G., Kumar, S. and Lal, R., 2018. Cereal+ legume intercropping: An option for improving productivity and sustaining soil health. *Legumes for soil health and sustainable management*, pp.347-386.

Ledermann, R.; Schulte, C.C.M.; Poole, P.S., 2021.How Rhizobia Adapt to the Nodule Environment.*J. Bacteriol*. 203, e00539-20.

Li, T., Hu, Y. J., Hao, Z. P., Li, H., Wang, Y. S., and Chen, B. D.,2013. First cloning and characterization of two functional aquaporin genes from an arbuscular mycorrhizal fungus Glomusintraradices.*New Phytologist*, *197*(2), 617-630.

Maikhuri, R. K., and Rao, K. S.,2012. Soil quality and soil health: A review. *International Journal of Ecology and Environmental Sciences*, *38*(1), 19-37.

Mccann, J.C.,2005. Maize and Grace: Africa’s encounter with a new World crop. *Harvard University Press*, USA. 1500–2000.

McGonigle, T.P., Mille, H.M., Evans, G.D., Fairchild, L.G. and Swan A.J.,1990. A new method which gives an objective measure of colonization of roots by vesicular-arbuscular mycorrhizal fungi.*New Phytol*.115: 495-501.

McHugh, O.V., Steenhuis, T.S., Abebe, B. and Fernandes, E.C.M., 2007.Performance of In situ rainwater conservation tillage techniques on dry spell mitigation and erosion control in the drought-prone North Wello zone of the Ethiopian highlands. *Soil Tillage Res.* 97(1): 19–36.

Meddich, A., Jaiti, F., Bourzik, W., El Asli, A., and Hafidi, M.,2015.Use of mycorrhizal fungi as a strategy for improving the drought tolerance in date palm (Phoenix dactylifera).*ScientiaHorticulturae*, *192*, 468-474.

Mehboob, I.; Naveed, M.; Zahir, Z.A., 2009. Rhizobial Association with Non-Legumes: Mechanisms and Applications. Crit. Rev. Plant Sci., 28, 432–456.metabolism and respiration in leaves of higher plants. In *Photosynthesis* (pp. 153-175).Springer, Dordrecht.

Mengesha K. 2009. Effect of in-situ rain water harvesting techniques on yield and yield components of field crops grown in Babile, Eastern Ethiopia.

Miller, G. A. D., Suzuki, N., Ciftci- Yilmaz, S. U. L. T. A. N., and Mittler, R. O. N. ., 2010.Reactive oxygen species homeostasis and signalling during drought and salinity stresses. *Plant, cell and environment*, *33*(4), 453-467.

MoA, 2000. (Ministry of Agriculture).Agro-Ecological Zones of Ethiopia, Natural Resource Management and Regulatory Department, Addis Ababa.

MoARD, 2006.(Ministry of Agriculture and Rural Development).*Crop Development Department Crop Variety Register*.Issue.No. 10. Addis Ababa, Ethiopia. 181p.

Mohammed, T.G.,2002. The Impact of Commercialization on Household Food Crops Production in Western Sudan Dryland Agriculture.

Mortimer, P. E., P´ erez-Fern´andez, M. A. and Valentine, A. J. 2008. “The role of arbuscular mycorrhizal colonization in the carbon and nutrient economy of the tripartite symbiosis with nodulatedphaseolus vulgaris," *Soil Biology and Biochemistry*, vol. 40, no. 5, pp. 1019–1027.

Mostofa, M. G., Li, W., Nguyen, K. H., Fujita, M., and Tran, L. S. P.,2018.Strigolactones in plant adaptation to abiotic stresses: An emerging avenue of plant research. *Plant, cell and environment*, *41*(10), 2227-2243.

Nishida, H., and Suzaki, T.,2018. Nitrate-mediated control of root nodule symbiosis. Curr.Opin. *Plant Biol*. 44, 129–136.

Osakabe, Y., Osakabe, K., Shinozaki, K., and Tran, L. S. P.,2014. Response of plants to water stress. *Frontiers in plant science, 5,* 86.

Ouledali, S., Ennajeh, M., Ferrandino, A., Khemira, H., Schubert, A. and Secchi, F.,2019. Influence of arbuscular mycorrhizal fungi inoculation on the control of stomata functioning by abscisic acid (ABA) in drought-stressed olive plants. *South African Journal of Botany*, *121*, pp.152-158.

Pal, U.R. and Murari, K., 1985.Length X width measurement for estimating leaf area of grain sorghum. *Samaru Journal of Agricultural Research (Nigeria*).

Parihar, M., Rakshit, A., Meena, V. S., Gupta, V. K., Rana, K., Choudhary, M.,and Jatav, H. S., 2020. The potential of arbuscular mycorrhizal fungi in C cycling: a review. *Archives of microbiology*, *202*, 1581-1596.

Parvathi KR, Venkateswarlu K, Rao AS.,1985. Proceedings of the Indian Academy of Science (*Plant Science*) 95:35.

Patterson, N.A. Cheit, I. and Kapulink, Y., 1990.Effect of Mycorrhizal inoculation on nodule initiation activity and contribution to legume productivity symbiosis.*Annals of Biology*, 8: 9-20.

Peterson, R.L. and Massicotte, H.B.,2004. Exploring structural definitions of mycorrhizas, with emphasis on nutrient-exchange interfaces. *Canadian Journal of Botany*, *82*(8), pp.1074-1088.

Quiroga, G., Erice, G., Aroca, R., Chaumont, F., and Ruiz-Lozano, J. M.,2017. Enhanced drought stress tolerance by the arbuscular mycorrhizal symbiosis in a drought-sensitive maize cultivar is related to a broader and differential regulation of host plant aquaporins than in a drought-tolerant cultivar. *Frontiers in plant science*, *8*, 1056.

Reddy, M.S.and Georgis, k., 1993.Dryland farming research in Ethiopian review of the past and thrust in the nineties. *Institute of Agricultural Research*.

Rillig, M. C., and Mummey, D. L., 2006.Mycorrhizas and soil structure. *New Phytologist*, *171*(1), 41-53.

Rillig, M. C., Wright, S. F., Nichols, K. A., Schmidt, W. F., and Torn, M. S.,2001.Large contribution of arbuscular mycorrhizal fungi to soil carbon pools in tropical forest soils. *Plant and Soil*, *233*(2), 167-177.

Ruiz- Lozano, J. M., Aroca, R., Zamarreño, Á. M., Molina, S., Andreo- Jiménez, B., Porcel, R.,and López- Ráez, J. A.,2016. Arbuscular mycorrhizal symbiosis induces strigolactone biosynthesis under drought and improves drought tolerance in lettuce and tomato. *Plant, cell and environment*, *39*(2), 441-452.

Sabia, E., Claps, S., Morone, G., Bruno, A., Sepe, L., and Aleandri, R.,2015. Field inoculation of arbuscular mycorrhiza on maize (Zea mays L.) under low inputs: preliminary study on quantitative and qualitative aspects. *Italian J. Agron*. 10, 30–33.

Santander, C., Aroca, R., Ruiz-Lozano, J. M., Olave, J., Cartes, P., Borie, F., et al.,2017. Arbuscular mycorrhiza effects on plant performance under osmotic stress. *Mycorrhiza* 27, 639–657.

Segal, L. M., and Wilson, R. A., 2018.Reactive oxygen species metabolism and plant-fungal interactions. *Fungal Genetics and Biology*, *110*, 1-9.

Shahidur Rashid, KindieGetnet, and Solomon Lemma.,2010. Maize Value Chain Potential in Ethiopia Constraints and Opportunities for enhancing the system.*International Food Policy Research Institute*, Ambo College, Ethiopia.

Sharma, P., Jha, A. B., Dubey, R. S., and Pessarakli, M.,2012.Reactive oxygen species, oxidative damage, and antioxidative defense mechanism in plants under stressful conditions.*Journal of botany*.

Shiferaw, B., Prasanna, B.M., Hellin, J. and Bänziger, M., 2011. Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food security*, *3*, pp.307-327.

Smith, F. A., Grace, E. J., and Smith, S. E.,2009. More than a carbon economy: nutrient trade and ecological sustainability in facultative arbuscular mycorrhizal symbioses. *New Phytologist*, *182*(2), 347-358.

Smith, Sally E., and David J. Read.,2010. *Mycorrhizal symbiosis*.Academic press.

Stagnari, F., Galieni, A., and Pisante, M.,2016. Drought stress effects on crop quality. *Water stress and crop plants: a sustainable approach, 2*, 375-392.

Sultan, I., Khan, I., Chattha, M. U., Hassan, M. U., Barbanti, L., Calone, R., et al.,2021. Improved salinity tolerance in early growth stage of maize through salicylic acid foliar application.*Ita. J. Agron*. 16:1810.

Talaat, N. B. and Abdallah, A. M. 2008. "Response of faba bean (Vicia fava L.) to dual inoculation with rhizobium and VAmycorrhiza under different levels of N and P fertilization," *Journal of Applied Sciences Research*, vol. 4, no. 9, pp. 1092–1102.

Tallury, S.P. and Goodman, M.M.,2000. The state of the use of maize genetic diversity in the USA and sub-Saharan Africa.

Thirkell, T. J., Pastok, D., and Field, K. J.,2020. Carbon for nutrient exchange between arbuscular mycorrhizal fungi and wheat varies according to cultivar and changes in atmospheric carbon dioxide concentration. *Global change biology*, *26*(3), 1725-1738.

Vázquez, M. M., César, S., Azcón, R., and Barea, J. M.,2000. Interactions between arbuscular mycorrhizal fungi and other microbial inoculants (Azospirillum, Pseudomonas, Trichoderma) and their effects on microbial population and enzyme activities in the rhizosphere of maize plants.*Applied Soil Ecology*, *15*(3), 261-272.

Wardell, G.E.; Hynes, M.F.; Young, P.J.; Harrison, E.,2022. Why are rhizobial symbiosis genes mobile? *Philos.Trans. R. Soc. B Biol. Sci.* 377, 20200471.

Worku Alebachew, 2006. Quantifying Rainfall-Runoff Relationships on Selected Bench mark Ecotypes in Ethiopia: A Primary step in Water Harvesting Research. A *PhD Dissertation presented to University of Free State*. 222p.

Worku, A., 2011. Sustainable management of biodiversity: implication for adaptation to and mitigation of climate change in dry lands of Ethiopia. *Ethiopia*, p.45.

Wu, Q. S., Srivastava, A. K., and Zou, Y. N.,2013. AMF-induced tolerance to drought stress in citrus: a review. *ScientiaHorticulturae*, *164*, 77-87.

Wu, Q.-S., He, J.-D.,Srivastava, A. K., Zou, Y.-N.and Kuča, K.,2019. Mycorrhizas enhance drought tolerance of citrus by altering root fatty acid compositions and their saturation levels. Tree Physiol. 39, 1149–1158 .

Wu, S., Shi, Z., Huang, M., Li, Y. and Gao, J., 2023. Effects of arbuscular mycorrhizal Fungi on leaf N: P: K stoichiometry in agroecosystem. *Agronomy*, *13*(2), p.358.

Yang, Y., Tang, M., Sulpice, R., Chen, H., Tian, S., and Ban, Y.,2014. Arbuscular mycorrhizal fungi alter fractal dimension characteristics of Robiniapseudoacacia L. seedlings through regulating plant growth, leaf water status, photosynthesis, and nutrient concentration under drought stress. *Journal of Plant Growth Regulation*, *33*(3), 612-625.

Zhang, F., Zou, Y. N., and Wu, Q. S.,2018a.Quantitative estimation of water uptake by mycorrhizal extraradical hyphae in citrus under drought stress.*ScientiaHorticulturae*, *229*, 132-136.

Zhang, T.; Yang, X.; Guo, R.; Guo, J.,2016.Response of am fungi spore population to elevated temperature and nitrogen addition and their influence on the plant community composition and productivity. Sci. Rep.6, 24749.

Zou, Y. N., Huang, Y. M., Wu, Q. S., and He, X. H.,2015. Mycorrhiza-induced lower oxidative burst is related with higher antioxidant enzyme activities, net H 2 O 2 effluxes, and Ca 2+ influxes in trifoliate orange roots under drought stress. *Mycorrhiza*, *25*(2), 143-152.

Zou, Y. N., Srivastava, A. K., and Wu, Q. S.,2018.Water redistribution in mycorrhizosphere of trifoliate orange.*Indian Journal of Agricultural Sciences*, *88*(8), 1198-1201.

Zou, Y. N., Wang, P., Liu, C. Y., Ni, Q. D., Zhang, D. J., and Wu, Q. S.,2017. Mycorrhizal trifoliate orange has greater root adaptation of morphology and phytohormones in response to drought stress. *Scientific reports*, *7*(1), 1-10.

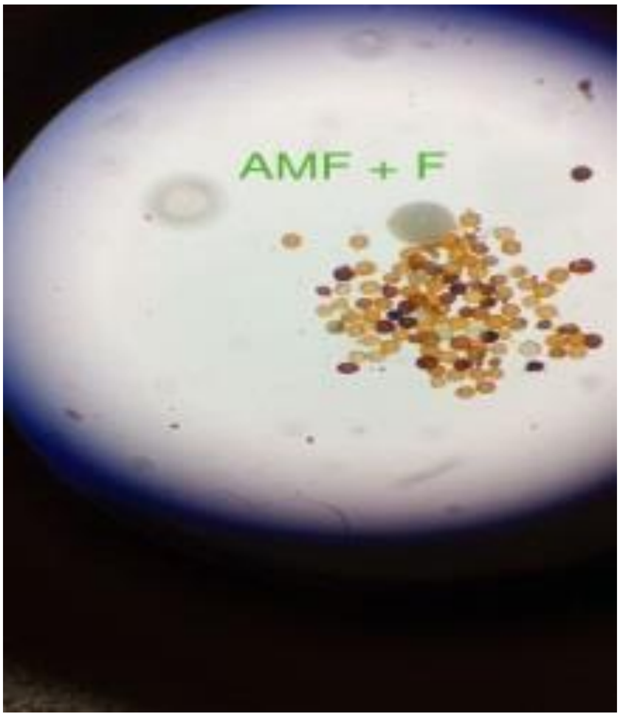
Zou, Y. N., Wu, Q. S., and Kuča, K.,2021.Unravelling the role of arbuscular mycorrhizal fungi in mitigating the oxidative burst of plants under drought stress.*Plant Biology*, *23*, 50-57.

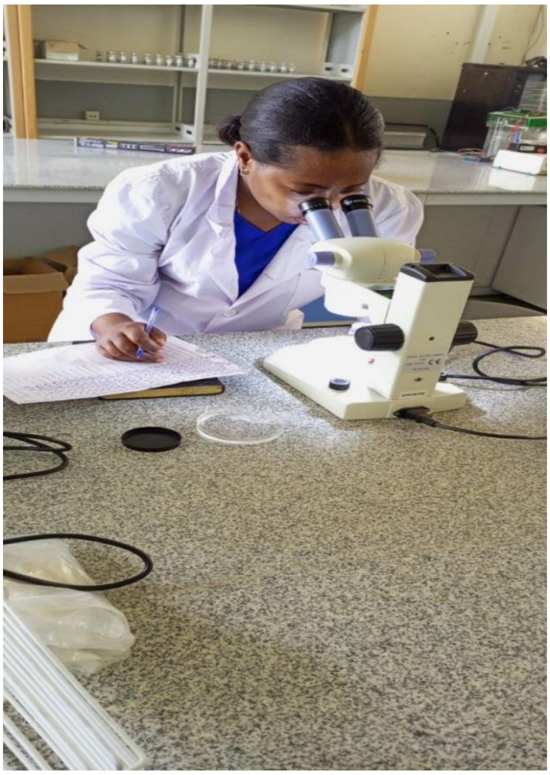
APPENDIXES

Appendix 1pictures from the experiments

View of maize growth condition of IRWH

View of maize growth condition of AMF and Rhizobium inoculation in field





Appendix 2 Raw data of growth and yield components

Effect of AMF and Rhizobium inoculation:

Treatment	Height	LA	SD	SWW	SDW	RWW	RDW	Yield/plot(kg)	Yield/hectar(kg)	100 seed weight
AMF	83.6	708	20.7	0.43	107.8	0.055	24.9	3.8	6333.3	35.88
	44.8	557.9	17.3	1.315	29.9	0.065	26.2	4.5	7500.0	34.2
	84.6	865.92	22.07	0.9	209.6	0.08	32.5	4.2	7000.0	34
R	62.4	562.2	20.706	1.05	206	0.07	18	3.5	5833.3	31.2
	52	443,2	15.06	0.98	231.2	0.06	27.6	3.33	5550.0	28
	76.4	564.8	19.662	0.8	179.2	0.07	32.9	4.2	7000.0	26.12
F	94	803.1	24.706	0.92	274.3	0.095	42.3	4.5	7500.0	28.5
	92.4	805.4	20.09	1.17	197.5	0.105	42.8	5.5	9166.7	27.8
	83.8	669.8	23.55	0.995	233	0.13	44.6	3.2	5333.3	29
AMF+R	68.8	556.8	18.274	0.905	167.7	0.075	18.1	5	8333.3	36.5
	80.4	684.6	19.872	0.94	2134	0.105	44.7	4	6666.7	37.2
	111.6	818.4	22.368	0.75	190	0.035	32.6	5	8333.3	36
AMF+F	96.8	892.6	23.972	1.14	272.3	0.225	40.6	4.21	7016.7	38.5
	119.4	941	25.186	1.8	362.8	0.28	36.4	5.65	9416.7	36
	124.2	1047.6	31.224	1.94	385.7	0.355	60	5.5	9166.7	34.6
AMF+F+R	84.6	644	20.338	1.98	274.7	0.33	27.6	5.5	9166.7	30.8
	83.2	668.4	18.564	1.195	434.3	0.085	150.2	4.2	7000.0	29
	112.2	904	23.274	1.275	304.3	0.085	30.9	4	6666.7	31
Control	66	500	20.52	0.51	185.6	0.03	21.11	3.25	5416.7	26.3
	59.8	588	12.8	0.945	165.1	0.02	18	3	5000.0	22
	35	450	15.5	0.62	210	0.1	22	1.25	2083.3	25.5

Effect of maize- haricot bean intercropping:

Treatment	**Height**	**LA**	**SD**	**SWW**	**SDW**	**RWW**	**RDW**	**Yield/plot(kg)**	**Yield/hec.(kg)**	**100 seed weight**
Inter cropping	150.8	1579	31.2	2.43	476.2	0.175	63.2	6.76	11266.7	28.6
	135.8	1113	30.13	1.99	437.4	0.11	65.9	4.35	7250.0	29
	135.2	1289	29.43	2.79	327.1	0.205	28.3	5.55	9250.0	30

In-field rain water harvesting techniques:

Treatment	**Height**	**LA**	**SD**	**SWW**	**SDW**	**RWW**	**RDW**	**Yield/plot(kg)**	**Yield/hec,(kg)**	**100 seed weight**
IRWH1	95.3	675.43	13.323	1.095	198	0.145	22.7	3.25	5417	34
	104.3	576.47	13.11	1.56	341.8	0.165	69.2	4	6667	35.6
	88.16	791.5	11.63	0.845	256	0.06	52.7	4.15	6917	34.2
IRWH1.5	89.3	466.2	8.74	1.065	149.3	0.125	17.7	4.2	7000	32
	100	819.78	10.913	0.615	262.3	0.075	44.1	3.56	5933	31
	88.76	758.893	8.15	1.415	375.2	0.13	37.2	2.68	4467	29.5
TR	91.06	737.76	9.703	0.905	196.6	0.12	38.7	4.23	7050	35.8
	90.3	779.486	10.36	0.8	148.7	0.1	26.3	4.11	6850	36
	59.96	720.626	11.393	0.625	227.4	0.115	37.2	3.85	6417	35.5
CT	97.7	606.83	8.25	1.355	340.1	0.1	25.01	2.25	3750	28
	72	648.856	9.11	1	222.4	0.11	30.2	0.65	1083	24
	56	620	8.65	0.815	230.7	0.105	34.1	3.2	5333	26.5