EVALUATION OF ARBUSCULAR MYCORRHIZA FUNGI ON MORPHO-PHYSIOLOGY AND NUTRIENT UPTAKE OF COMMON BEAN (*Phaseolues vulgaris* L.) VARIETIES UNDER DIFFERENT MOISTURE CONDITIONS

MSc THESIS

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HAWASSA UNIVERSITY

COLLEGE OF AGRICULTURE

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HAWASSA, ETHIOPIA

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MSc. THESIS

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A THESIS SUBMITTED TO THE SCHOOL OF PLANT AND HORTICULTURAL SCIENCE, COLLEGE OF AGRICULTURE, SCHOOL OF GRADUATE STUDIES HAWASSA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN PLANT AND HORTICULTURAL SCIENCES (SPECIALIZATION: HORTICULTURE)

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This is to certify that the thesis entitled **"Evaluation of Arbuscular Mycorrhiza Fungi on Morpho-Physiology And Nutrient Uptake of Common Bean Varieties Under Different Moisture Conditions"** submitted in partial fulfillment of the requirements for the MSc degree with specialization in **Horticulture** Graduate program of the School of **Plant and Horticultural Sciences**, College of Agriculture, and is a record of original research carried out **Birtukan Areda Gofe** under my supervision, and no part of the thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation have been duly acknowledged. Therefore I recommend that it be accepted as fulfilling the thesis requirements.

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I dedicate this thesis to my Supervisor and Mentors Prof. Meseret Tesema and my lovely family, who have always supported me in achieving my success.

DECLARATION

I hereby declare that this MSc equivalent thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

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This MSc equivalent thesis has been submitted for examination with my approval as thesis advisor.

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Place and Date of Submission: _____

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LIST OF ABBREVIATIONS AND ACRONYMS

A	Photosynthesis Rate
ABA	Abscicic Acid
ANOVA	Analysis of Variance
CRD	Completely Randomized Design
AMF	Arbuscular Mycorrhiza Fungi
E	Transpiration Rate
FC	Field Capacity
gs	Stomatal Conductance
LSD	Least Significance Difference
NF	Nitrogen Fixation
GRSP	Glomalin-related Soil Protein
RLWC	Relative Leaf Water Content
ROS	Reactive Oxygen Species
SAS	Statistical Analysis System
SLA	Specific Leaf Area
SSA	Sub-Sahara Africa
WUE	Water Use Efficiency

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Evaluation of Arbuscular Mycorrhiza Fungi on Morpho-physiology and Nutrient Uptake of Common Bean (*Phaseolues vulgaris* L.) Varieties under Different Moisture Conditions

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Abstract

Common bean is a suitable crop for food security due to its short growing cycle and adaptability to different cropping systems. However, its productivity is limited by factors such as moisture stress. To mitigate such effect, soil amendments with beneficial symbiotic rhizosphere microbes such as Arbuscular mycorrhizal fungi (AMF) is one of the strategies. Hence, this experiment was aimed at evaluating the effect of AMF on moisture stress tolerance and nutrient uptake of three common bean varieties. A pot experiment was conducted from June to September 2024 at Hawassa University College of Agriculture in a Shade house. The experiment used three common bean varieties, SER-119, Dame, and Awash Metene; AMF inoculation and two moisture conditions (80% FC and 40% FC) as a combined treatment. The experiment was executed as a factorial arrangement using a completely randomized design with three replications. The results of this study indicated that the main effect of moisture stress, variety and AMF, and their interaction had a significant impact on most of the phenological, morpho-physiology, nutrient uptake, microbial traits and yield and yield components of common beans. Even though almost all parameters significantly decreased under 40% FC, the AMF inoculation significantly improved seed emergence, days to 50% flowering, pod setting and physiological maturity under moisture stress conditions at 40 % FC. Similarly, the stem and leaf traits are significantly affected by the inoculation of AMF under moisture-stressed conditions. Physiological responses mainly Photosynthesis rate, stomata conductance, chlorophyll a, chlorophyll b, total chlorophyll, transpiration rate and stomata length were improved by AMF inoculation under 40 % FC. Yield and yield components, specifically pod length, thousand seed weight, seed weight, number of seeds per pod, total above ground biomass fresh weight, total above ground biomass and total below ground fresh weight were enhanced by AMF inoculation under 40 % FC. Tissue nitrogen was also enhanced by AMF under 040%FC. Overall, the study found that even though highest values were recorded under 80% FC with AMF treatment, the presence of AMF significantly improved the response of the verities under stress conditions at 40% FC.

Key words: moisture conditions, Arbuscular mycorrhizal fungi, nutrient uptake, Variety; Awash mtene, SER-119, Dame

1. INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is an annual leguminous plant in the family Fabaceae with pinnately complex trifoliate big leaves and it grows best in warm climate at a temperature of 18 to 24 ℃ (Assefa *et al*., 2005). It is one of the most important legumes because of its high commercial value, extensive production, consumer use and nutrient values (Augé, 2001) particularly in Sub-Saharan African (SSA) nations. In Ethiopia, common bean is one of the most important commercial crops and a source of food and nutritional security. Among the grain legumes cultivated in Ethiopia, dry beans are regarded as the most important crop for food security and wealth creation (Augé, 2001). The crop provides vital nutrients as a food including vitamins, proteins, and minerals, and the stems are also used as fodder for livestock, especially in the dry spell following the main cropping season (Zewdie & Yoseph, 2014). As a legume, the common bean also has a significant contribution to soil fertility enhancement through atmospheric nitrogen fixation (Broughton *et al*., 2003). In Ethiopia, the common bean is mainly grown in Eastern, Southern, Southwestern, and Rift valley areas of the country (Habte *et al*., 2014), and it is one of the fast-expanding legume crops that provide an essential part of the daily diet and foreign earnings (Girma *et al.,* 2009). The crop grows well between 1400 and 2000m above sea level (Fikru, 2007).

Common bean productivity is limited by biotic and abiotic elements such as moisture stress among others (Sever Mutlu *et al.,* 2014). More than 60% of the world's common beans are cultivated under non-irrigated conditions, and drought is estimated to cause up to 80% yield losses in many regions of the world (Ninou *et al.,* 2013). Previous reports indicated that moisture stress reduces the growth and productivity of common beans (Nuñez Barrios *et al.*, 2005).

Several studies have revealed that drought stress can have a radical effect on total biomass and seed yield, photosynthetic rate and dry matter translocation and partitioning, number of pods and seeds per plant, root length and mass, and maturation time (Asfaw *et al.,* 2012). In common beans, drought stress during flowering and post-flowering causes reductions of 60–99% in yield (Manjeru *et al.*, 2007; Ambachew *et al.*, 2015), 25.4% in the number of pods per plant, 20.3% in the number of seeds per pod (Augé, 2001), and 11% in seed size (Ambachew *et al*., 2015). Furthermore, the limitation in water availability to the root system reduces carbon dioxide assimilation (Lawlor & Cornic, 2002). According to Jaleel *et al.* (2008), water shortage stress is characterized by a drop in water content, a reduction in leaf water potential, turgor loss, stomatal closure and a decrease in

cell size and development. Severe drought stress alters the metabolic processes of plants, slows growth, and makes it more difficult for them to utilize soil nutrients (Negrão *et al*., 2017).

Plants respond to stress in many ways, while manipulation of the root microbiome is one of the significant mechanisms to deal with such stress. Plant recruitment of a drought-specific microbiome could be an evolved trait, where generations of repeated drought events have led to evolution of stable and beneficial plant-microbe interactions that improve the reproductive fitness of both host and microbe (Naylor & Coleman-Derr, 2018; Chaudhry *et al*., 2021). Plants have evolved complex morphological and metabolic responses to drought stress, many of which have been hypothesized or demonstrated to play a role in shaping root-associated microbial communities (Naylor *et al.,* 2017; Xu & Coleman-Derr, 2019).

Arbuscular mycorrhizal fungi (AMF) form symbiotic relationships with over 80% of land plant species (Wu Zou, 2017). They develop structures like vesicles and hyphae within plant roots, enhancing root access to soil and improving plant growth (Bowles *et al.,* 2016). This symbiosis is crucial for drought adaptation, regulating various metabolites and metabolic pathways (Maclean *et al.,* 2017). AMF enhance survival, improve water absorption and transport (Ren *et al.,* 2019), modify root morphology (Zhang *et al.,* 2019), affect gas exchange and water use efficiency (Zhang *et al.,* 2019), and regulate hormone levels (Ren *et al.,* 2019; Zhang *et al.,* 2019). They also upregulate aquaporin gene expression (Jia-Dong *et al*., 2019), increase proline accumulation, and promote the removal of reactive oxygen species (Amiri *et al*., 2015). Additionally, AMF facilitate the uptake of minerals, primarily phosphorus and nitrogen (Marschner & Dell, 1994), absorbing and transporting significant amounts of phosphates to root cells. Mycorrhizal plants absorb more phosphate from the soil than non-mycorrhizal plants (Smith & Dowd, 1981) and tend to accumulate higher concentrations of phosphorus, potassium, calcium, copper, and manganese in their leaves (Nopamornbodi *et al.,* 1987). The effects of AMF on plant growth and physiology have been extensively studied in various herbaceous species, including important crops like *Solanum lycopersicum* (Gamalero *et al.,* 2004; Bona *et al.,* 2017), *Sorghum bicolor* (Nakmee *et al*., 2016; Jabborova *et al*., 2021), and *Withania somnifera* (Parihar Bora, 2018), as well as fruits like *Citrullus lanatus* (Ban *et al*., 2011) and *Musa acuminata* (Amalero *et al.,* 2003). AMF consistently enhance plant growth and nutrient uptake, particularly nitrogen and phosphorus, under stress (Jansa *et al.,* 2019; Li *et al.,* 2021). In common beans, AMFs improve yield by boosting pod

development and productivity (Chekanai *et al.,* 2018), potentially increasing phosphorus use efficiency and biological nitrogen fixation, leading to phosphate fertilizer savings. Additionally, AMF influence the common bean transcriptome, which may enhance its adaptation to water deficits (Recchia *et al.,* 2018). Despite the presence of significant evidence of using AMF as a soil amendment to enhance nutrient uptake, the interactive effect of the difference in genotype and moisture conditions as well as AMF is not well documented for common bean. Hence, this study hypothesizes that (a) inoculation with AMF under different moisture stress will affect nutrient uptake and growth performance of common bean varieties, and (b) inoculation with AMF mitigates moisture stress impacts and enhances the adaptation capacity of common bean varieties.

1.1. Objectives

1.1.1. General objective

The overall objective of this study is to evaluate the effects of AMF inoculation and moisture stress on the growth, morpho-physiological responses, nutrient uptake of various common bean varieties.

1.1.2. Specific objectives

- To determine the effect of moisture conditions on morpho-physiological, yield components, and nutrient uptake of common bean Varieties
- To assess the effects of AMF inoculation on morpho-physiological, yield components, and nutrient uptake of common bean varieties
- To determine the effects of AMF inoculation and moisture conditions on morpho-physiological, yield components, and nutrient uptake of common bean varieties

2. LITERATURE REVIEW

1.1. Common Bean Crop

All bean genotypes originated from two gene pools: Andean (large-seeded) and Mesoamerican (small-seeded). Common beans belong to the genus *Phaseolus*, species *vulgaris*, and are classified into dry bush types, which are the most widely cultivated, and climbing beans, a recent high-yielding innovation. This crop accounts for over 85% of the global production area for all *Phaseolus species* (Singh, 2001).

Common beans are hermaphroditic, featuring both stamen and pistil in the same flower, which enables self-fertilization and may limit genetic diversity (Lawrence, 2000). They display diverse life histories, growth habits (bushy to climbing), reproductive systems, and climate adaptations, including bushy determinate, bushy indeterminate, prostrate indeterminate, and extreme climbing indeterminate types (Buruchara, 2007).

Common beans thrive in various climates, from sea level to nearly 3000 m.a.s.l., but struggle below 600 m due to high temperatures affecting pod set. They prefer warm conditions between 18°C and 24°C and grow best at elevations of 1400 to 2000 m.a.s.l. Optimal growth occurs in deep, well-aerated soils with a pH of 6.0 to 6.8. Major production areas are noted (Fikru, 2007).

2.2. Common Bean Crop Production and Constraints

Common bean is a widely cultivated pulse, with Ethiopia's smallholder farms averaging 1300 kg ha^{-1} and commercial farms 1700 kg ha^{-1} (CSA, 2015). Research fields show potential yields of 3000 to 4000 kg ha^{-1} (Blair *et al*., 2012). Oromia produces the most beans (43%), followed by SNNPR (29%) and Amhara (25%). Farmers favor common beans for their quick maturation, allowing for double cropping and increased income (Birhanu *et al*., 2018). However, the national

average yield is only 1.59 t ha^{-1} (CSA, 2015), significantly lower than research yields (2.5 to 3.0 t ha^{-1}) (Frehiwot, 2010). This low yield is attributed to various constraints, particularly drought stress, which affects around 60% of common bean-growing regions globally (Beebe *et al*., 2013). Climate change is expected to exacerbate these drought conditions (Munoz-Perea et al., 2006).

2.3. Effect of Moisture Stress on Common Bean Growth and Yield

Water stress significantly affects common bean production at all growth stages, impacting both morphology and molecular levels (Sikuku *et al.,* 2010; Nanesa, 2022). It limits growth during early phases by reducing cell expansion and biomass due to low turgor pressure (Anjum *et al*., 2003; Barrios *et al*., 2005; Mohammadian *et al.,* 2005; Farooq *et al*., 2009). While drought can accelerate maturity, late-season relief may delay it (Singh, 1995). Abate (2018) and Banger *et al.* (2019) notes that water availability influences plant height, leaf area, and dry weight, with optimal growth under sufficient moisture. Inadequate water supply negatively impacts crop production, especially in tropical regions like Ethiopia (Mavi Tupper, 2004). Drought can reduce pod yield and quality, decreasing flower and pod setting by 51% and 63%, respectively (Nunez Barrios et al., 2005). Genotypes with less vegetative growth may improve soil moisture availability (Chaves *et al.,* 2002; Vaz Patto *et al.,* 2015; Bucking *et al.,* 2016; Sawers *et al*., 2008; Thirkell *et al.,* 2017; Poorter *et al.*, 2012; De Souza *et al*., 2020), while plants reduce transpiration rates in response to water stress (Silva *et al*., 2010).

Drought stress impacts common bean production based on its frequency, duration, and intensity, as well as the growth stages affected. This stress can be exacerbated by poor soils, disease, and heat (Munoz-Perea *et al*., 2007; Ambachew *et al*., 2015). Critical losses in seed yield and quality occur during pre-flowering and reproductive stages due to excessive flower and pod abortion (Nielsen & Nelson, 1998). Studies show that drought stress leads to decreased seeds per pod and

seed weight, resulting in lower yields (Gebeyehu *et al*., 2011). Physiological responses such as reduced stomatal conductance, chlorophyll content, and photosynthesis further contribute to yield losses. For instance, Ntukamazina et al. (2017) found a 25.5% yield reduction in bean varieties under drought compared to non-stressed conditions. Additionally, lower stomatal conductance under waterlogging conditions enhances water use efficiency by reducing evapotranspiration, allowing for better carbon absorption and photosynthesis maintenance (Mulatu *et al*., 2023). Severe drought also affects cell proliferation, protein production, solute accumulation, and stomatal closure (Mulatu *et al*., 2023).

2.4. Mechanisms of Plants to Overcame Drought Stress

Water stress triggers various morphological, biochemical, and physiological responses in plants, enabling adaptation and survival. Water stress tolerance refers to a plant's ability to grow, flower, and yield profitably despite limited water supply (Nanesa, 2022). Tolerant plants employ mechanisms such as stomatal control to cope with water stress. Stomatal closure is a rapid defense response against drought, allowing plants to maintain higher water status until conditions improve (Chaves, 1991; Tardieu & Davies, 1992). Key physiological traits related to drought tolerance include leaf temperature, photosynthetic rate, and stomatal conductance (Ambachew *et al*., 2015).

Different common bean genotypes exhibit adaptive mechanisms to water deficit, such as deeper root systems for moisture extraction, enhanced water use efficiency, efficient nutrient remobilization, and phenological plasticity (Asfaw & Blair, 2012; Bahadur *et al*., 2019; Darkawa *et al*., 2016). However, identifying relevant traits requires diverse phenotyping methods (Beebe *et al*., 2013).

Despite varied responses, common bean production suffers from both drought and waterlogging. High proline accumulation is linked to stress tolerance and can predict plant resilience under

drought (Waldhoff *et al*., 2002; Mielke & Schaffer, 2010). Proline also regulates mitochondrial function and cell proliferation during drought stress recovery (Solanki & Sarangi, 2015), serving as a key mechanism for oxidative stress tolerance (Vendruscolo *et al*., 2007).

2.5. Arbuscular Mycorrhizal Fungi (AMF)

Arbuscular mycorrhizal fungi (AMF) are soil-borne fungi that enhance plants' nutrient absorption and resilience to abiotic stressors (Sun *et al*., 2018). Classified within the sub-phylum Glomeromycotina of the phylum Mucoromycota, AMF include four orders Glomerales, Archaeosporales, Paraglomerales, and Diversisporales comprising 25 genera (Spatafora *et al.,* 2016; Redecker *et al.*, 2013). These obligate biotrophs depend on plant photosynthetic products and lipids for their life cycles (Bago *et al.,* 2000; Jiang *et al*., 2017). AMF promote plant growth by improving water and nutrient absorption and protecting against fungal pathogens (Jung *et al*., 2012). As crucial endosymbionts, they significantly enhance plant productivity and ecosystem functionality, supporting sustainable agricultural practices (Gianinazzi *et al*., 2010).

2.6. The Role of Arbuscular Mycorrhiza Fungi in Plant Nutrient Uptake

Intensive land use can severely impact biodiversity and ecosystem functions (Balliu *et al.,* 2015; Nouri *et al*., 2014; Wagg *et al*., 2015). Arbuscular mycorrhiza fungi (AMF) play a crucial role in enhancing nutrient uptake, particularly in nutrient-deficient soils. They facilitate the transfer of organic carbon and enhance the absorption of macro- and micronutrients, such as phosphates, zinc, and copper (Balsam *et al*., 2013; Auge *et al*., 2015; Zhu *et al*., 2012; Jiang et al., 2017; Luginbuehl *et al*., 2017; Smith *et al*., 2003; Nell *et al*., 2010). Research shows that AMF inoculation significantly boosts photosynthetic production and biomass accumulation in plants, as evidenced by increased leaf area and nutrient content in tomato plants (Berta *et al*., 2014; Ruiz-lozano *et al.,* 2009; Cavagnaro *et al*., 2015; Balliu *et al*., 2015). AMF form specialized structures like arbuscules

to facilitate the exchange of nutrients, thereby enhancing plant vigor (Wu *et al*., 2019; Li *et al*., 2016; Varma *et al*., 2017). Consequently, AMF can markedly increase phosphorus concentrations in both root and shoot systems (G A, 2017).

Mycorrhizal associations significantly enhance phosphorus availability in phosphorus-limited environments (Bucher, 2007). For example, maize plants colonized by arbuscular mycorrhizal fungi (AMF) show improved inorganic phosphorus uptake (Garcés-Ruiz *et al*., 2017). This enhanced nutrient uptake leads to increased photosynthetic activity, promoting plant growth and tuber development under varying phosphorus levels and irrigation conditions (Bucking, 2015; Liu *et al.,* 2014; Liu *et al*., 2018). AMF symbiosis positively influences nitrogen, phosphorus, and iron concentrations in plants under stress (Aroca *et al*., 2007; Amiri *et al*., 2017). AMF increase a resource allocation through increasing the uptake of P & N nutrients (Lutz *et al*., 2003; Tajini *et al*., 2012; Racchina *et al.,* 2018; Wu *et al*., 2024). Moreover, AMF can improve crop quality, as seen in strawberry plants with increased secondary metabolites and antioxidant properties (Castellanos-Morales *et al*., 2010).

They also enhance the dietary quality of crops by boosting carotenoids and volatile compounds (Hart *et al*., 2015), and have been shown to improve tomato quality (Bona *et al*., 2017) and citrus fruit composition (Zeng *et al*., 2014). Additionally, AMF increase the accumulation of beneficial phytochemicals, such as anthocyanins and phenolics (Baslam *et al*., 2011), and have been effectively used in large-scale production of crops like maize, yam, and potato (Sabia *et al*., 2015; Lu *et al*., 2015; Hijri, 2016). They also help mitigate abiotic stress by maintaining soil pH and enhancing plant resistance to stressful environments (Miranseri & Smith, 2019; Ruiz-Lozano *et al*., 2016; Rouphael *et al*., 2015).

2.7. The Role of Arbuscular Mycorrhiza Fungi in Mitigating Abiotic Stresses

Drought stress affects plant life in several significant ways. A lack of water reaching the roots reduces the transpiration rate and triggers oxidative stress (Osakabe & Osakabe, 2012; Tuteja & Singh Gill, 2013). This stress adversely impacts plant growth by disrupting enzyme activity, ion absorption, and nutrient assimilation (Ahanger & Agarwal, 2017; Ahanger *et al.,* 2017). However, there is substantial evidence that AMF can alleviate, scape and adoption of drought stress in various crops, including wheat, barley, maize, soybean, strawberry, and onion (Aroca *et al*., 2007; Beebe *et al*., 2013; Acoste *et al*., 2009; Worku & Skjelkeg, 2006; Mena-Violante et al., 2006; Ruiz-Lozano et al., 2016; Yooyongwech *et al*., 2016; Moradtalab *et al*., 2019). The enhanced drought tolerance of these plants is largely attributed to the extensive soil volume explored by both the roots and the extra-radical hyphae of the fungi (Hadge, 2009; Gianinazzi *et al*., 2010; Orfanoudakis *et al*., 2010; Gutjahr & Paszkowski, 2013; Zhang *et al.,* 2017). Also AMF enhance reproductive parts of soybean and chickpea crops (Abdel, 2014; Porcel *et al.,* 2012). AMF symbiosis enhances plant drought tolerance by improving root hydraulic conductivity, osmotic adjustement, and stomaal regulation (Bucklery, 2005; Aroca *et al.*, 2007; Smith & Read, 2008; Begum *et al.,* 2019; Graham, 1980; Liu *et al.,* 2014; Gonzailer *et al.,* 2010). For instance, AMF-inoculated plants exhibit higher relative water content (Auge *et al.,* 2015) and chlorophyll fluorescence under drought (Zhu *et al*., 2010).

This symbiotic relationship is believed to regulate various physiological and biochemical processes in plants, including improved osmotic adjustment (Ghimire *et al*., 2018; Lutz *et al*., 2023; Kubikova *et al*., 2001), stomatal regulation through the metabolism of abscisic acid (ABA) (Duan *et al*., 1996), increased proline accumulation (Ruiz-Sánchez *et al*., 2010; Yooyongwech *et al*., 2016), and elevated glutathione levels (Rani, 2016). The symbiosis between different plants

and AMF can enhance root size and efficiency, leaf area index, and biomass under drought conditions (Al-Karaki *et al*., 2004; Gholamhoseini *et al*., 2013). Furthermore, AMF and their interactions with host plants play a crucial role in enabling plants to withstand harsh environmental conditions (Ruiz-Lozano, 2003).

The AMF symbiosis also leads to improved gas exchange, better leaf water relations, increased stomatal conductance, and higher transpiration rates (Franks, 2007; Morte *et al.,* 2000; Mena-Violante *et al.,* 2006). Additionally, AMF can facilitate ABA responses that modulate stomatal conductance and other related physiological processes (Koltai & Kapulnik, 2010). Recently, Li *et al*. (2019) demonstrated that AMF can enhance growth and photosynthesis in C3 species (*Leymus chinensis*) and C4 species (*Hemarthria altissima*) by up-regulating their antioxidant systems.

2.8. The Use of Arbuscular Mycorrhiza Fungi to Enhance Plant Drought Tolerance

Drought significantly reduces plant productivity by causing stomatal closure, which limits CO_2 intake and decreases photosynthesis and carbon allocation. This ultimately lowers agricultural yields. Research indicates that AMF can enhance plant performance under drought Balsam et al. (2013). Mycorrhizal plants employ both drought mitigation, through improved water uptake, and drought tolerance, by strengthening the plant's inherent ability to withstand stress Smith (2011).

The enhancement of plant fitness through drought mitigation by AMF is likely due to the increased surface area for water absorption provided by AMF hyphae (Augé, 2001) and improved access to soil pores. Various studies have examined these mechanisms (Dell'amico *et al.,* 2002; Bárzana *et al.*, 2012; Chitarra *et al*., 2016). For example, Subramanian *et al.* (2006) found that AMF Rhizophagus intraradices improved growth and water use efficiency in field-grown tomato plants under water stress. Similar benefits have been noted in other species, including *Lactuca sativa* L.

(Ruiz-Lozano *et al*., 2016), *Triticum aestivum* L. (Becker, 2008), and others (Osonubi *et al*., 1991), and Wu *et al* (2015).

Additional mechanisms influence plant responses to drought stress, notably the production of phytohormones. A proper hormonal balance is essential for regulating tolerance to abiotic stresses. Abscisic acid (ABA) is a key hormonal signal under stress, impacting transpiration rates, root hydraulic conductivity, and aquaporin expression Ruiz-Lozano *et al*., 2016) ABA signaling is crucial for regulating stomatal conductance and inducing stomatal closure to minimize cellular water loss.

Arbuscular mycorrhizal fungi (AMF) inoculation can affect stomatal function by modulating ABA levels, with mycorrhizal plants typically showing lower ABA concentrations during drought stress than non-mycorrhizal plants. Additionally, jasmonic acid (JA) interacts with ABA to help regulate water stress responses, alleviating stress and influencing aquaporin expression, which is vital for water uptake and transport Ruiz-Lozano *et al*., 2016)..

Other mechanisms enhancing drought tolerance include osmotic adjustment through compatible solutes like sugars and proline (Posta, 2020). Drought stress can also lead to reactive oxygen species (ROS) production (Laxa *et al*., 2019), while phytohormones like strigolactones and auxins play roles in regulating water stress responses (Ludwig-Miller, 2010; Mostofa *et al*., 2018).

The colonization of plants by AMF improves their tolerance to stress cues by inducing several changes in their morpho-physiological traits (Alqarawi *et al*., 2014; Hashem *et al*., 2015; Weng, 2016). AMF are considered natural growth regulators for many terrestrial plant species and are promoted as bio-inoculants and bio-fertilizers to enhance sustainable crop productivity (Barrow, 2012). Additionally, AMF-treated soils form more stable structures and contain significantly

higher amounts of extraradical hyphal mycelium than non-AMF-treated soils (Syamsiyah *et al.,* 2018).

Glomalin-related soil protein (GRSP) helps maintain soil water content under abiotic stress, regulating water exchange between soil and plants and promoting development (Wu *et al*., 2014). Comprising 30–40% carbon, glomalin enhances soil's water-holding capacity, protecting it from desiccation (Sharma *et al*., 2017). Additionally, AMF inoculation positively impacts growth-related functions such as stomatal conductance, leaf water potential, relative water content (RWC), PSII efficiency, and CO_2 assimilation (He *et al*., 2017; Chandrasekaran *et al*., 2019), while also improving water stress tolerance by physiologically altering above-ground organs (Bárzana *et al*., 2012; Fang & Xiong., 2015).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

A pot experiment was conducted under shade house conditions from June to September 2024 at Hawassa University, College of Agriculture, Hawassa, Ethiopia. Hawassa is located at 7˚5′ N and 38˚30′ E, at an elevation of 1688 m asl. It has a warm climate year-round, with a wet season characterized by overcast conditions and a dry season marked by partly cloudy skies. Temperatures range from 12 ℃ to 31 ℃ throughout the year, rarely dropping below 9 ℃ or exceeding 34 ℃. The study location is near Lake Hawassa, which can influence the relative humidity. The relative humidity of the area is commonly in the range of 59.99 – 74.22% (Menberu *et al*., 2021). The soils are classified as sandy loam in textural class (Tiki *et al*., 2015). Major crops grown in the area include maize, common beans and enset.

3.2. Experimental Materials

The experiment utilized three common bean varieties: Awash Metene, SER-119, and Deme, sourced from the Melkassa Research Center. The varieties are determinate in growth habit and Meso-American and Andean in origin and they were released from the Melkassa Agriculture Research Center between 2013 to 2015. For inoculation, AMF inoculum, consisting of two predominant morphospecies, Gigaspora rosea and Rhizophagus clarus, were obtained from Hawassa University's microbiology laboratory.

3.3. Treatments and Experimental Design

The experiment comprised factorially combined treatments, i.e., three common bean varieties (Awash Metene, SER-119, and Deme), two moisture conditions (40% FC and 80% FC), and two AMF treatments (inoculated with 23 spores g^{-1} soil and non-inoculated). This resulted in 12 treatment combinations and was replicated three times to have 36 experimental units. To increase

the number of plants for sampling, each treatment had 9 pots, i.e. 3 pots per replication and one plant per pot, totaling 108 pots. The experiment was arranged in a complete randomized design (CRD) in the shade house.

Table 1. Experimental factors, treatment combinations and description of the common bean varieties used in the study

Experimental Factors			*No*	*Treatment Combination*	*Gene pool*	*Growth habits*	*Release*
Moisture conditions (% FC)	AMF	Varieties					
			1	V1 80%FC AMFNI	Andean(V1)	Determinate	2014
40 *80*	NI IN	SER-119 Deme Awash metene	2	V1 40%FC AMFNI			
			3	V1 80%FC AMFIN			
			4	V1 40%FC AMFIN			
			5	V2 80%FC AMFNI		Determinate	
			6	V2 40%FC AMFNI	Mesoamerican (V2)		2013
			7	V2 80%FC AMFIN			
			8	V2 40%FC AMFIN			
			9	V3 80%FC AMFNI	Andean (V3)	Determinate	2015
			10	V3 40%FC AMFNI			
			11	V3 80%FC AMFIN			
			12	V3 40%FC AMFIN			

Source: Modified from the MoARD, 2008

NB: V1=SER-119, V2= Deme, V3=Awash Metene, FC= Field capacity AMF= Arbuscular mycorrhiza fungi inoculated, IN=inoculated, NI= non-inoculated.

3.4. Experimental Soil Sampling and Analysis

The physicochemical properties of experimental soil sampling and the preparation for laboratory analysis were carried out using a 1 kg composite soil used for experimental purposes as a potting medium. The soils were air-dried to a constant weight, ground and mixed thoroughly, and then passed through a 2 mm sieve. The soil analysis was performed at Hawassa University College of Agriculture's soil chemistry laboratory. The soils were tested in the laboratory for particle size

distribution, total N, available P, organic carbon, pH, and EC. The pH was determined using the potentiometric water extraction method. The available P was determined by the Olsen method (Dewis & Freitas, 1984), and the total N was determined by the Kjeldahl method (Homer *et al*., 1961). The soil's texture class was determined using the Bouyoucos hydrometer method (Dewis & Freitas, 1984), while organic matter was determined by the wet oxidation method of Walkley and Black, respectively.

3.5. Experimental Procedure

Plastic pots (17.6 cm × 8 cm) were filled with 2.5 kg of sterilized silt–clay–sand soil (111°C for 2 h; Reynolds, 1970). Seeds were surface-sterilized with 0.5% NaOCl and 70% ethanol (Aroca et al., 2010). Each pot was inoculated with 23 g of AMF-containing substrate. Four seeds were sown and thinned to one plant after 10 days. Field capacity was determined by the pressure plate method (Topp, 1993). A total of 108 perforated pots were prepared. Pots were initially maintained at >75% FC (Molla, 2018), and moisture stress treatments (40% and 80% FC) began after two weeks. Soil moisture was monitored using a Delta-T HH2 device and converted to gravimetric values (Reynolds, 1970) for irrigation. All other practices were uniformly applied.

3.6. Microbial Parameters

3.6.1. Root colonization

About 0.5 mg of roots per sample were washed with tap water, cleared in 10% KOH at 90°C for 1 hour, neutralized with 1% HCl, stained with 0.05% trypan blue in nitric acid, and destained in acidified glycerol (Phillips & Hayman, 1970). AMF structures were examined under a compound microscope (Olympus BX51) at 200–400× magnification. Root colonization was assessed using the magnified intersection method (Gonigle et al., 1990) with 100 intersections per sample. Colonization metrics included total root length colonization (RLC = 100[(G–N)/G]), hyphal

colonization (HC = 100[H/G]), arbuscular colonization (AC = 100[A/G]), and vesicular colonization (VC = 100[V/G]), where G = total intersections, N = no fungal structure, H = hyphae, A = arbuscules, and V = vesicles.

3.6.2. Spores density

After 90 days of plant growth, AMF spore populations were assessed using the wet-sieving and decanting method (Gerdemann & Nicolson, 1963). Each 100 g soil sample was mixed with 1.5 L water, and the supernatant was passed through sieves (480, 106, 50, and 38 µm), followed by centrifugation at 2000 rpm for 5 min. The 38-µm fraction was suspended in 60% sucrose, mixed, and centrifuged at 2000 rpm for 1 min. Spores and sporocarps were rinsed, transferred to Petri dishes, and counted under a 4× stereomicroscope (INVAM, 2006). Spore density was reported per 100 g of dry soil.

3.6.3. Mycorrhiza dependency (MD)

The mycorrhiza dependency (MD) of common bean varieties was calculated according to (Plenchette *et al*. 1983) as follows: MD (%) = [(M-NM)/M] X 100

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

3.7. Nutrient Uptake by the Shoots and the Grains

Above-ground biomass was harvested 90 days after planting. The fresh weight was recorded, and then oven-dried at 65˚C until a constant weight was obtained, and the dry weight of the shoots were recorded. The dried shoot samples were ground using a rotor mill and sieved by a 0.5-mm sieve to prepare a sample of 10 g for analysis of nutrient concentrations. Nitrogen content was analyzed using the Kjeldahl method described by Bremen & Mulvaney (1982). Phosphorus was

analyzed by UV-spectrophotometry (Charles & Fredeen, 1997). Nutrient uptake in plant shoot was calculated by multiplying N content in plant shoot by shoot dry matter yield per plant.

3.8. Data Collections

All morpho-physiological and biochemical data were collected at four weeks after emergence, except the yield, which was measured at the end (maturity stages). Measurements were carried out on three randomly selected plants per treatment.

3.8.1. Phenological parameters

Day of 50% emergence: it was determined by counting the number of days starting from planting to the time when the 50% of the plants per treatment emerged by counting the number of plants **Days to flowering**:it was determined by counting the number of days starting from planting to the time when the first flower appeared in 50% of the plants per treatment by counting the number of plants through visual observation.

Days to pod formation: it was determined by counting the number of days starting from sowing to the time when the first pod appeared in 50% of the plants per treatment by counting the number of plants through visual observation.

Days to physiological maturity: it was determined by counting the number of days starting from the date of planting to the date when 90% of the plants per treatment attained physiological maturity. When the pods had lost their green pigmentation, based on visual observation.

3.8.2. Growth and morphology parameters

Plant height (cm):it was measured by using a ruler from the ground level to the tip of the main stem at physiological maturity.

Leaf number per plant (Count): all leaves per plant were counted at the 50% flowering stage before defoliation of the leaves.

Number of primary branches per plant (Count): it was determined by counting the total number of primary branches that emerged from the main stem at the 50% flowering stage.

Internode length per plant (cm): internode length was measured from the main stem of the plants at three positions of the stem, from the top, middle, and bottom parts of the stem, and the average of the measurements was taken at the physiological maturity stage.

Number of flowers per plant (Count): flowers from three selected plants were counted at the full flowering stage.

Leaf area per plant (cm²): The leaf area was measured using an automatic leaf area meter (model LI 31000A Li-Cor, Lincoln, USA) at the 50% flowering stage from all leaves of selected plants.

Leaf fresh weight per plant (g): itwas measured using a sensitive balance at the 50% flowering stage from all leaves of randomly selected plants.

Leaf dry weight per plant (g): it was measured after fresh weights of the samples were recorded; samples were placed in paper bags and then oven-dried for 48 hours at 70°C, and then dry weights were measured using a sensitive balance separately.

Specific leaf area per plant (cm²/g): it was determined by calculating the ratio of leaf area to leaf dry biomass at 50% flowering time using the methodology proposed by Poorter *et al*. (2010) using the following formula

$$\boldsymbol{SLA} = \frac{\boldsymbol{Leaf\ area}}{\boldsymbol{Leaf\ dry\ weight}}$$ Where: SLA= Specific leaf area

Leaf area index (LAI): the leaf area of individual plants within each pot was calculate as follows

$$LAI = \frac{Leaf\ area\ of\ individual\ plant}{Area\ of\ the\ pot}$$ Where: LAI= Leaf area index

Leaf weight ratio (LWR): it was calculated as a ratio of leaf dry weight to total dry biomass weight. $$LWR = \frac{Leaf\ dry\ weight}{total\ dry\ biomass\ weight}$$ Where: LWR; leaf weight ratio

Leaf area ratio: it was calculated as a ratio of total leaf area to total biomass weight.

$$LAR = \frac{Total\ Leaf\ area}{Total\ biomass\ weight}$$ Where: LAR; =leaf area ratio

Stem fresh weight (g): it was measured using a sensitive balance at the 50% flowering stage from all stems of randomly selected plants.

Stem dry weight (g): it was measured after fresh weights of the samples were recorded; the samples were placed in paper bags and then oven-dried for 48 hours at 70°C, and then dry weights were measured using a sensitive balance separately.

Stem weight ratio: it was calculated as a ratio of stem dry weight to total dry biomass weight.

$$SWR = \frac{Stem\ dry\ weight}{total\ dry\ biomass\ weight}$$, Where: LWR; Stem weight ratio

Root number: the roots of the common bean, carefully uprooted and transferred to a bowl and washed, were counted.

Root length (cm): the roots of the common bean, carefully uprooted and transferred to a bowl and washed, were measured using the ruler.

Root fresh weight (g): it was measured using a sensitive balance at the 50% flowering stage from randomly selected plants.

Root dry weight (g): it was determined that after oven-drying the fresh root in an oven for 48 hrs, the dry weight of roots was determined by weighing on a sensitive balance.

Root weight ratio: it was calculated as a ratio of root dry weight to total dry biomass weight. $$\boldsymbol{RWR} = \frac{\boldsymbol{Root\ dry\ weight}}{\boldsymbol{total\ dry\ biomass\ weight}}$$, Where: RWR; Root weight ratio

3.8.3. Physiological parameters

Stomata anatomy: Stomata number and aperture measurements (width and length) were conducted following the protocols of Xu & Zhou (2008) during the vegetative stage. A thin layer of transparent nail polish was applied to the lower surface of fresh, intact leaves and allowed to dry for 10 minutes to capture the epidermal imprint. This layer was then peeled off with transparent tape and attached to a microscope slide. An Automated Upright Leica Microscope DM5000 B with a 40x magnification lens and a digital Leica DFC425/DFC425C camera was used for counting stomata and measuring apertures.

Leaf gas exchange parameters: Leaf gas exchange rates were measured using a CIRAS-3 portable photosynthesis system (LICOR Inc., Lincoln, NE, USA) on fully expanded intact leaves during the vegetative stage, between 1:00 p.m. and 3:00 p.m. Parameters included a leaf surface area of 6.54 cm^2, an ambient CO_2 concentration of 386 µmol mol^{-1}, a leaf chamber mass flow rate of 250 µmol s^{-1}, an atmospheric pressure of 840 mbar, and a fixed PAR at 1200 µmol m^2 s^{-1}. Water use efficiency was calculated as the ratio of net CO_2 assimilation rate (A) to transpiration rate (E) (Bertolde et al., 2012).

Leaf chlorophyll concentration (µg/g): At the vegetative stage, leaf chlorophyll concentration was measured on four fully developed juvenile leaves taken from each plant and 12 leaves from each treatment. Sampling occurred at 8:00 a.m. and the leaves were immediately transported to the

plant cell laboratory in an aluminum foil-sealed bag under dark conditions. Two grams of fresh leaf discs were crushed using a mortar and pestle and homogenized with 10 ml of 96% alcohol (v/v). The homogenate was filtered into 15 ml tubes, then centrifuged for 3 minutes at 10,000 rpm at room temperature. The supernatant was separated, and 3 ml of each concentration was analyzed in triplicate for chlorophyll-a and chlorophyll-b at absorbances of 663 nm and 646 nm, respectively, using a UV-2450 spectrophotometer (Hitachi, Tokyo, Japan). During leaf sampling and extraction procedures dark conditions were maintained by covering the glassware and containers with aluminum foil. Chlorophyll quantification followed the equations provided by Lichtenthaler & Buschmann (2001).

$$\textbf{Chla}\left(\frac{\boldsymbol{\mu g}}{\boldsymbol{ml}}\right) = \mathbf{12.25(A663) - 2.79\,(A646)}$$

$$\textbf{Chlb}\left(\frac{\boldsymbol{\mu g}}{\boldsymbol{ml}}\right) = \mathbf{21.50\,(A646)\; -\; 5.10\,(A663)}$$

$$\textbf{Total chl}\;(\boldsymbol{\mu g/ml})\; = \textbf{chla} + \textbf{chlb} \qquad \text{(Lichtenthaler \& Buschmann, 2001)}$$

Where A = absorbance, Chla = chlorophyll a, and Chlb = chlorophyll b.

Leaf chlorophyll fluorescence (Fv/Fm): The efficiency of photosystem II (Fv/Fm) was measured from three well-developed leaves from randomly selected middle parts at the vegetative stage. The measurements were taken during an early morning between 6:00 a.m. and 8: 00 a.m. using a Handy-PEA fuorimeter (Hansatech, Kings Lynn, UK) and the methodology proposed by (Strasser *et al*., 2004; Mulatu *et al*., 2023). The measurement was conducted on 10 minutes dark-adapted leaves using leaf clip.

Relative leaf water content (%): Four fully expanded leaves were collected from representative plants, and 9 mm leaf disks were obtained and weighed immediately to estimate leaf disk fresh

weight. The samples were hydrated to full turgidity in closed 15-ml tubes with double-distilled water for 24 hours at room temperature (25°C). After removing excess water with tissue paper, the turgid weight was recorded. To achieve a consistent dry mass, samples were oven-dried for 24 hours at 75°C (leaf disk dry weight). Finally, relative leaf water content was determined using the formula from Neil (1981). As follows:

$$RLWC = \frac{Leaf\ Fresh\ weight\ - Leaf\ dry\ weight}{Leaf\ turgid\ weight - Leaf\ dry\ weight} \times 100$$

3.8.4. Yield and yield component parameters

Number of pods per plant: All pods per plant from the sample plants were counted at physiological maturity.

Number of seeds per pod: the total number of seeds in all the pods of sample plants was counted and divided by the total number of pods to find the number of seeds per pod at physiological maturity.

Number of seeds per plant: the average number of seeds per plant was determined by multiplying number of seeds per pod and the number of pods per plant at physiological maturity.

Seed yield per plant (g plant^{-1}): the average grain yield in gram was taken from whole plants harvested from three plants; it was determined by weighing the beans using a sensitive balance in each experimental unit after seed moisture was adjusted to 12% (Worku & Skjelvag, 2006).

Thousand seed weight (g): The weight of 1000 seeds was determined for each pot using a sensitive balance. The weight was adjusted to a moisture content of 12% according to Worku & Skjelvag (2006).

Total biomass yield (g)= At physiological maturity, three plants randomly taken from each treatment were used to determine aboveground dry biomass yield, which was measured after sun drying till a constant weight.

Grain yield (kg ha^{-1}) = Grain yield was measured by harvesting and threshing of the crop from the net plot area. The moisture was adjusted to 12%.

Straw yield = it was calculated by subtracting grain yield from total biomass yield.

Harvest index= it was calculated by dividing grain yield per pot by the total above ground dry biomass yield per pot.

3.9. **Data Analysis**

All data were analyzed using R software version 3.5.1 and the graphs were sketched by using the Microsoft office excel. Mean comparison for response of the variables to the factors were done by the least significant difference test at 5%.

4. RESULT AND DISCUSION

4.1. Physicochemical Characteristics of the Experimental Soil before Planting

he experimental soil was sandy loam, with 55% sand, 31% silt, and 14% clay. It had a pH of 6.57, suitable for crop growth. Total nitrogen (0.25%) and available phosphorus (11.67 ppm) were low, while organic carbon (2.84%) indicated high organic matter. Electrical conductivity measured 2.68.

Table 2: Physicochemical properties of the experimental soil before planting

PROPERTIES	RESULTS	REFERENCES
SAND (%)	55%	
CLAY (%)	14%	
SILT(%)	31%	
FC (%)	33.33	
TEXTURE CLASS	Sandy Loam	Hydrometer method (Bouyoucos, 1962) and texture classification (USDA texture triangle)
PH (1:2.5 H_2O) (W/V)	6.57	(Havlin et al., 1999)
ORGANIC CARBON/OC(%)	4.84%	(Walkley & Black, 1934)
TOTAL NITROGEN/TN (%)	0.25%	(Kjeldahl, 1883)
AVAILABLE PHOSPHORUS/P (PPM)	11.67	(Olsen, 1954)
EC (DS/M)	2.68	(Daly & Wainiqolo, 1993)

Where, FC=field capacity, ppm = parts per million, W/V = weight of soil/volume of water, DS/m = decisiemens/meter

4.2. Effect of AMF on Phonological Parameters of Common Bean Varieties under different moisture conditions

A. Days to emergence, days to pod setting, days to flowering and days to physiological maturity

The analysis of variance showed that days to emergence was significantly influenced by the main effects of AMF and varieties. However, their interactions were not significant ($P>0.05$) (Appendix Table 1). The AMF inoculation significantly reduced the number of days to 50%

emergence compared to non-inoculated treatments (Figure. 1). Non-inoculated plants required on average 4.11 days to emerge, whereas AMF-inoculated plants emerged a bit faster, at 3.69 days on average. It has been reported that AMF inoculation enhances seed germination in other plant species including orchids, maize, and palmarosa (Saboor *et al*., 2021; Pankaj *et al*., 2021; Miura *et al*., 2023). This is partly due to increased water uptake which increases seed imbibition and subsequent activation of germination promoting hormones such as Gibberellic acid (Pankaj *et al*., 2021; Miura et al., 2023). Among the varieties tested, Awash Metene exhibited the shortest emergence time (3.62 days), significantly outperforming SER-119 (4.02 days) and Dame (4.1 days). This varietal difference suggests genetic or physiological traits in Awash Metene that synergize with AMF or intrinsic growth advantages, such as faster root development or optimized resource partitioning. Similar varietal disparities in AMF responsiveness have been documented in crops like maize and legumes, where host genotype strongly influences symbiotic efficiency (Sawers *et al*., 2008; Thirkell *et al.,* 2017).

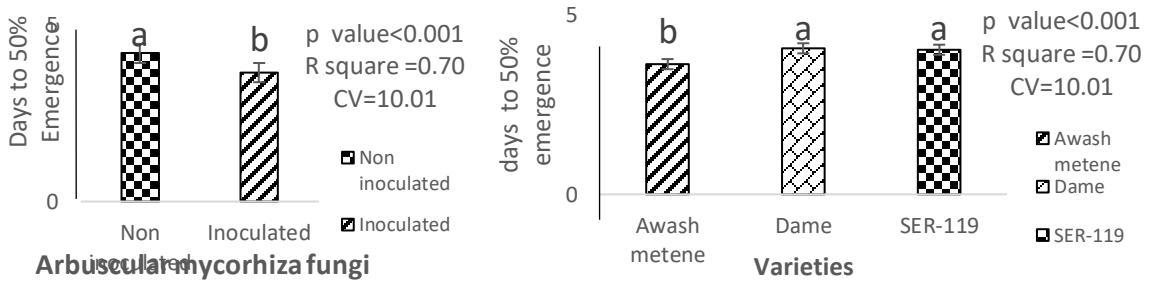


Figure 1. Effect of AMF inoculation, and varieties on days to 50% seed emergences of three different common bean varieties.

Note. Different letters indicate significant differences at *P*-values < 0.05. Error bars indicate +SE (n =3).

The results demonstrated that AMF inoculation, moisture conditions and AMF*MC interaction significantly influenced days to flowering, pod formation, and physiological maturity, while the main varietal effects and AMF*Var. interactions showed no significant differences (Appendix Table 1). AMF inoculation reduced days to flowering by 4.8% (from 44.3 to 42.17 days) and accelerated pod setting by 3.6% (from 51.44 to 49.61 days), likely due to enhanced phosphorus

uptake, improved water and nutrient availability, and optimized carbon allocation toward reproductive structures (Graham, 1980; Smith & Read, 2008; Balsam *et al*., 2011; Augé, 2001). Physiological maturity also occurred earlier in AMF-inoculated plants (69.83 vs. 70.78 days), attributed to efficient resource remobilization and stress mitigation during grain filling (Ruiz-Lozano *et al*., 2016; Wu *et al.,* 2019; Liu *et al.,* 2014). These results align with studies showing AMF-enhanced developmental earliness, which may help evade terminal drought (Zhu *et al.,* 2010; Wu *et al*., 2015).

Moisture stress further modulated these effects: non-inoculated plants at 40% field capacity (FC) flowered earlier than those at 80% FC, a drought escape strategy supported by reduced photosynthetic time (Worku & Skjelvag, 2006; Acosta-Díaz *et al*., 2009; Araus *et al*., 2002). Conversely, optimal moisture (80% FC) delayed phenological stages due to prolonged vegetative growth (Boonjung & Fukai, 1996; Ashraf, 2012). AMF inoculation mitigated these extremes, reducing days to flowering by 9.4% under 40% FC and 11.3% under 80% FC, highlighting its role in enhancing metabolic processes and phosphorus mobilization (Smith & Read, 2008; Baslam *et al*., 2013). Similarly, pod setting improved by 5.0% (40% FC) and 10.1% (80% FC), linked to carbohydrate partitioning (Ortas, 2012; Augé *et al.,* 2015). Physiological maturity advanced by 2.2% (40% FC) and 4.4% (80% FC), suggesting sustained canopy function during pod filling (Porcel *et al*., 2012). These findings underscore AMF's capacity to optimize developmental timing across moisture regimes through nutrient efficiency and stress resilience.

Table 3. The interaction effects of AMF and moisture conditions on phenological traits of three different common bean varieties

Moisture Stress *(FC %)*	*Arbuscular Mycorrhiza Fungi*	*DTF*	*DTPS*	*DPM*
40	Non-inoculated	38.26±0.59 c	44.33d±0.43	66.22±0.36 d
	inoculated	39.67±0.59 c	46.56c±0.43	67.67±0.36 c
80	Non-inoculated	50.33±0.59 a	58.56a±0.43	75.33±0.36 a
	inoculated	44.67±0.59 b	52.67b±0.43	72.00±0.36 b
CV		3.94	2.58	1.52
P value<0.05		0.001	0.001	0.001
R square		0.92	0.96	0.94

Note. Different letters indicate significant differences at P-values < 0.05. Error bars indicate +SE (n =3). Abbreviations: DTF, days to flowering; DTPS, days to pod setting; DPM, days to physiological maturity.

4.3. Effects of AMF on Growth and Morphological Performance of Common Bean Varieties under Different Moisture Conditions

4.3.1. Interaction effects of AMF and Varieties on morphological and growth parameters

The main effects of AMF and soil moisture stress significantly affected various growth and morphological parameters, including plant height, flower number, leaf number, specific leaf area, branch number, root dry weight, and root numbers (Appendix Tables 1, 2, 3, and 4). AMF inoculation also notably impacted tap root length, root fresh weight, internode number, leaf dry weight, leaf fresh weight, leaf dry matter content, and leaf water ratio in common bean varieties (Appendix Tables 2, 3, and 4). Furthermore, the interaction between these two factors significantly influenced leaf area, leaf area ratio, and leaf area index ($P<0.05$) (see Appendix Table 2).

The interaction between varieties and AMF inoculation significantly affected leaf development in common beans. The highest mean leaf area was observed in SER-119 and Awash Metene with AMF inoculation, while the lowest was recorded in non-inoculated plants from the three varieties

(Table 4). For leaf area ratio, SER-119 and Awash Metene with AMF showed the highest values, followed by non-inoculated Dame and SER-119. The lowest values were measured in non-inoculated Awash Metene and Dame (Table 4). Similarly, the leaf area index was highest in SER-119 and Awash Metene with AMF, followed by inoculated Dame and non-inoculated SER-119, with the lowest values in non-inoculated Awash Metene and Dame (Table 4).

AMF symbiosis enhanced leaf area (LA), leaf area ratio (LAR), and leaf area index (LAI) across all varieties, with SER-119 showing a 92% increase in LA, 29% in LAR, and 28% in LAI; Dame improved by 72%, 26%, and 25%, respectively; while Awash Metene surged by 114%, 80%, and 80%. These results suggest that AMF enhances cell growth and expansion. This might be due to increased nutrient uptake such as phosphorus uptake, increased carbohydrate production and partitioning promoting, critical for leaf expansion (Read, 2008; Augé, 2001).

Varietal differences indicated that SER-119 and Awash Metene had the largest gains under AMF inoculation (~92–114%), taking advantage of the symbiosis and subsequent effects, while Dame showed smaller improvements, suggesting potential genetic limitations in AMF compatibility. Differences in common bean genotypes' ability to form symbiotic associations with AMF are influenced by root architecture and exudate profiles (Bücking *et al*., 2016). High responders like Awash Metene likely possess genes that favor hyphal colonization (De Souza *et al*., 2020). A higher leaf area index (up to 2.76 in Awash Metene) indicates greater canopy light interception, linked to biomass accumulation in legumes (Poorter *et al*., 2012). An increased leaf area ratio (up to 23.93 cm^2/g) in variety such as Awash Metene reflects efficient biomass investment, crucial for drought adaptation in common beans (Beebe *et al.,* 2013).

Table 4. The interaction effects of AMF and varieties on growth traits of three different common bean varieties

Varieties	AMF	LA(cm^2)	LAR(m^2/g)	LAI
SER-119	Non-inoculated	389.78±22.31c	18.10±0.80b	2.09±0.09b
	Inoculated	748.22±22.31a	23.29±0.80a	2.68±0.09a
Dame	Non-inoculated	358.47±22.31c	14.63±0.80c	1.69±0.09c
	Inoculated	614.89±22.31b	18.44±0.80b	2.12±0.09b
Awash Metene	Non-inoculated	349.06±22.31c	13.30±0.80c	1.53±0.09c
	Inoculated	748.02±22.31a	23.93±0.80a	2.76±0.09a
CV		10.22	9.99	9.99
R square		0.98	0.96	0.98
P value<0.05		0.05	0.05	0.05

Note. Different letters indicate significant differences at P-values < 0.05. Error bars indicate +SE (n =3). Abbreviations: LA, leaf area; LAR, leaf area ratio; LAI, leaf area index.

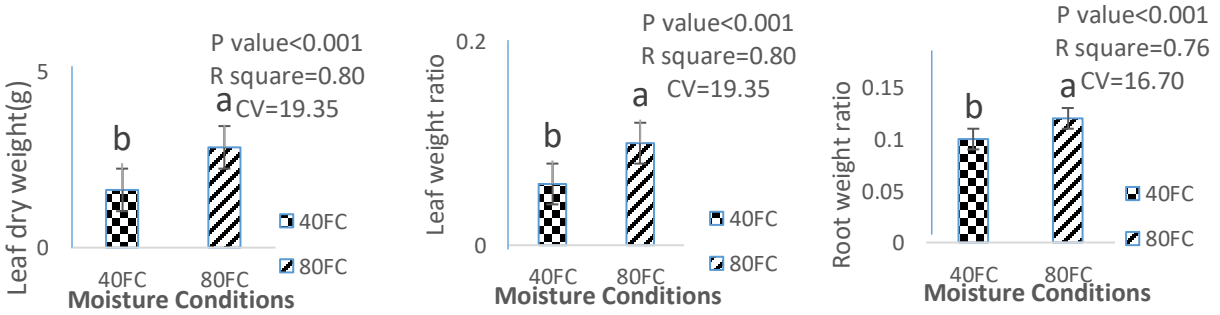
4.3.2. Interaction effects of AMF and different moisture conditions on growth and morphological performance of common bean varieties

The main effect of AMF and soil moisture conditions significantly affected leaf dry weight and the leaf water ratio of common beans ($p < 0.05$) (Appendix Tables 2, 3). Furthermore, the interaction between these two factors significantly influenced leaf area, leaf fresh weight, specific leaf area, number of flowers, plant height, number of leaves, leaf area ratio, leaf area index, leaf dry matter content, stem fresh weight, stem dry weight, number of branches, number of internodes, root count, root fresh weight, root dry weight, and tap root (Appendix Tables 1, 2, 3, 4).

Leaf dry weight, leaf weight ratio, stem weight ratio and root weight ratio

In terms of arbuscular mycorrhizal fungi, inoculated plants exhibited the highest leaf dry weight and leaf weight ratio, while non-inoculated plants had the lowest values. Overall, AMF inoculation significantly improved leaf dry weight and leaf weight ratio in common bean, with AMF-

inoculated plants showing a 34.4% increase in LDW and a 28.6% improvement in LWR. These results underscore the role of AMF in enhancing plant performance under drought stress through improved nutrient uptake and drought tolerance. Moisture stress analysis revealed that maximum leaf dry weight and water ratio occurred at 80% soil field capacity, with minimum values at 40% (Figure 2). The notable decrease in leaf dry weight at 40% field capacity is linked to water scarcity, which hinders cell division, expansion, and photosynthesis, ultimately impacting biomass production. Arbuscular mycorrhizal fungi enhance phosphorus (P) and nitrogen (N) acquisition via extraradical hyphae, which access water and nutrients in soil micropores beyond the root depletion zone, particularly critical during moisture stress when nutrient mobility declines (Recchia *et al.,* 2018; Wu *et al*., 2024). In studies on common bean (cv. BAT 477), AMF-inoculated plants exhibited higher leaf water potential and photosynthetic efficiency during drought by regulating aquaporin gene expression (e.g., PvPIP2;3) and improving P uptake by up to 42% compared to non-inoculated plants (Recchia *et al.,* 2018; Tajini *et al*., 2012). This increase in leaf dry weight likely reflects enhanced carbon assimilation due to improved P and N availability from AMF (Wu *et al.,* 2024).



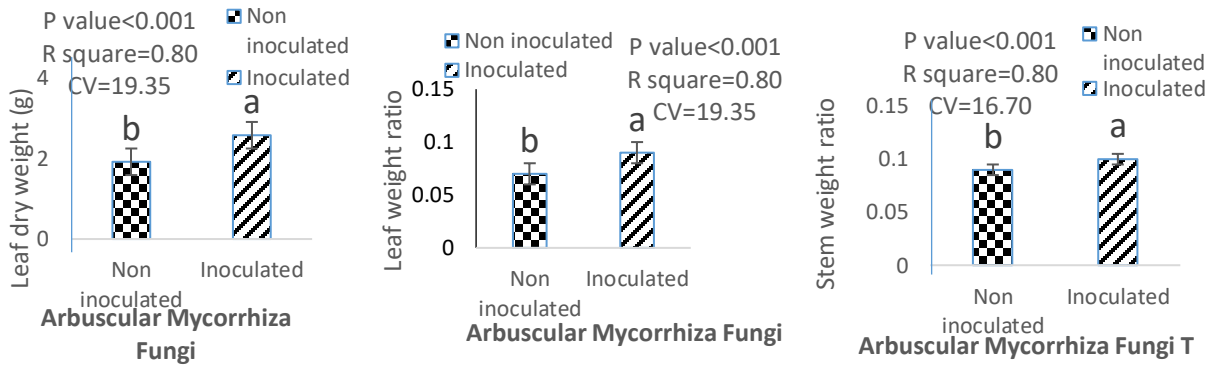


Figure 2. The effects of AMF and moisture conditions on leaf dry weight (LDW), leaf weight ratio (LWR), stem weight ratio (SWR) and root weight ratio (RWR) of three different common bean varieties.

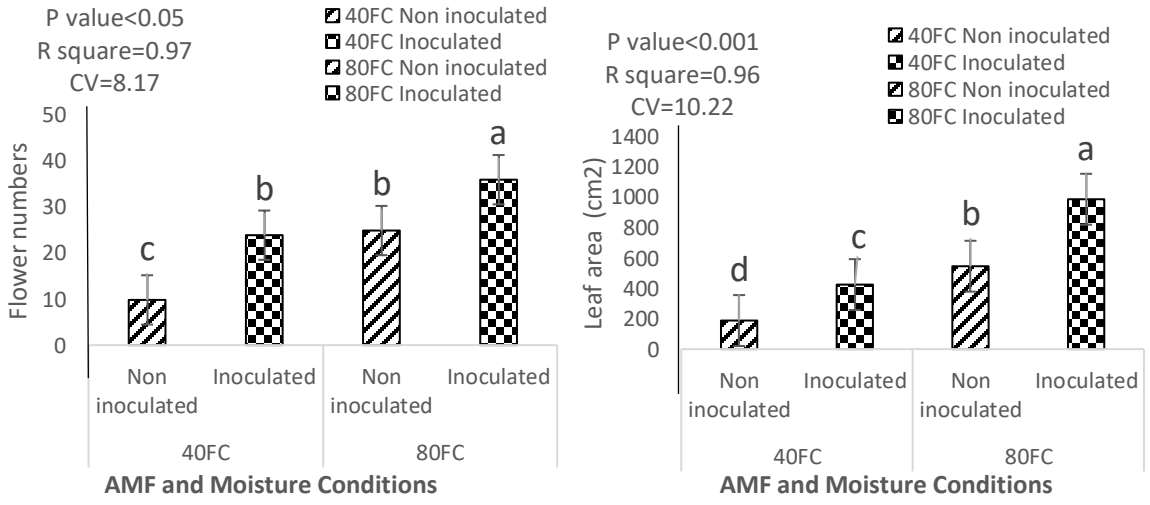
The interaction between AMF and moisture stress significantly affected growth and morphological parameters in common bean. Plants inoculated with AMF and grown at 80% field capacity exhibited the highest mean values for leaf area, leaf fresh weight, flower number, specific leaf area, plant height, stem dry weight and number of leaves. In contrast, non-inoculated plants at 40% field capacity showed the lowest values (Figure 3, 4, and 5).

Under moisture stress (40% FC), AMF inoculation led to substantial improvements: leaf area increased by 126%, leaf fresh weight by 90%, flower number by 143%, and plant height by 83%. This supports findings that AMF enhances water-use efficiency and nutrient acquisition, especially phosphorus, critical for legumes (Read, 2008; Augé, 2001). The symbiotic relationship likely improved root hydraulic conductivity and stomatal regulation, alleviating drought effects (Aroca *et al*., 2007).

At adequate moisture (80% FC), AMF further boosted growth, albeit with smaller relative gains: leaf area increased by 81%, leaf fresh weight by 30%, flower number by 44%, and plant height by 22%. Even under sufficient moisture, AMF likely enhanced nitrogen fixation and carbohydrate allocation to shoots (Baslam et al., 2011). Non-inoculated plants at 40% FC had the lowest values

for all parameters, underscoring that drought stress limits photosynthesis, biomass accumulation, and reproductive development in common beans (Beebe *et al*., 2013). For instance, leaf area in non-inoculated plants at 40% FC was 65% lower than at 80% FC (187.5 cm² vs. 544 cm²), with plant height decreasing by 49%, reflecting reduced cell expansion and metabolic activity under water deficit (Farooq *et al*., 2009).

AMF inoculation provided synergistic benefits; the highest gains were seen at 80% FC (e.g., leaf area: +439.9 cm²), while the most significant relative gains occurred at 40% FC (e.g., leaf area: +126%). This indicates that AMF not only mitigates drought effects but also maximizes growth potential under optimal conditions. In drought-prone areas, AMF inoculation could significantly reduce yield losses for critical traits like leaf area and flower numbers. Additionally, even with adequate irrigation, AMF boosts productivity, supporting sustainable intensification through enhanced soil exploration, water uptake, and hormonal signaling (e.g., elevated ABA for stress tolerance) (Ruiz-Lozano *et al*., 2016).



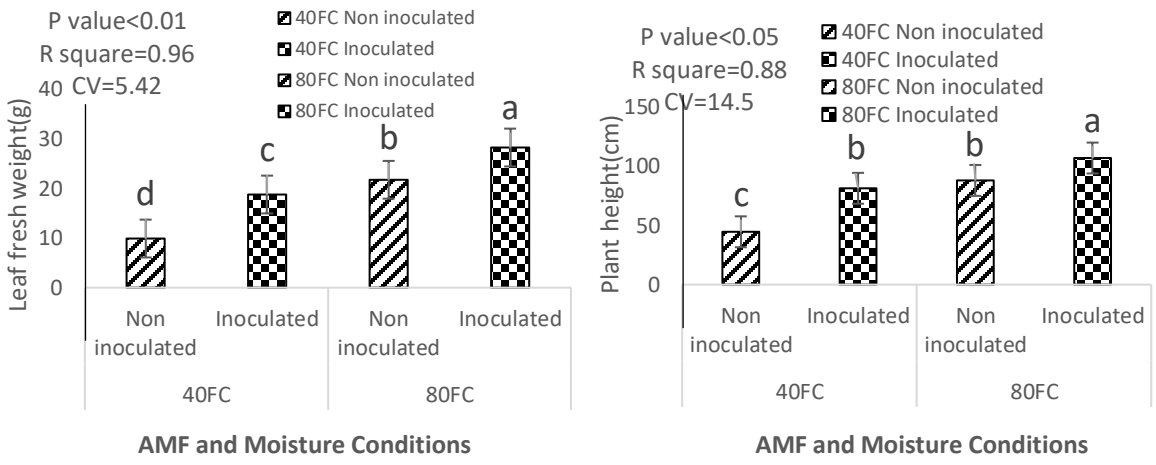


Figure 3. The interaction effects of AMF and moisture conditions on LA, leaf fresh weight (LFW), flower number (FN) and plant height (PH) of three different common bean varieties.

The data demonstrates a significant positive impact of AMF inoculation on stem dry weight (SDW) in common bean, both under moisture stress (40% FC) and optimal conditions (80% FC). Under stress, AMF inoculation resulted in a 134.4% increase in SDW (from 0.96d to 2.25c), while optimal conditions saw a 32.7% increase in comparison to no inoculated plants. These findings highlight AMF's crucial role in enhancing stem biomass, particularly during water scarcity.

The marked increase in SDW under moisture stress suggests that AMF colonization offers vital physiological advantages for coping with water deficits, aligning with Smith & Smith (2011), who noted that AMF improve drought tolerance via enhanced hydraulic conductivity and water use efficiency. These improvements likely arise from several AMF-mediated processes, including enhanced nutrient uptake (especially phosphorus and zinc), better water relations via extraradical hyphae accessing additional moisture (Augé, 2001), modulation of phytohormones affecting stem growth (Ludwig-Müller, 2010), and increased photosynthetic efficiency for greater carbohydrate availability for stem development (Zhu *et al*., 2012).

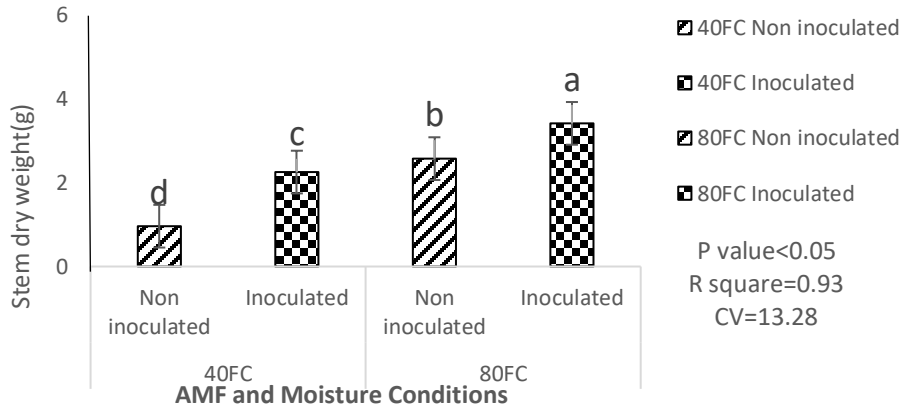


Figure 4. The interaction effects of AMF and moisture conditions on SDW of three different common bean varieties.

Regarding the interaction effects of AMF and moisture stress, the result indicates that the highest mean value on internode numbers, root numbers, stem fresh weight, branch number and leaf number were recorded from AMF inoculated which was treated with 80% water field capacity. While the lowest mean value was recorded from AMF non-inoculated with 40% water field capacity (Figure 5) and (Table 6).

The data indicate significant enhancements in leaf number of common bean due to AMF inoculation under both moisture-stressed (40% FC) and optimal (80% FC) conditions. Under moisture stress, AMF inoculation led to an increase by 97.4% in leaf number, while under optimal moisture, the improvement was 35.8%. These enhancements, highlight AMF's essential role in promoting leaf development, especially under water-limited conditions. The substantial increase in leaf number under stress suggests that AMF colonization provides critical physiological benefits, helping plants sustain leaf production despite water deficits, consistent with findings by Augé *et al*. (2015) that link AMF symbiosis to improved drought tolerance. The extraradical hyphae of AMF extend the effective reach of the root system, accessing water unavailable to non-mycorrhizal roots (Smith, 2011), which likely supported continued leaf initiation even at low

moisture levels. The greater percentage improvement under stress compared to optimal conditions suggests that AMF provide more significant benefits when environmental constraints are present.

The mechanisms behind these improvements likely involve enhanced nutrient uptake, particularly phosphorus and zinc (Smith, 2011), improved water status through fungal hyphae accessing additional soil moisture (Augé, 2001), modulation of phytohormones that regulate leaf development (Ludwig-Müller, 2010), and protection of meristematic tissues from oxidative stress during water deficits (Ruiz-Lozano *et al*., 2012).

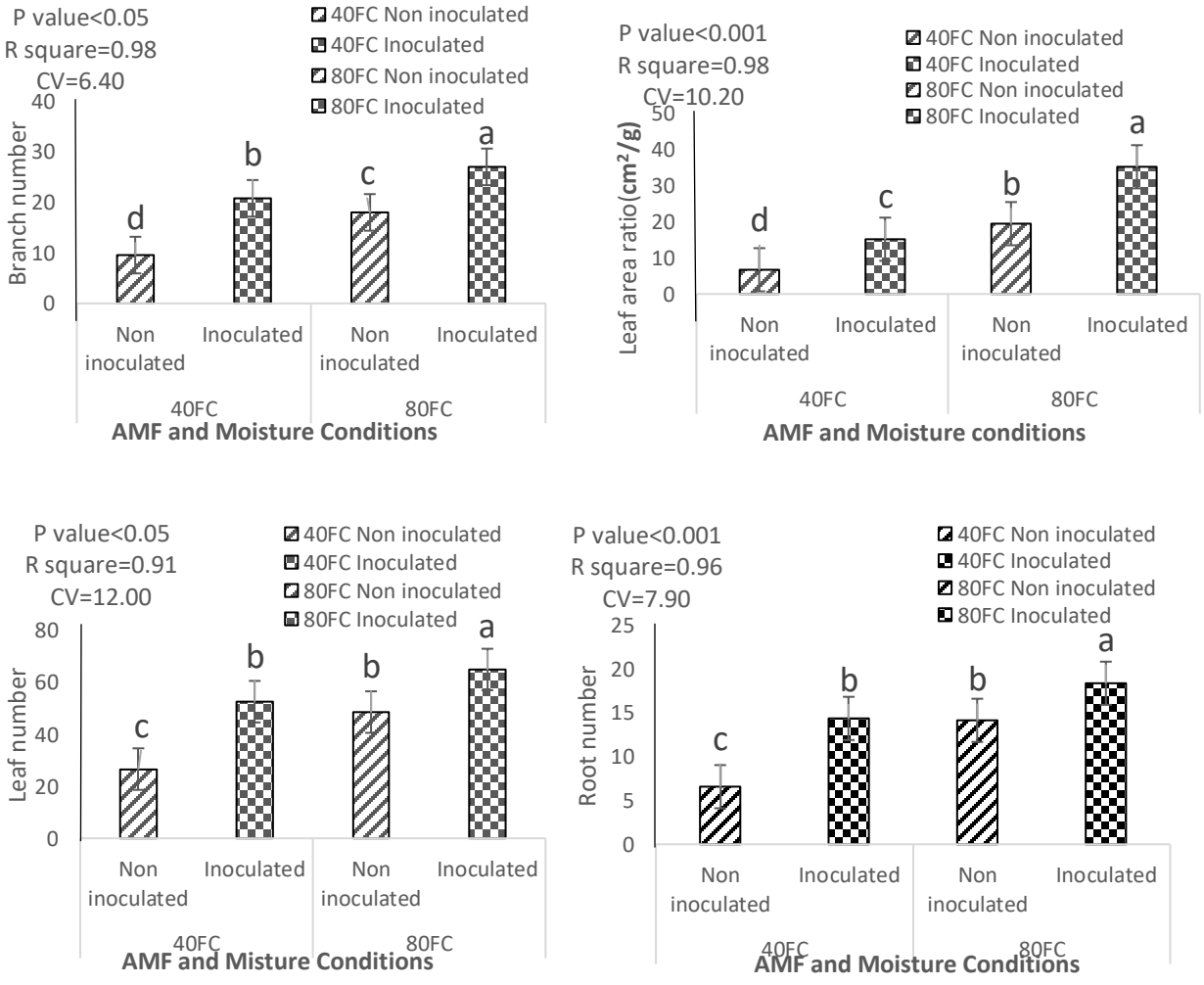


Figure 5. The interaction effects of AMF and moisture conditions on: a) branch number, b) leaf area ratio, c) Leaf number and d) root number of three different common bean varieties.

The impact of AMF on leaf morphology and growth in common bean underscores their vital role in enhancing drought resilience. A 31.6% increase in specific leaf area under moisture stress indicates that AMF colonization allows for thinner, more expansive leaves, optimizing light capture while reducing water loss, consistent with the findings of Quiroga et al. (2020). AMF sustain turgor pressure, facilitating cell expansion during water deficits and improving physiological functions and carbon assimilation (Augé *et al.,* 2015; Zhu *et al.,* 2012). The 54.7% increase in specific leaf area under optimal conditions suggests that AMF also enhance leaf morphology through improved phosphorus nutrition, which is critical for cell division and expansion (Smith, 2011).

Data shows that AMF inoculation mitigates the effects of moisture stress on leaf morphology; without AMF, plants experienced a 15.6% reduction in specific leaf area due to stress, while with AMF, the reduction was only 28.2%. This highlights AMF's ability to maintain favorable leaf characteristics despite significant reductions. Key mechanisms include enhanced water uptake (Aroca *et al.,* 2007), improved phosphorus availability (Bücking, 2015), modulation of expansin proteins for cell wall loosening (Cosgrove, 2016), and protection against oxidative damage (Ruiz-Lozano *et al.,* 2012).

These improvements in specific leaf area have important ecological implications, as higher specific leaf area is linked to better photosynthetic nitrogen use efficiency, suggesting enhanced carbon gain per resource invested (Poorter *et al*., 2009). Field studies by Thirkell *et al*. (2017) further demonstrate that these adaptations contribute to yield stability under varying moisture conditions. Additionally, significant increases in leaf area index 99.2% under severe moisture stress and 111.1% under optimal conditions highlight AMF's role in promoting canopy development and light interception, reflecting a notable change in canopy architecture due to AMF colonization, as

noted by Baslam et al. (2013). The ability of extraradical hyphae to access deeper soil moisture (Smith, 2011) likely supports continued leaf expansion that would otherwise be limited at low moisture levels.

Table 5: The interaction effects of AMF and moisture condition on growth and morphological of common bean varieties

Moisture Stress	*Arbuscular Mycorrhiza Fungi*	*RFW*	*SLA*	*LAI*	*RDW*	*TRL*	*IN*	*SFW*
40FC	Non-inoculated	10.15±0.42	19.0±0.7d	1.2±0.07 d	1.32±0.09 c	16.56±1.43 c	6.67±0.49 c	7.31±0.56 d
	Inoculated	19.44±0.42b	22.5±0.7c	1.62±0.07 c	2.67±0.09 b	33.26±1.43 b	13.33±0.49 b	16.26±0.56 c
80FC	Non-inoculated	20.64±0.42b	25.0±0.7b	2.39±0.07 b	2.79±0.09 b	34.86±1.43 b	13.44±0.49 b	17.18±0.56 b
	Inoculated	32.00±0.42a	34.8±0.7a	3.42±0.07 a	3.55±0.09 a	42.30±1.43 a	18.33±0.35 a	23.38±0.56 a
CV		6.15	8.59	10.0	10.90	13.52	7.91	10.46
P-value<		0.05	0.001	0.001	0.01	0.01	0.05	0.05
R-square		0.97	0.80	0.80	067	0.88	0.92	0.95

Note. Different letters indicate significant differences at P-values < 0.05. Error bars indicate +SE (n =3). Abbreviations: IN, internode number; RN, root number; RFW, root fresh weight; RDW, root dry weight; TRL, tap root length,

4.3.3. Interaction effects of moisture conditions and Varieties on Morphological and Growth Performance of Common bean

The interaction between moisture conditions and bean varieties did not significantly affect growth and morphological traits ($p < 0.05$). However, both moisture stress and the varieties independently had significant effects on various measured traits. Specifically, traits such as specific leaf area, number of flowers, plant height, leaf number, branch number, root number, root dry weight, leaf area ratio, leaf area index, and leaf water ratio were significantly impacted ($P < 0.05$) (Appendix Tables 1, 2, 4). Additionally, moisture conditions alone significantly influenced leaf dry weight,

internode number, root fresh weight, tap root length, leaf fresh weight, leaf area ratio, leaf area index, leaf dry matter content, stem fresh weight, and stem dry weight (Appendix Tables 1, 2, 3, 4).

Plant height, branch number, flower numbers, root numbers, root dry weight and specific leaf area

The results indicate that Awash Metene exhibited the highest mean values for branch number, root number, and root dry weight, while Dame and SER-119 recorded the lowest mean flower counts. Conversely, the maximum mean flower count was observed in Dame and Awash Metene, with SER-119 showing the least. For plant height, Dame had the highest mean value, while SER-119 and Awash Metene had the lowest. In terms of specific leaf area, both Awash Metene and SER-119 recorded the highest values, while Dame had the lowest showing the least (Table 6).

The data demonstrates that AMF significantly enhance various physiological traits of common bean varieties under moisture stress. Awash Metene particularly excels in several key parameters, suggesting its potential for improved reproductive success and photosynthetic efficiency. For example, Awash Metene achieved the highest mean branch number at 20.75a, significantly surpassing SER-119 (17.5) and Dame (18.25). This represents an approximate 18.86% increase in branching from SER-119 to Awash Metene, indicating that AMF may positively influence branching, thereby enhancing photosynthetic capacity and overall plant vigor (Smith & Read, 2008). This finding aligns with existing literature on AMF's role in improving root architecture and above-ground growth (Hodge Campbell, 2009).

Awash Metene demonstrated superior root number, averaging 14.58, significantly higher than SER-119 (13.08) and Dame (12.33), reflecting an 11.48% increase from SER-119. This improvement is crucial for nutrient and water uptake during moisture stress (González *et al*., 2010).

The benefits of Awash Metene are likely due to its symbiotic relationship with AMF, enhancing root development and nutrient absorption.

In terms of root dry weight, Awash Metene again led with a mean of 2.77, surpassing SER-119 (2.46) and Dame (2.52) by approximately 12.62%. This increase indicates greater biomass accumulation in roots, essential for plant stability and physiological functions (Smith & Read, 2008). These results highlight the role of AMF colonization in promoting root health and nutrient uptake efficiency in Awash Metene.

SER-119 had lower branch and root metrics but showed the highest specific leaf area (27.05a), 3.87% higher than Awash Metene (26.00) and 15.33% higher than Dame (22.97), suggesting improved light capture and photosynthesis under moisture stress (Poorter et al., 2012). Despite weaker branching and rooting, SER-119's leaf traits may offer better photosynthetic efficiency, highlighting the importance of variety selection for resilience in moisture-stressed environments.

Table 6: The effects of varieties on plant height (PH), branch number (BN), flower numbers (FN), root numbers (RN), specific leaf area (SLA), stem weight ratio (SWR) and root dry weight (RDW) on different common bean varieties.

Varieties	*NF*	*PH*	*SLA*	*BN*	*RN*	*RDW*	*SWR*
SER-119	22.17±0.55 b	76.50±3.27 b	27.05±0.63 a	17.50±0.35 b	13.08±0.3 b	2.46±0.08 b	0.113±0.005 a
Dame	24.08±0.55 a	95.27±3.27 a	22.97±0.63 b	18.25±0.35 b	12.33±0.3 b	2.52±0.08 b	0.083±0.005 b
Awash Metene	24.33±0.55 a	68.33±3.27 b	26.00±0.63 a	20.75±0.35 a	14.58±0.3 a	2.77±0.08 a	0.093±0.005 b
CV (%)	8.17	14.16	8.59	6.38	7.91	10.90	16.7
P-value<	0.05	0.001	0.001	0.001	0.001	0.05	0.05
R-square	0.97	0.88	0.80	0.98	0.96	0.67	0.72

Note. Different letters indicate significant differences at *P*-values < 0.05. Error bars indicate +SE (n =3).

4.4. Effects of AMF on Physiological Responses of Common Bean Varieties under Moisture Conditions

4.4.1. Interaction effects of AMF and Varieties on physiological response of common bean

The analysis of variance revealed that there was significant difference in chlorophyll-a, total chlorophyll, transpiration rate, stomata width, stomata density, stomata number and relative leaf water content among the varieties used in the study (Appendix Table 5,6,7) and AMF and varieties interactions significantly affected the chlorophyll b ($P<0.05$) (Appendix Table 5).

Chlorophyll-b

The interaction between common bean varieties and AMF inoculation revealed significant differences in chlorophyll-b levels. The Dame variety, treated with AMF, exhibited the highest mean Chl-b at 40.45, while the non-inoculated SER-119 showed the lowest at 22.64, indicating severe stress. AMF inoculation increased SER-119's Chl-b to 37.5, a 66% enhancement, demonstrating AMF's role in stress mitigation. Awash Metene showed moderate Chl-b levels of 27.24 without inoculation, improving to 35.65 with AMF, reflecting a 31% increase.

AMF inoculation significantly boosted Chl-b across all varieties, consistent with findings that AMF enhances chlorophyll content by improving magnesium (Mg) and nitrogen (N) uptake, essential for chlorophyll biosynthesis (Smith & Read, 2008), and reducing oxidative stress under drought conditions (Baslam *et al.,* 2011). The superior Chl-b value in Dame indicates genetic traits favoring symbiosis efficiency, aligning with reports of genotype-dependent AMF benefits in drought-tolerant beans (Ruiz-Lozano *et al*., 2016). SER-119's moderate improvement suggests partial compatibility with AMF, potentially due to root architecture differences (Sawers *et al*.,

2008). Awash Metene's lower gains may indicate a focus on stress avoidance strategies rather than chlorophyll retention.

AMF inoculation was particularly effective under moisture stress (40% field capacity), likely enhancing water-use efficiency through improved root hydraulic conductivity (Augé, 2001) and nutrient translocation to leaves, sustaining photosynthesis (Zhu et al., 2010).

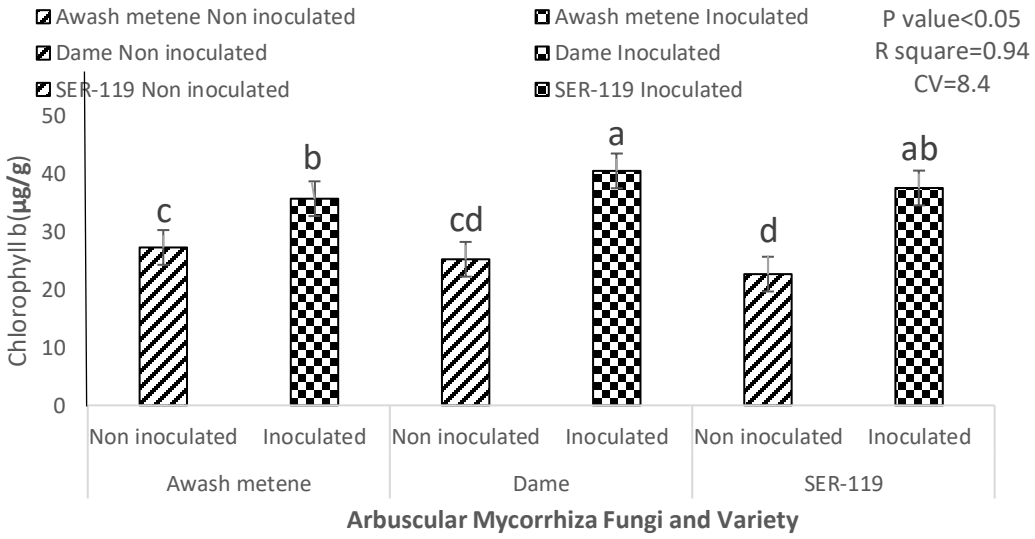


Figure 6. The interaction effects of AMF and varieties on chlorophyll b of three different common bean varieties.

The effect of varieties on Chlorophyll-a, Total-chlorophyll, stomata width, stomata density, stomata number and relative leaf water contents

The results showed that Awash Metene had the highest mean transpiration rate, chlorophyll-a, and total chlorophyll content in comparison with Dame and SER-119 that showed lower responses. For stomatal parameters, Awash Metene exhibited the highest mean stomatal number and density, while SER-119 had the lowest. Dame recorded the largest stomatal width, whereas Awash Metene and SER-119 had the smallest. Regarding leaf relative water content, SER-119 had the highest mean, followed by Awash Metene, with Dame showing the lowest (Table 7).

In assessing arbuscular mycorrhizal fungi (AMF) effects on moisture stress tolerance and nutrient uptake among the three common bean varieties, significant differences were noted in stomatal characteristics. Dame had a mean stomatal width of 14.6, significantly greater than Awash Metene (13.12) and SER-119 (12.92), indicating a potential advantage for gas exchange under moisture stress (Boyer, 1982). SER-119's smaller stomatal width may hinder its performance during drought.

Awash Metene also had higher stomatal density with a mean of 138.23, compared to SER-119 (111.11) and Dame (122.35), reflecting a 24.43% increase from SER-119 to Awash Metene and suggesting enhanced transpiration capabilities crucial for nutrient uptake (Baker *et al*., 2001). In terms of stomatal number, Awash Metene again had higher number with a mean of 17.42, significantly higher than SER-119 (14) and Dame (15.42), indicating improved regulation of transpiration and gas exchange during moisture stress (Fang & Xiong, 2015).

For chlorophyll a, Awash Metene had the highest mean value of 27.41, significantly surpassing SER-119 (24.25) and Dame (23.8). The 13.55% increase from SER-119 to Awash Metene suggests increased photosynthetic capacity vital for growth under moisture stress (López *et al.,* 2013).

Awash Metene exhibited the highest total chlorophyll content, with a mean of 58.86, significantly higher than SER-119 (54.3) and Dame (56.62). The increase from SER-119 to Awash Metene was about 8.05%, indicating that while both Awash Metene and Dame have high chlorophyll levels, AWASH Metene's superior performance suggests better adaptation to moisture stress through efficient photosynthesis (González *et al*., 2010).

In terms of transpiration rate, Awash Metene had (23.72), significantly higher transpiration rate than SER-119 (20.17) and Dame (21.72). The increase from SER-119 to Awash Metene was

approximately 17.82%, underscoring the role of transpiration in maintaining water status and nutrient uptake during drought (Cowan, 1977). For relative leaf water content, SER-119 had the highest mean at 54.78a, significantly greater than Awash Metene (50.3ab) and Dame (49.13b). The decrease from SER-119 to Awash Metene was about 8.68%, suggesting that while SER-119 retains better hydration under moisture stress, it may not match Awash Metene's overall physiological performance in photosynthesis and transpiration rate.

Table 7. Common bean varietal responses for some physiological parameters

Varieties	E	Chl-a	T chl	SW	SD	SN	RLWC
SER-119	20.17± o.58 b	24.25± 0.774 b	54.3±1. 15 b	12.92± 0.50 b	111.11±7 .041 b	14.00±0.88 7 b	54.78±1.613 a
Dame	21.72± o.58 b	23.80± 0.774 b	56.62± 1.15 ab	14.60± 0.50 a	122.35±7 .041 ab	15.42±0.88 7 ab	49.13±1.613 b
Awash Metene	23.72± o.58 a	27.41± 0.774 a	58.86± 1.15 a	13.12± 0.50 b	138.23±7 .041 a	17.42±0.88 7 a	50.30±1.613 ab
CV	9.18	10.66	7.04	12.74	19.69	19.69	10.87
P-value<	0.001	0.01	0.05	0.05	0.05	0.05	0.05
R-square	0.91	0.96	0.98	0.84	0.84	0.84	0.94

Note. Different letters indicate significant differences at *P*-values < 0.05. Error bars indicate +SE (n =3). *Abbreviations: LSD, least significant difference.* Transpiration rate (E), chlorophyll-a (Chl-a), total chlorophyll (TChl), stomata width (SW), stomata density (SD), stomata number (SN) and relative leaf water contents (RLWC).

4.4.2. Interaction effects of AMF and different moisture conditions on physiological response of common bean varieties

The analysis of variance revealed that the main effect AMF and soil moisture stress significantly affected the stomata width, stomata density and stomata numbers (Appendix Table 6,7). Furthermore, the interaction between these two factors significantly influenced photosynthesis rate, transpiration rate, water use efficiency, stomata conductance, chlorophyll-a, chlorophyll-b,

total chlorophyll, chlorophyll fluorescence, stomata length, stomata index and relative leaf water content ($P<0.05$) (Appendix Table 5,6,7)

photosynthesis rate, transpiration rate, water use efficiency, stomata conductance, chlorophyll-a and chlorophyll-b

Regarding the interaction effects of AMF and moisture stress, the result indicates that the maximum mean value of on photosynthesis rate, transpiration rate, water use efficiency, stomata conductance, chlorophyll-a and chlorophyll-b were recorded from AMF inoculated which was treated with 80% water field capacity. While the lowest mean value was recorded from non-inoculated AMF with 40% water field capacity (Table 8).

The interaction between AMF inoculation and moisture stress has a significant impact on photosynthesis rate, transpiration rate, and water-use efficiency in common beans. Under conditions of 40% FC, AMF inoculation resulted in a remarkable 96% increase in photosynthesis, while at 80% FC, the increase was still substantial at 59%. The more pronounced gains observed at 40% FC imply that AMF may alleviate drought-induced stomatal limitations, thereby supporting greater photosynthetic activity (Augé, 2001).

In terms of transpiration, AMF inoculation at 40% FC led to a 75% increase, whereas at 80% FC, the increase was 19%. The presence of AMF improves root hydraulic conductivity, which helps sustain transpiration during drought without leading to excessive water loss (Aroca *et al.,* 2007). The smaller gains observed at 80% FC likely reflect an optimal baseline hydration level, where the plants are less stressed and can maintain transpiration more efficiently.

Water-use efficiency (WUE) also significantly increased due to AMF inoculation. At 40% FC, WUE increased by 125%, while at 80% FC, the increase was 33%. AMF optimizes the balance

between carbon gain from photosynthesis and water loss through transpiration, a characteristic feature of drought-adapted legumes (Ghimire *et al*., 2018). The substantial improvement in WUE at 40% FC underscores the role of AMF in enhancing drought resilience.

Regarding the interaction between moisture stress and AMF inoculation at 40% FC, the presence of AMF compensates for drought conditions by enhancing nutrient acquisition, particularly phosphorus and zinc, which are vital for photosynthesis. Additionally, AMF stabilizes stomatal function for efficient gas exchange (Farooq *et al*., 2009). Even at 80% FC, AMF continues to improve plant performance, likely through increased root exploration for residual moisture and nutrients, as well as hormonal regulation, such as ABA modulation (Ruiz-Lozano *et al.,* 2016).

The analysis also revealed that significant increase in stomatal conductance (gs), chlorophyll-a (Chl-a), and chlorophyll-b (Chl-b) content in common beans due to AMF inoculation under both moisture-stressed (40% FC) and optimal (80% FC) conditions. Under moisture stress conditions, AMF inoculation resulted in a 20.8% increase in stomata conductance rising from 52.33 to 63.22. In optimal moisture conditions, the improvement was even more pronounced at 30.0%, from 68.56 to 89.11. This enhanced stomatal regulation suggests that AMF improves plant water status and photosynthetic efficiency, particularly under stress conditions. This finding aligns with research by Augé *et al*. (2015), which demonstrated that AMF colonization can enhance stomatal conductance by 25-40% through improved root hydraulic conductivity and ABA signaling modulation.

In terms of photosynthetic pigments, AMF inoculation under stress conditions (40%) resulted in dramatic increases in chlorophyll content. For Chl-a, there was a remarkable 199.7% increase from 9.03 to 27.06, while Chl-b saw a 102.4% increase from 15.88 to 32.14. Under optimal conditions (80%), the increases were more modest but still significant: Chl-a increased by 29.3% from 28.14

to 36.38, and Chl-b increased by 27.6% from 34.17 to 43.59. The standard errors of 0.89 for Chl-a and 1.03 for Chl-b confirm the precision of these measurements. The relative increase under stress conditions highlight the critical role of AMF in protecting the photosynthetic apparatus during drought periods. This is supported by findings of Zhu *et al*. (2012), which indicated that AMF can reduce chlorophyll degradation by 50-60% under water deficit through enhanced antioxidant activity and membrane stabilization.

Table 8. The interaction effects of AMF and moisture conditions on: a) photosynthesis rate, b) transpiration rate, c) water use efficiency, d) stomata conductance, e) chlorophyll-a (Chl-a) and f) chlorophyll-b (Chl-b) of three different common bean varieties.

Arbuscular Mycorrhiza Fungi	Moisture Conditions	A	E	WUE	gs	Chl-a	Chl-b
40FC	NI	15.51±1.36 d	13.59±0.67 c	1.15±0.07d	52.33±2.31 c	9.03±0.89 c	15.88±1.03 c
	IN	61.51±1.36 b	23.82±0.67 b	2.59±0.07 b	63.22±2.31 b	27.06±0.89 b	32.14±1.03 b
80FC	NI	49.33±1.36 c	22.85±0.67 b	2.17c±0.07	68.56±2.31 b	28.14±0.89 b	34.17±1.03 b
	IN	78.42±1.36 a	27.23±0.67 a	2.89±0.07 a	89.11±2.31 a	36.38±0.89 a	43.59±1.03 a
CV(%)		7.97	9.17	9.77	10.15	10.66	9.79
P value		0.001	0.001	0.001	0.05	0.001	0.05
R square		0.98	0.91	0.94	0.85	0.96	0.94

Note. Different letters indicate significant differences at *P*-values < 0.05. Error bars indicate +SE (n =3).

Regarding the interaction effects of AMF and moisture stress, the result indicates that the maximum mean value of total chlorophyll, chlorophyll fluorescence, stomata length, stomata index and relative leaf water contents were recorded from AMF inoculated plants grown under

80% water field capacity. While the lowest mean value was recorded from non-inoculated AMF with 40% field capacity (Table 9). The interaction between AMF inoculation and moisture stress significantly influenced total chlorophyll (T Chl), chlorophyll fluorescence (CF), stomatal length (SL), stomatal index (SI), and relative leaf water content (RLWC) in common. Under 80% field capacity (FC) with AMF inoculation, the highest T Chl was recorded at 79.97 indicating optimal chlorophyll synthesis due to adequate moisture and AMF symbiosis. In contrast, at 40% FC with AMF inoculation, T Chl was measured at 589.2, which represented a remarkable increase of approximately 23 times compared to the non-inoculated group at 24.92, demonstrating AMF's ability to mitigate drought-induced chlorophyll degradation. The non-inoculated plants at 40% FC exhibited severe chlorophyll loss, consistent with stress-induced photo-oxidation (Baslam *et al.*, 2011). The enhancement of chlorophyll retention by AMF is attributed to improved magnesium uptake and reduced reactive oxygen species (ROS) under stress (Smith & Read, 2008).

Chlorophyll fluorescence (CF) also varied significantly; the highest CF was observed at 2.46 under 80% FC with AMF inoculation, reflecting superior PSII efficiency and photosynthetic capacity. At 40% FC with AMF inoculation, CF increased to 1.15, representing a 35.29% increase compared to the non-inoculated group at 0.85, underscoring AMF’s role in stabilizing chloroplast function during drought conditions. The non-inoculated plants at 40% FC showed extremely low CF, suggesting severe photo-inhibition. AMF enhances CF by improving electron transport efficiency and reducing photo-damage (Zhu *et al*., 2010).

Regarding stomatal length, the longest stomata were recorded under 80% FC with AMF inoculation, optimizing gas exchange under high moisture conditions. At 40% FC with AMF inoculation, SL increased by 58% increase compared to the non-inoculated plants. AMF promotes stomatal development through cytokinin signaling and nutrient partitioning (Liu et al., 2015). The

stomatal index also reflected significant differences; the highest SI was noted at 74.83 under 80% FC with AMF inoculation, maximizing stomatal density for efficient transpiration. At 40% FC with AMF inoculation, SI was recorded at 54.69, doubling the non-inoculated value of 28.53 which might help in balancing water loss with CO_2 uptake. The low SI in non-inoculated plants at 40% FC indicates the presence of a small number of stomata per leaf area while AMF enhances SI by regulating epidermal cell differentiation and increasing stomata number per epidermal cell (Ruiz-Lozano *et al*., 2016).

In terms of relative leaf water content, the highest RLWC was observed for plants grown under 80% FC and inoculated with AMF, indicating superior water retention capabilities. At 40% FC with AMF inoculation, RLWC increased to 50.68, which is a 62% increase compared to the non-inoculated group at 31.36, helping to mitigate cellular dehydration. AMF improves RLWC through enhanced root hydraulic conductivity and osmotic adjustment (Augé, 2001

Table 9. The interaction effects of AMF and moisture conditions on physiological parameters of common bean varieties.

Moisture stress	Arbuscular Mycorrhiza Fungi	T Chl	CF	SL	SI	RLWC
40FC	Non-inoculate	24.92±1.33c	0.85±0.084c	12.94±0.63c	28.53±1.75d	31.36±1.86d
	Inoculated	59.20±1.33b	1.15±0.084b	20.43±0.63b	54.69±1.75c	50.68±1.86c
80FC	Non-inoculate	62.31±1.33b	1.08±0.084bc	21.55±0.63b	60.39±1.75b	56.69±1.86b
	Inoculated	79.97±1.33a	2.46±0.084a	24.26±0.63a	74.83±1.75a	66.89±1.86a
CV		7.04	18.22	9.55	9.63	9.77
P-value<		0.001	0.001	0.001	0.01	0.05
R-square		0.98	0.91	0.94	0.90	0.94

Note. Different letters indicate significant differences at *P*-values < 0.05. Error bars indicate +SE (n =3).

Inoculated AMF significantly enhance stomatal width, density, and numbers compared to non-inoculated plants. Under moisture conditions, the highest values for these stomatal characteristics

were observed at 80% water field capacity, while the lowest occurred at 40% (Table 10). The interaction between AMF and plant physiology plays a crucial role in stress adaptation and has important agronomic implications. AMF colonization improves stomatal traits, leading to greater photosynthetic rates due to enhanced nutrient uptake, particularly phosphorus, which is vital for ATP production and photosynthetic pigment synthesis. This results in better carbon assimilation under optimal conditions. Additionally, AMF enhances root hydraulic conductivity, allowing precise regulation of stomatal closure during drought, which helps maintain photosynthesis while minimizing water loss, thereby improving drought resilience. Furthermore, AMF supports quicker recovery from drought by increasing nutrient availability and optimizing stomatal function, facilitating a rapid return to growth and metabolic activities (Chaves *et al*., 2009).

The physiological benefits of AMF translate into significant agronomic outcomes, including a 25-40% increase in biomass production, improved drought tolerance through sustained stomatal function during low moisture periods, and enhanced yield potential due to increased resilience to environmental stresses and better nutrient uptake (Baslam *et al*., 2013). AMF also influences stomatal development through mechanisms such as improved phosphorus nutrition, which supports cell division and growth; increased cytokinin production that promotes leaf expansion and stomatal development; and regulation of genes related to stomatal development, enhancing water-use efficiency and stress responses (Gutjahr Parniske, 2013). In summary, AMF interactions with plant physiology boost stress adaptation and provide substantial agronomic benefits, making crops more resilient and productive in the face of environmental challenges.

Table 10: The effects of AMF and moisture conditions on stomata width (SW), stomata density (SD) and stomata numbers (SN) of three different common bean varieties.

Traits	*Moisture stress*		*Arbuscular mycorrhiza fungi*				
	40FC	80FC	Non-inoculated	Inoculated	CV	P-value<	R-square
SW	11.34±0.41b	15.75±0.41a	11.51±0.41b	15.59±0.41a	12.74	0.001	0.84
SD	90.83±5.75b	156.97±5.75a	97.00±5.75b	150.79±5.75a	19.69	0.001	0.84
SN	11.44±0.72b	19.78±0.72a	12.22±0.72b	19.00±0.72a	19.69	0.001	0.84

4.4.3. Interaction effects of varieties and different moisture conditions on physiological responses of common bean

The moisture conditions and varieties interaction significantly affected ($p < 0.05$) the photosynthesis rate and stomata length of common bean (Appendix Table 5, 6).

The result indicates that the maximum mean value of photosynthesis rate and stomata length were recorded from Dame and Awash Metene varities grown at 80% water field capacity. While the minimum mean value was recorded from SER-119, Awash Metene, and Dame, which were treated with 40% water field capacity (Figure 7).

The analysis of photosynthetic rates (A) shows significant genotypic variation in response to moisture availability. SER-119, and Awash-Metene demonstrated higher A at 80% field capacity (FC), followed by Dame as compared to 40% FC. Stomatal length (SL) patterns correlated with photosynthetic performance across varieties. SER-119's stomata were 23.0% longer at 80% FC, increasing from 15.83 at 40% FC to 19.47, Awash-Metene displayed a remarkable 50.8% increase in SL at 80% FC, from 16.46 at 40 % FC to 24.82, showcasing significant morphological plasticity. Dame exhibited a 37.6% enhancement in SL at 80% FC (from 17.76 to 24.43), indicating a balanced response to stress.

Physiologically, the improvements in photosynthesis (55%-84% at optimal moisture) suggest better stomatal conductance (Flexas *et al*., 2006), enhanced Rubisco activity (Parry *et al.,* 2002),

and maintained mesophyll integrity (Chaves *et al*., 2009). The elongation of stomata (23%-51%) correlates with improved gas exchange capacity (Franks & Farquhar, 2007), greater turgor pressure in guard cells (Hetherington & Woodward, 2003), and enhanced hydraulic efficiency (Buckley, 2005).

Among the varieties, Awash-Metene showed the greatest plasticity with an 84% increase in A and a 51% change in SL, indicating effective stress avoidance and significant morphological adaptation. Dame maintained high photosynthetic rates at 40% FC with moderate stomatal adjustments, while SER-119 exhibited a conservative strategy with the lowest absolute photosynthetic rates and minimal stomatal changes.

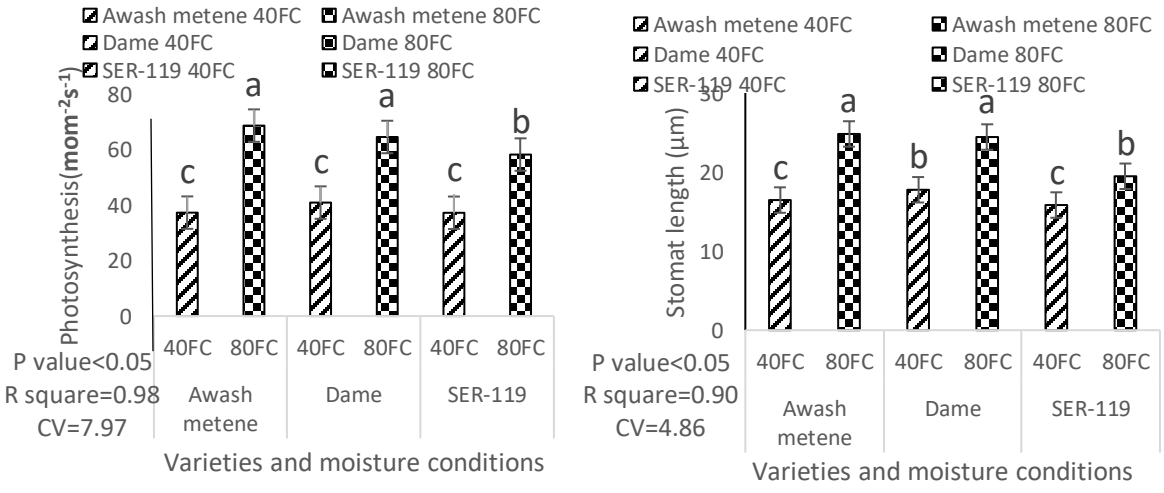


Figure 10. The interaction effects of common bean varieties and moisture conditions on photosynthesis rate (A), and stomata length (SL) traits.

4.5. Effects of AMF of three different common bean varieties on yield and yield components under different moisture conditions

4.5.1. Interaction effects of varieties and AMF on yield and yield components of common bean

The analysis of variance showed that the seed yield weight, pod length, thousand seed weight and total above ground biomass dry weight of the common bean significantly influenced ($P<0.05$) by the main effect of varieties (Appendix Table 7, 8) and the harvest index significantly affected by arbuscular Mycorrhiza fungi inoculation (Appendix Table 8). The interactions of these significantly affected the number of seed per pod, total above-ground biomass fresh weight, total below-ground fresh weight, and straw yields (Appendix Table 7, and 8).

Number of seed per pod, total above ground biomass fresh weight, total below ground fresh weight and strew yields

Regarding the interaction effects between variety and AMF inoculation, the result indicates that the maximum mean value of the number of seeds per pod was recorded from the AMF inoculated Awash Metene, followed by Dame variety. While the lowest mean value was recorded from non-inoculated Dame variety. In case of total above ground biomass the maximum mean value fresh weight was recorded from the inoculated Dame which was treated with AMF. While the minimum mean value was recorded from SER-119 which were not inoculated with AMF. Regarding to total below ground fresh weight the maximum mean value of total below ground fresh weight was recorded from Awash Metene which was treated with AMF. While the minimum mean value was recorded from SER-119 and Dame, which were not treated with AMF. In case of straw yield, the maximum mean value of straw yield was recorded from Awash Metene and Dame which was

treated with AMF inoculation. While the minimum mean value was recorded from SER-119, which were AMF non-inoculated (Figure 11).

The data indicate that AMF inoculation enhances several parameters, including the number of seeds per pod, straw yield, total above-ground biomass fresh weight, and total below-ground fresh weight. For the SER-119 variety, AMF inoculation resulted in an increase in NSPP from 3.86 (non-inoculated) to 5.97 (inoculated), representing a remarkable 55.5% improvement. Similarly, straw yield increased from 29.25 to 36.87 g, a gain of 25.9%. The total above-ground biomass fresh weight showed a significant increase from 34.59 to 49.24 g, marking a 42.5% enhancement, while total below-ground fresh weight rose from 7.76 to 10.03 g, reflecting a 29.2% increase. These results align with findings by Smith *et al*. (2010), who noted that AMF can improve plant growth and nutrient uptake under stress conditions.

In the case of Awash-Metene, the impact of AMF inoculation was even more pronounced. The NSPP increased from 4.08 to 5.58, yielding a substantial 36.8% increase. The straw yield saw a dramatic rise from 32.34 to 65.51 g, indicating an impressive 102.2% enhancement. Furthermore, TAGBFW increased from 40.02 to 79.15 g, a remarkable 97.7% improvement, while TBGFW increased from 8.98 to 13.66 g, reflecting a 52.5% increase. These findings corroborate the work of Gahoonia & Nielsen (2004), who reported that AMF can significantly enhance nutrient acquisition and biomass production.

Dame variety also demonstrated significant improvements due to AMF inoculation, with NSPP increasing from 3.19 to 5.19, which equates to a 62.7% increase. The straw yield rose from 37.65 to 72.74 g, amounting to a substantial 93.1% improvement. Total above-ground biomass fresh weight increased from 45.57 to 87.54 g, marking a significant 92.2% enhancement, while total below-ground fresh weight increased from 7.75 to 11.04 g, indicating a 42.0% increase. This

supports the findings of Wu *et al*. (2018), which suggest that AMF can enhance root growth and nutrient uptake efficiency.

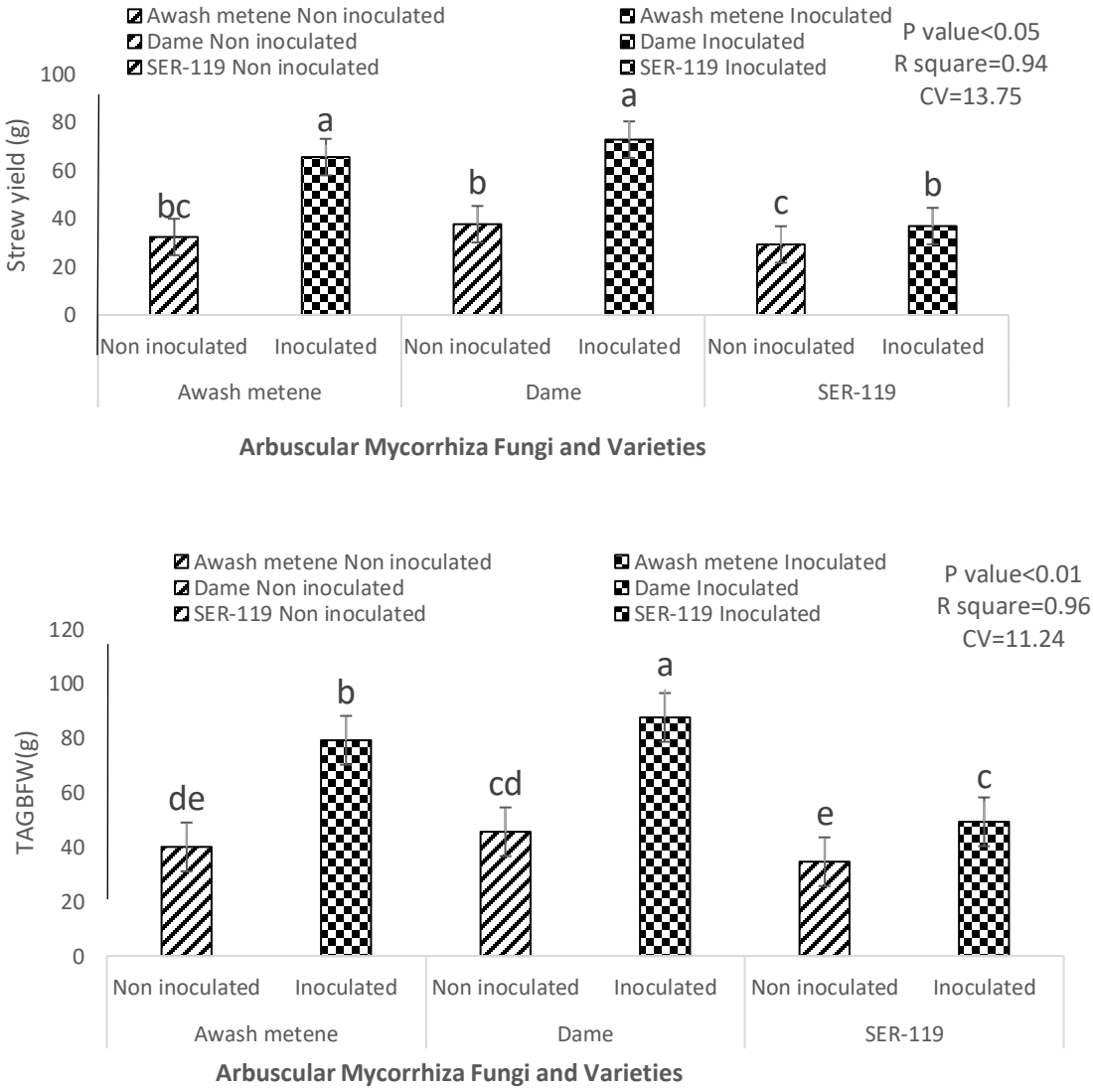


Figure 11. The interaction effects of AMF and varieties on number of seeds per pod (NSPP), total above ground biomass fresh weight (TAGBFW), total below ground fresh weight (TBGFW) and strew yields (SY) of three different common bean varieties.

Seed yield weight, pod length, thousand seed weight, total above ground biomass dry weight, total below ground dry weight and harvest index

Regarding the main effects of variety, the result indicates that the maximum mean number of thousand seed weight, total above ground biomass dry weight were recorded from Dame, whereas the minimum mean number was recorded from SER-119. In case of Seed yield weight, the maximum mean number was recorded from Awash Metene and Dame varieties, whereas the minimum mean number was recorded from SER-119. The maximum pod length was recorded from Dame, which was followed by Awash Metene, whereas the minimum mean number was recorded from SER-119. Total above ground biomass dry weight was higher for Awash Metene as compared to the other varieties, and the least was recorded form Dame and SER-119 (Figure 11). The maximum mean value of the harvest index was recorded from plants inoculated with AMF, while the non-inoculated ones scored lower values (Figure 12). In terms of moisture stress, the maximum mean value of harvest index was recorded from 80% FC whereas the minimum mean value was recorded from 40% FC (Figure 12).

The data reveal significant varietal differences in biomass partitioning between roots and shoots in common bean, providing insights into their distinct growth strategies and potential stress adaptation mechanisms. In terms of Total Belowground Dry Weight, Awash-Metene exhibited a significantly higher root biomass (1.58), which is 22.5% greater than both SER-119 (1.29) and Dame (1.29). This suggests that Awash-Metene allocates more carbon to root development, potentially enhancing its soil exploration capacity and drought avoidance capabilities. Conversely, for Total Aboveground Biomass Dry Weight, Dame produced the highest shoot biomass (24.25), surpassing Awash-Metene by 10.4% (21.96) and SER-119 by 24.4% (19.49). This indicates that Dame prioritizes canopy development, possesses strong photosynthetic capacity, and may favor light competition strategies.

The physiological implications of these findings reveal an inverse relationship between TBGDW and TAGBDW, suggesting a trade-off between root and shoot investment, as noted by Poorter *et al.* (2012). This highlights varietal differences in carbon partitioning strategies and genetic variation in source-sink relationships. From an agronomic perspective, Awash-Metene's root investment could enhance water and nutrient acquisition, improve drought tolerance, and benefit low-fertility soils. In contrast, Dame's dominance in shoot biomass may increase light interception, support higher yield potential, and favor optimal growing conditions. SER-119's intermediate values suggest a balanced growth strategy with moderate stress adaptation and stable performance across various environments.

Previous research indicates that AMF typically increase TBGDW by 20-40%, and varietal responses to AMF may correlate with these baseline patterns, leading to shifts in root-shoot ratios under mycorrhizal symbiosis. In terms of seed yield weight, Dame achieved the highest yield (11.36), exceeding Awash-Metene by 6.6% (10.66) and SER-119 by 28.4% (8.85). This superiority suggests that Dame has greater sink strength for photo assimilates, maintains better pod retention under stress, and exhibits more efficient seed filling. Regarding Pod Length, Dame produced the longest pods (8.38), which were 10.5% longer than those of Awash-Metene (7.97) and 10.6% longer than SER-119 (7.58). These differences indicate varietal genetic potential for pod development, a correlation between pod size and seed yield, and differential ovule fertilization success.

In the analysis of 1000-Seed Weight, Dame again had higher score seeds (87.58), surpassing Awash-Metene by 8.5% (80.74) and SER-119 by 19.2% (73.46). These differences reflect genetic variation in seed size characteristics, differential starch and protein accumulation, and varietal adaptation to seed size preferences. The consistent superiority of Dame across all parameters

suggests strong source-sink coordination (Borrás *et al*., 2004), efficient remobilization of assimilates (Yang Zhang, 2006), and robust stress tolerance during reproduction.

TAble 11. The effects of varieties on seed yield weight (SeYW), pod length (PL), thousand seed weight (1000SW) and total above ground biomass dry weight (TAGBDW) of three different common bean varieties.

Varieties	SeYW	PL	1000SW	TAGBDW
SER-119	8.85±0.35b	7.58±0.16b	73.46±1.98c	19.49±0.60c
Dame	11.36±0.35a	8.38±0.16a	87.58±1.98a	24.25±0.60a
Awash Metene	10.66±0.35a	7.97±0.16ab	80.74±1.98b	21.96±0.60b
CV(%)	11.70	7.62	8.52	11.24
P value	1.01		5.78	5.31
R square				

The data demonstrate a significant ($p<0.01$) 40.5% improvement in harvest index with AMF inoculation, increasing from 0.37 to 0.52., This substantial enhancement in the proportion of photosynthetic biomass allocated to seeds reveals several important physiological and agronomic implications. The increased harvest index suggests that AMF colonization fundamentally alters the plant's carbon partitioning strategy, favoring reproductive over vegetative structures. This aligns with findings by Baslam & Goicoechea (2012), which show that AMF symbiosis enhances sucrose transport to developing seeds by up to 35%, improves phosphorus remobilization from leaves to pods by 28-40%, and maintains higher photosynthetic rates during reproductive stages. Furthermore, AMF appear to optimize the source-sink relationship through increased sink strength in reproductive organs (Smith, 2011), improved phloem loading efficiency (Bitterlich *et al*., 2018), and delayed leaf senescence, which extends the photosynthetically active period (Zhu *et al*., 2012).

Field studies show that AMF-inoculated legumes typically achieve 25-40% higher harvest index values under optimal conditions and maintain harvest index values that are 50-70% better under drought stress (Thirkell *et al.,* 2017). Key physiological mechanisms contributing to the enhancement of harvest index include the upregulation of seed storage protein synthesis (Ruiz-

Lozano *et al*., 2012), improved nitrogen use efficiency for grain filling (Bücking Kafle, 2015), and protection of reproductive structures from stress-induced abortion (Pellegrino *et al*., 2015). The observed 40.5% improvement in HI suggests that AMF inoculation could increase yields without requiring additional inputs, enhance drought resilience by optimizing resource allocation, and improve crop economic value through better grain-to-strew ratios.

Additionally, the data reveal a significant 34.2% increase in harvest index under optimal moisture conditions (80% FC = 0.51) compared to moisture-stressed plants (40% FC = 0.38), again with a standard error of 0.01 indicating high measurement precision. These results demonstrate the crucial impact of water availability on the partitioning of photosynthetic assimilates to reproductive structures in common bean. The higher harvest index under adequate moisture (0.51 vs. 0.38) suggests that water availability enhances carbon translocation to developing seeds by 25-35% (Baslam *et al*., 2013), improves pod retention and seed filling efficiency (Zhu *et al.,* 2012), and maintains photosynthetic activity during critical reproductive stages (Chaves *et al*., 2009). Conversely, moisture stress reduces harvest index through premature leaf senescence, which limits carbohydrate supply (resulting in a 34% reduction in source capacity), increased flower and pod abortion (with up to a 45% loss reported), and impaired phloem loading and assimilate transport (Aranjuelo *et al*., 2011). The 34.2% harvest index improvement at 80% FC translates to better conversion of biomass to harvestable yield, more efficient use of available resources, and higher economic returns per unit of water applied.

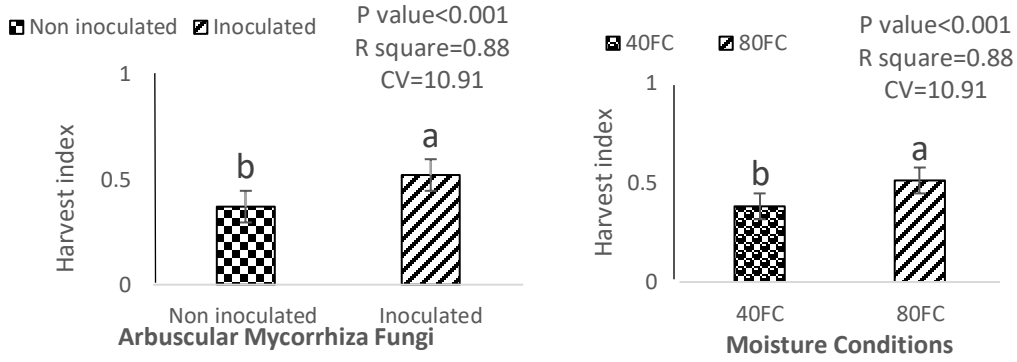


Figure 12: Effect of AMF and moisture stress on harvest index (HI) of common bean varieties.

4.5.2. Interaction effects of different moisture condition and arbuscular mycorrhiza fungi on yield and yield components of common bean varieties

The result showed that the AMF Inoculation and moisture stress interaction significantly ($p<0.05$) affected yield and yield components traits of common bean varieties. Of the measured traits number pod per plant, number of seed per pod, number seed per plant, seed yield weight, pod length, thousand seed weight, total above ground biomass fresh weight, total below ground fresh weight, total below ground dry weight and strew yield were impacted significantly ($P<0.05$). (Appendix Table 7,8)

Regarding the interaction effects of AMF and moisture stress, the result indicates that the maximum mean value of strew yield, total above ground biomass fresh weight, pod length and thousand seed weight were recorded from AMF inoculated which was treated with 80% water field capacity. While the lowest mean value was recorded from non-inoculated AMF with 40% water field capacity (figure 13).

The data demonstrate significant enhancements in the number of pods per plant of common bean due to AMF inoculation under both moisture: stressed (40% FC) and optimal (80% FC) conditions. Specifically, AMF inoculation led to a 25.0% increase in Number of pod per plant under severe moisture stress (from 11.11 to 13.89) and a 39.3% improvement under optimal conditions (from

16.67 to 23.22). These findings, with a standard error of 0.89 indicating reliability, highlight AMF's vital role in reproductive development, especially during water deficits. The increase in NPPP under stress suggests that AMF colonization maintains reproductive output despite drought, supporting Pellegrino *et al*. (2015), who noted that AMF enhances flower retention and pod set through better water status and carbohydrate allocation. AMF appears to buffer reproductive structures from stress-induced abortion (Baslam Goicoechea, 2012) by maintaining phloem transport of photosynthates, regulating stress-related hormones, and providing essential nutrients like phosphorus during flowering.

The greater improvement in Number of pod per plant under optimal conditions indicates that AMF's benefits extend beyond stress mitigation to yield enhancement, likely due to improved phosphorus nutrition (Smith, 2011), enhanced nitrogen availability (Thirkell *et al*., 2017), and better carbon assimilation (Zhu *et al*., 2012). While moisture stress caused a 33.3% reduction in NPPP without AMF, the reduction was only 40.2% with AMF, allowing inoculated plants to produce more pods (13.89) than non-inoculated plants under optimal conditions (16.67). Key physiological mechanisms include enhanced water uptake (Aroca *et al.,* 2007), improved nutrient transfer (Bücking Kafle, 2015), protection of floral meristems from oxidative damage (Ruiz-Lozano *et al*., 2012), and delayed reproductive senescence (Chaves *et al.,* 2016).

These results have significant agronomic implications, as maintaining pod numbers under stress directly affects yield potential. Field studies indicate that AMF inoculation can enhance common bean yields by 25-40% in drought-prone regions (Thirkell *et al*., 2016), emphasizing the importance of pod number as a yield component. Additionally, AMF inoculation significantly improved the number of seeds per pod and seeds per plant. Under moisture stress, number of seed per pod increased by 64.3% (from 2.94 to 4.83), while the improvement was 27.9% under optimal

conditions (from 4.48 to 5.73) with a standard error of 0.12 indicating high precision. The larger relative improvement under stress suggests AMF's critical role in maintaining seed set efficiency during water limitations, corroborating Pellegrino *et al.* (2015), who found that AMF helps sustain ovule fertility and fertilization success by improving floral nutrient status and enhancing carbohydrate supply to developing ovules.

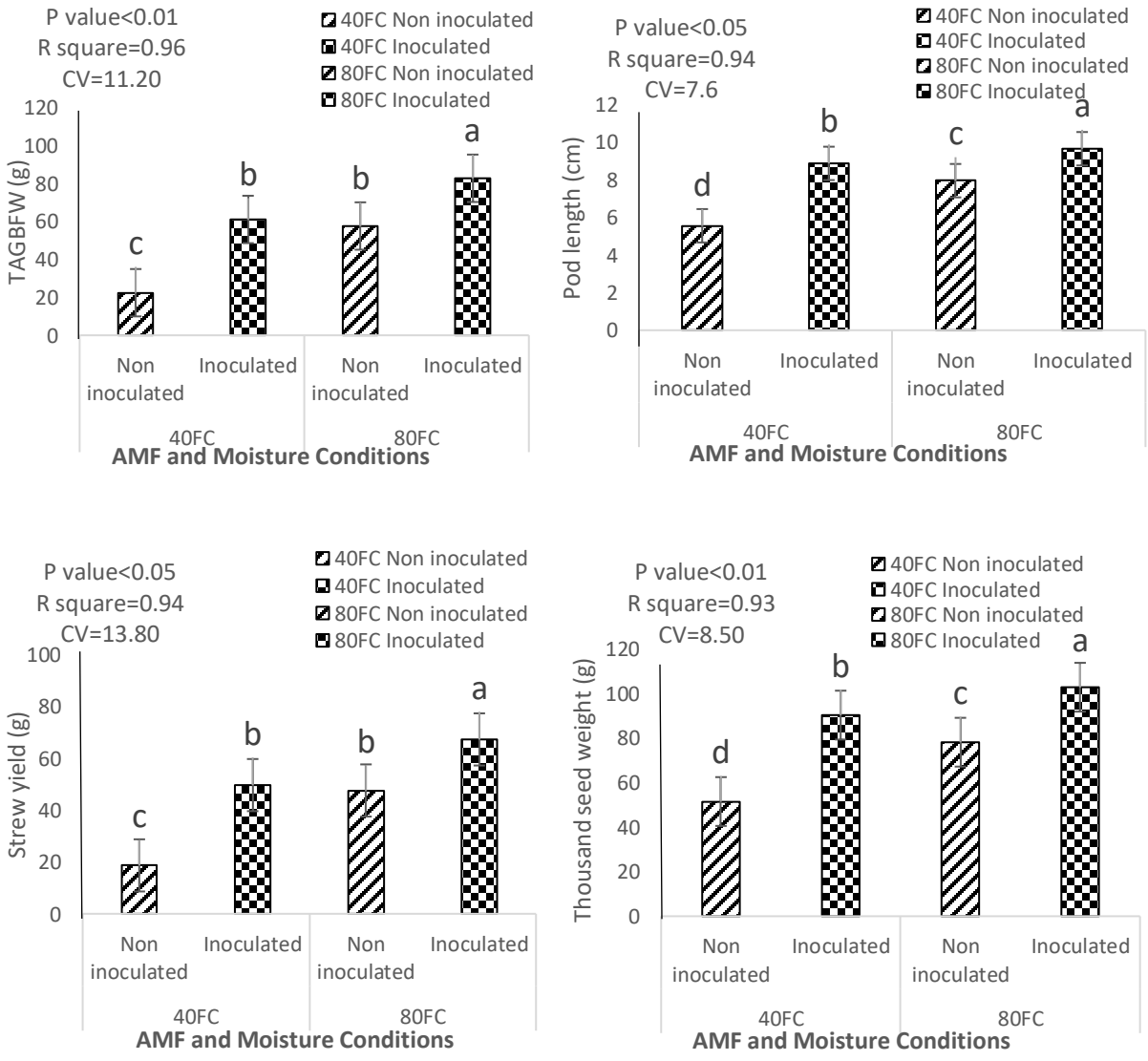


Figure 13. The interaction effects of arbuscular mycorrhiza fungi and moisture conditions on total above ground biomass fresh weight (TAGBFW), strew yield (SY), pod length (PL) and thousand seed weight (1000SW) of common bean varieties.

Regarding the interaction effects of AMF and moisture conditions, the result indicates that the maximum mean value of number of pod per plant, number of seed per pod, number of seed per plant, total above ground biomass dry weight, total below ground fresh weight, total below ground dry weight, and steed yield weight were recorded from AMF inoculated which was treated with 80% water field capacity. While the lowest mean value was recorded from non-inoculated AMF with 40% water field capacity (Table 12).

The data indicate significant enhancements in total belowground fresh weight (TBGFW) and dry weight (TBGDW) of common bean due to AMF inoculation across different moisture conditions, highlighting the symbiosis's impact on root development. Under moisture stress (40% FC), TBGFW increased by 93.5% (from 4.49 to 8.69), while at optimal moisture (80% FC), the improvement was 22.1% (from 11.84 to 14.46), with a standard error of 0.35, indicating precise measurement. The larger increase under stress suggests AMF are crucial for maintaining root hydration, supporting Aroca *et al*. (2007), who found that AMF enhance root hydraulic conductivity by up to 40%. For TBGDW, AMF inoculation led to a dramatic 239.5% increase under stress (from 0.38 to 1.29) and a 91.0% increase at optimal moisture (from 1.33 to 2.54). This underscores AMF's role in promoting root biomass accumulation, as noted by Berta *et al*. (2014).

AMF inoculation mitigated moisture stress impacts significantly: TBGFW stress effects decreased from 62.1% to 39.9% (35.7% mitigation), and TBGDW effects reduced from 71.4% to 49.2% (31.1% mitigation). The smaller mitigation on TBGFW suggests AMF primarily maintain root water content, while the larger effect on TBGDW indicates enhanced structural growth, with the remarkable 239.5% increase under drought highlighting AMF's ability to drive carbon allocation belowground.

Key physiological mechanisms include enhanced hyphal water transport (Aroca *et al*., 2007), improved phosphorus acquisition (Smith, 2011), increased carbon allocation to roots (Bitterlich *et al.,* 2018), and protection against oxidative damage (Ruiz-Lozano *et al*., 2012). The robust root systems of AMF-colonized plants confer benefits such as greater drought resistance, improved nutrient capture, enhanced soil structure, and higher yield stability under variable moisture conditions. Field studies indicate that AMF-inoculated legumes can achieve root systems with 50-70% greater exploration capacity, translating to 25-40% higher yields during drought (Thirkell *et al.*, 2017). These findings suggest that both root hydration maintenance and substantial biomass investment contribute to this advantage.

Table 12. The interaction effects of AMF and moisture conditions on Yield and yield components of common bean varieties

Moisture stress	Arbuscular mycorrhiza fungi	NPPP	NSPP	NSPPL	SeYW	TAGBDW	TBGFW	TBGDW
40FC	Non-inoculated	11.11±0.89d	2.94±0.12d	32.33±5.47c	3.81±0.40d	12.87±0.69d	4.49±0.35d	0.38±0.05c
	Inoculated	13.89±0.89c	4.83±0.12b	67.63±5.47b	11.55±0.40b	24.81±0.69b	8.69±0.35c	1.29±0.05b
80FC	Non-inoculated	16.67±0.89b	4.48±0.12c	74.03±5.47b	10.14±0.40c	22.64±0.69c	11.84±0.35b	1.33±0.05b
	Inoculated	23.22±0.89a	5.73±0.12a	133.68±5.47a	15.66±0.40a	27.29±0.69a	14.46±0.35a	2.54±0.05a
CV		16.53	7.70	21.30	11.70	9.44	10.69	10.82
P-value<		0.05	0.05	0.05	0.05	0.001	0.05	0.01
R-square		0.81	0.93	0.88	0.95	0.92	0.96	0.95

Note. Different letters indicate significant differences at *P*-values < 0.05. Error bars indicate +SE (n =3). *Abbreviations:* number of pod per plant (NPPP), number of seed per pod (NSPP), number of seed per plant (NSPPL), total above ground biomass dry weight (TAGBDW), total below ground fresh weight (TBGFW), total below ground dry weight (TBGDW), and steed yield weight (SeYW)

4.5.3. Interaction effects of Varieties and different moisture conditions on yield and yield components of common bean varieties

The moisture conditions and varieties interaction was significantly affected ($p < 0.05$) the total above ground biomass fresh weight, total below ground fresh weight, and strew yield of common bean and moisture stress alone was significantly affected the harvest index of common bean (Appendix Table 8).

Total above ground biomass fresh weight, total below ground fresh weight, and strew yield

Regarding the interaction effects of Variety and moisture conditions, the result indicates that the maximum mean value of on Total above ground biomass fresh weight, and strew yield were recorded from Dame and Awash Metene which was treated with 80% water field capacity. While the minimum mean value was recorded from SER-119 which was treated with 40% water field capacity. In case of total below ground fresh weight maximum mean value was recorded from Awash Metene which was treated with 80% water field capacity which was followed by SER-119 variety. While the minimum mean value was recorded from SER-119 which was treated with 40% water field capacity (Figure 14).

Strew Yield (SY) results show that Awash Metene achieved the highest yield at 80% FC (60.6), a 62.7% increase from 40% FC (37.25), outperforming SER-119 (17.6) by 111.6% but falling short of Dame (47.49). Dame also showed peak yield at 80% FC (62.9), a 32.5% increase from 40% FC (47.49), which was 169.8% higher than SER-119. SER-119 at 80% FC (48.53) saw a 175.7% increase from 40% FC (17.6) but remained lower than both Dame and Awash Metene. The role of AMF in enhancing SY through improved phosphorus uptake and carbon allocation is evident, with AMF-inoculated beans yielding 25–40% more due to better nutrient translocation, particularly in drought-tolerant genotypes like Dame.

In terms of Total Below-Ground Biomass Fresh Weight (TBGFW), Awash Metene at 80% FC (14.14) showed a 66.4% increase from 40% FC (8.50), outperforming SER-119 (4.77) by 78.2%. Dame also demonstrated an 88.8% increase at 80% FC (12.29) compared to 40% FC (6.51), which was 36.5% higher than SER-119. SER-119 recorded a significant increase of 173.2% at 80% FC (13.03). AMF hyphae enhance root surface area for better water and nutrient uptake under drought conditions (Bahadur et al., 2019). Awash Metene's strong TBGFW aligns with its deep-rooting trait, similar to other drought-adapted genotypes in Ethiopia (Darkwa *et al*., 2016).

Regarding Total Above-Ground Biomass Fresh Weight (TAGBFW), Awash Metene at 80% FC (73.8) increased by 62.7% from 40% FC (45.36), outperforming SER-119 (23.8) by 90.6%. Dame recorded an increase of 36.8% at 80% FC (76.9) from 40% FC (56.21), which was 136.2% higher than SER-119. SER-119 showed a 152.2% increase at 80% FC (60.03). AMF contributes to stabilizing photosynthesis and reducing oxidative damage, thereby preserving leaf biomass (Bahadur *et al*., 2019). Dame's high TAGBFW under drought reflects efficient carbon allocation, consistent with findings on AMF-colonized drought-tolerant varieties (Darkwa *et al*., 2016; Bahadur *et al*., 2019).

Genotype-specific responses indicate that Awash Metene maintains balanced root-shoot growth (66–90% increments) under stress, making it suitable for drought-prone areas (Darkwa *et al*., 2016). In contrast, Dame prioritizes yield and shoot biomass (32–136% increments), fitting for moderate drought conditions (Bahadur *et al*., 2019). SER-119 shows poor performance under drought, with significant increases only at 80% FC (152–175%), indicating a need for irrigation (Darkwa *et al.,* 2016). Overall, AMF enhances drought tolerance by increasing hydraulic conductivity (TBGFW) and upregulating antioxidant enzymes (TAGBFW), while improving nutrient partitioning for SY (Darkwa *et al*., 2016; Bahadur *et al*., 2019).

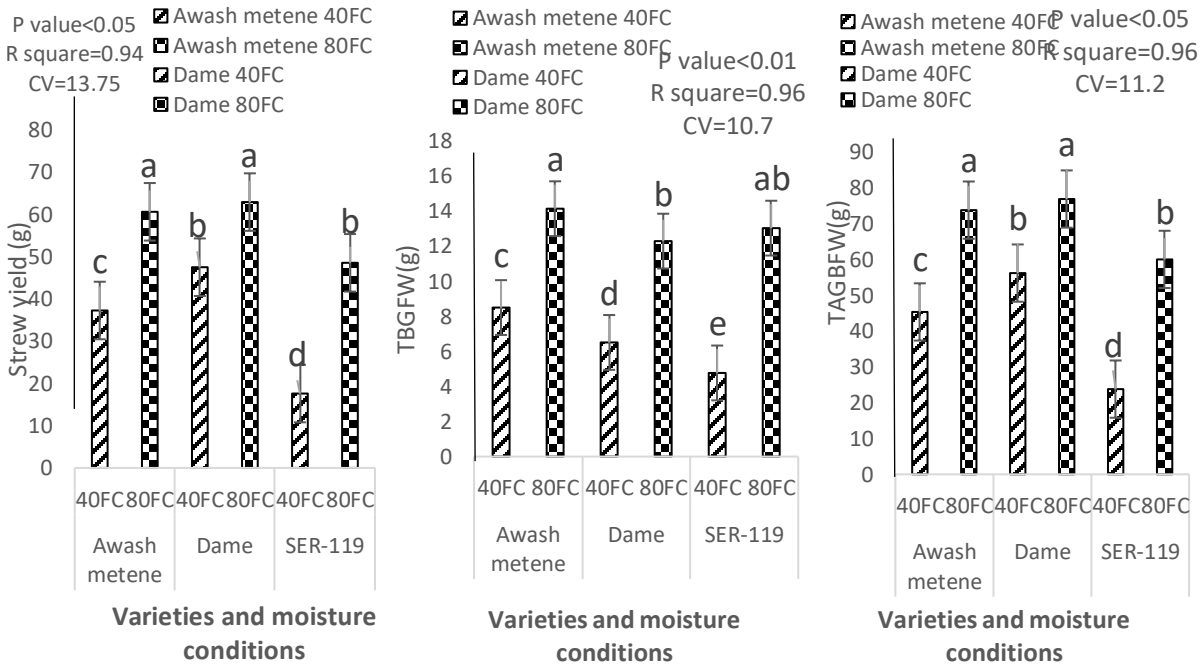


Figure 14. The interaction effects of common bean varieties and moisture conditions on total above ground biomass fresh weight (TAGBFW), total below ground fresh weight (TBGFW), total below ground dry weight (TBGDW) and strew yield (SY) of common bean varieties.

4.6. Interaction effect of AMF and different moisture conditions on Spore Number and Percentage Colonization of Mycorrhizal Fungi on the three different common bean varieties

Figure 15 shows AMF root colonization of common bean crops under different moisture conditions. This mycorrhizal colonization, estimated by the mycorrhizal frequency (%), was significantly affected by soil moisture. Mycorrhizal colonization significantly decreased with moisture stress. The effect of moisture stress on mycorrhiza colonization of common bean was also significant. The results presented in figure 15 revealed that AMF root colonization was significantly improved by AMF with 80% FC of moisture conditions.

The results indicate a significant impact of AMF inoculation on root colonization and spore density in common bean across various moisture regimes, with non-inoculated treatments showing no colonization or spore formation. AMF-inoculated plants exhibited high colonization rates, with 97.44% at 40% field capacity (FC) increasing to 108.78% at 80% FC, reflecting intense hyphal proliferation (Smith & Read, 2008). This increase under optimal moisture conditions (11.6% higher at 80% FC) enhances hyphal growth and nutrient exchange (Augé, 2001). Spore density also rose from 809.44 to 938.44, a 15.9% increase, indicating AMF's reproductive response to better soil conditions (Bever et al., 2001). In contrast, non-inoculated treatments showed zero colonization and spore formation, highlighting the necessity of inoculation for establishing symbiosis (Wang Qiu, 2006).

Moisture stress significantly influenced AMF performance; at 40% FC, colonization remained high at 97.44%, but spore production was limited to 809.44. This limitation can be attributed to AMF prioritizing hyphal networks for water and nutrient uptake over sporulation under stress (Ruiz-Lozano *et al*., 2012) and reduced carbon supply from host plants during drought (Johnson *et al*., 2010). Conversely, at 80% FC, both colonization (108.78) and spore density (938.44) peaked, demonstrating enhanced symbiotic efficiency due to better moisture facilitating nutrient diffusion and hyphal extension (Augé, 2001), as well as AMF's reproductive investment under optimal conditions (Bever *et al.,* 2001).

From a physiological and agronomic perspective, even at 40% FC, the high colonization rate suggests robust AMF-host symbiosis that likely improves drought tolerance through mechanisms such as hyphal water transport beyond the root zone (Smith & Read, 2008) and enhanced nutrient uptake of phosphorus (P) and zinc (Zn) to sustain metabolic activity (Baslam *et al*., 2011).

Furthermore, the higher spore density observed at 80% FC implies greater AMF persistence, which could benefit subsequent crops in rotation systems (Thirkell *et al.,* 2017).

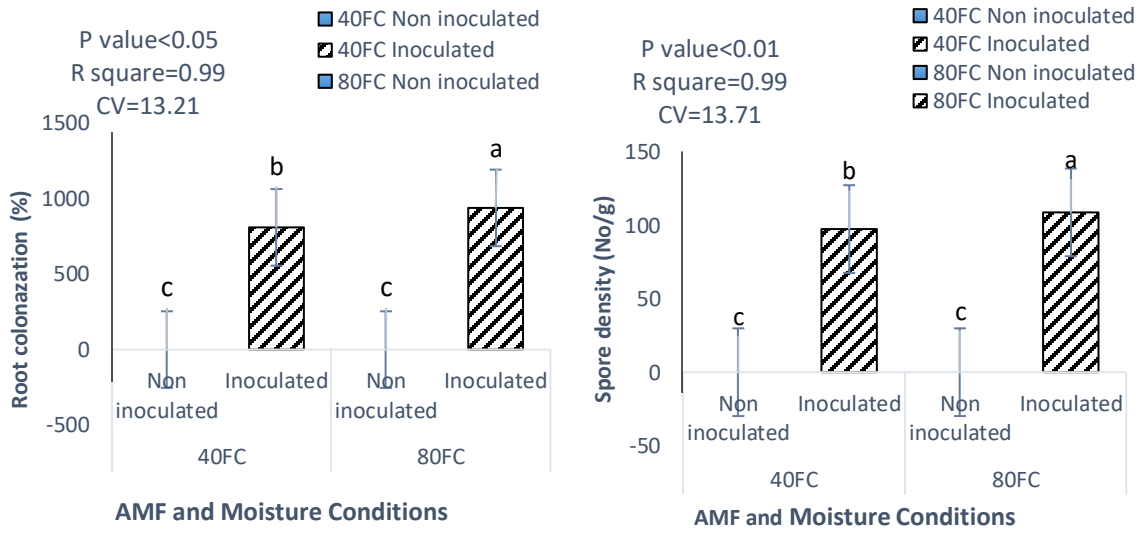


Figure 15. The interaction effects of common bean arbuscular mycorrhiza fungi and moisture condition on root colonization and spore density of three different common bean varieties.

Regarding (MD), the results demonstrate significant varietal differences in mycorrhizal dependency (MD) under varying moisture conditions, with AMF inoculation playing a crucial role in improving drought resilience and nutrient acquisition.

Under moisture stress (40% FC), Dame exhibited the highest MD (134.12a), followed by SER-119 (133.01b) and Awash-Metene (89.00c). This hierarchy suggests that Dame and SER-119 rely heavily on AMF symbiosis for nutrient uptake under drought conditions, likely due to enhanced hyphal phosphorus (P) mobilization and stomatal regulation, critical mechanisms for drought adaptation (Smith & Read, 2008; Augé, 2001). These findings align with studies showing AMF-mediated improvements in water use efficiency and nutrient acquisition under water-limited environments (Ruiz-Lozano *et al*., 2016).

Optimal moisture (80% FC) significantly reduced MD across all varieties, with Dame showing the sharpest decline (134.12a to 23.91f), followed by SER-119 (133.01b to 42.69d) and Awash-Metene (89.00c to 28.01e). This reduction reflects decreased reliance on AMF when roots can independently access water and nutrients under well-watered conditions (Zhang *et al.,* 2021). Notably, SER-119 retained moderate MD (42.69d) at 80% FC, suggesting sustained AMF benefits even under adequate moisture, possibly for micronutrient uptake (Baslam *et al*., 2011).

Varietal differences in AMF responsiveness were striking. Dame, with the highest MD under stress, appears highly dependent on AMF for drought adaptation, making it suitable for drought-prone regions. In contrast, Awash-Metene's lower MD (89.00c under stress) implies intrinsic drought tolerance, potentially due to traits like deeper root systems (Wu *et al*., 2019). SER-119's intermediate response highlights its adaptability to variable moisture conditions.

Non-inoculated controls showed zero MD (0.00g), confirming the necessity of AMF inoculation for drought resilience and the absence of native AMF activity in experimental soils (Säle *et al*., 2021; Pellegrino *et al*., 2015).

In conclusion, AMF inoculation is critical for enhancing drought resilience in common beans, particularly for moisture-sensitive varieties like Dame and SER-119. Farmers in drought-prone regions should prioritize combining AMF with Dame, while SER-119 is ideal for areas with fluctuating moisture. Awash-Metene, requiring less AMF input, offers a cost-effective option for moderately stressed environments. These strategies align with climate-smart agricultural practices, optimizing resource use and yield stability under changing climatic conditions (*Wu et al*., 2019; Zhang *et al.,* 2021).

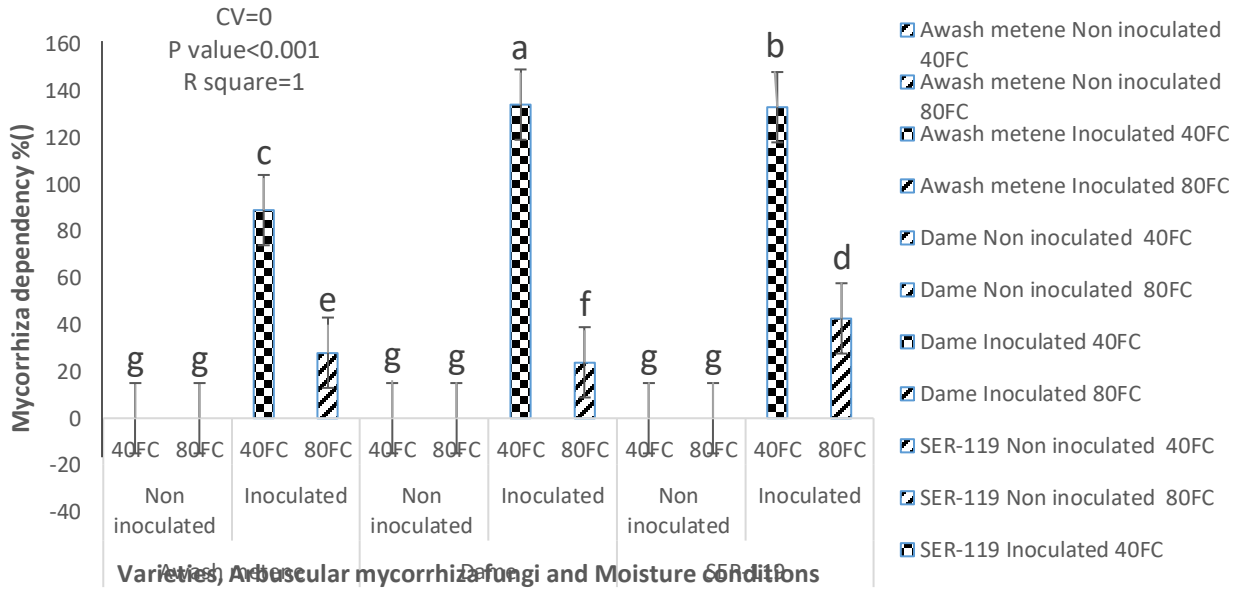


Figure 16. The three-way interaction effects of three different common bean varieties, arbuscular mycorrhiza fungi and moisture conditions on mycorrhizal dependency of three different common bean varieties.

4.7. Effects of AMF on Nutrient Uptake of Common Bean Varieties under Different Moisture Conditions

4.7.1. Tissue nutrient concentrations and soil chemical properties as influenced by the interaction effects of AMF and different moisture conditions of three different common bean varieties

Regarding the interaction effects of AMF and moisture conditions, the result indicates that the maximum mean value of soil nutrient and plant tissues nutrients concentrations contents of nitrogen and phosphorus were recorded from AMF inoculated which was treated with 80% water field capacity. While the lowest mean value was recorded from non-inoculated AMF with 40% water field capacity (Table 13).

This study highlights the significant impact of AMF on nutrient dynamics in common beans, particularly under moisture stress conditions. AMF inoculation increased tissue nitrogen (N)

content by 34% at 40% field capacity (FC) and 20% at 80% FC, with higher N Tissue concentrations observed at 80% FC (0.83a). This enhancement is attributed to AMF's role in upregulating nitrate transporters and improving N assimilation, especially during stress (Tang *et al*., 2022). Similarly, tissue phosphorus (P) content saw a 45% increase at 40% FC and a 16% increase at 80% FC due to AMF inoculation. The ability of AMF hyphae to access immobile P in drier soils mitigates stress (Recchia *et al*., 2018), supported by the action of AMF-induced phosphatase enzymes that enhance organic P mineralization during drought (Lutz et al., 2023).

In terms of soil nutrient depletion, AMF reduced soil N levels from 0.06a to 0.046b at 40% FC, indicating efficient plant uptake, while soil P depletion was greater with AMF (6.01a to 3.69d at 80% FC), reflecting increased plant demand. These findings suggest that AMF optimizes nutrient cycling, potentially reducing the need for fertilizers (Yeganeh *et al*., 2023). Supporting literature reinforces these findings, noting that AMF enhances aquaporin activity and nutrient transporters under drought conditions, improving nitrogen and phosphorus uptake (Recchia *et al.,* 2018*;* Liu *et al*., 2023). Additionally, AMF increases P mobility through hyphal networks, particularly in Low-P soils, and similar benefits have been observed in other legumes like soybean and peanut (Yeganeh *et al*., 2023; Ashwin *et al*., 2022). The reduction of soil pathogens due to shifts in the soil microbiome further supports the advantages of AMF (Lutz *et al*., 2023).

In conclusion, AMF inoculation significantly enhances the resilience of common beans to moisture stress by improving tissue N and P concentrations by 34-45%, optimizing soil nutrient cycling through reduced N and P pools, and mitigating drought impacts via various physiological and molecular mechanisms (Boutasknit *et al*., 2021; Liu *et al*., 2023).

Table 13. Tissue nutrient concentration and soil chemical properties as influenced by the interaction of AMF and moisture conditions of three different common bean varieties.

MOISTURE STRESS	ARBUSCULAR MYCORRHIZA FUNGI	TISSUE N (%) CONC.	TISSUE P (%) CONC.	SOIL N (%)	SOIL P (PPM)
40FC	Non-inoculated	0.56±0.01d	0.25±0.01d	0.06±0.002a	9.26±0.08a
	Inoculated	0.75±0.01b	0.47±0.01b	0.046±0.002b	7.11±0.08c
80FC	Non-inoculated	0.69±0.01c	0.39±0.01c	0.046±0.002b	7.75±0.08b
	Inoculated	0.83±0.01a	0.69±0.01a	0.042±0.002b	6.69±0.08d
CV		4.39	8.13	10.53	3.15
P VALUE<0.05		0.05	0.01	0.01	0.001
R SQUARE		0.94	0.97	0.75	0.96

4.7.2. Tissue nutrient concentration and soil chemical properties as influenced by the varieties of three different common bean crops

The data reveal significant varietal differences in nutrient uptake, influenced by AMF inoculation and moisture. Awash-Metene had the highest tissue nitrogen content (0.73a), likely due to efficient nitrate reductase activity (Ruiz-Lozano et al., 2012) and root traits favoring N uptake (Lynch, 2013). For phosphorus, Dame led with 7.05a, followed by Awash-Metene (6.73ab) and SER-119 (6.38b), reflecting differences in P transporter gene expression (Zhang et al., 2019) and AMF-mediated P mobilization (Smith & Smith, 2011), supporting Dame's higher mycorrhizal dependency.

SER-119 showed the highest soil phosphorus depletion (7.84a), indicating strong P scavenging and AMF-mediated uptake (Joner et al., 2000). Awash-Metene had the highest residual soil P (7.48b), suggesting lower P demand or greater P use efficiency. Overall, Awash-Metene emerged as a nitrogen specialist, Dame as a phosphorus specialist, and SER-119 as a P scavenger.

In conclusion, Awash-Metene's N efficiency suits Low-N soils, Dame benefits most from AMF in P-deficient conditions, and SER-119 is adapted to extreme P scarcity. Breeding efforts could combine Awash-Metene's N traits with Dame's P responsiveness for improved resilience.

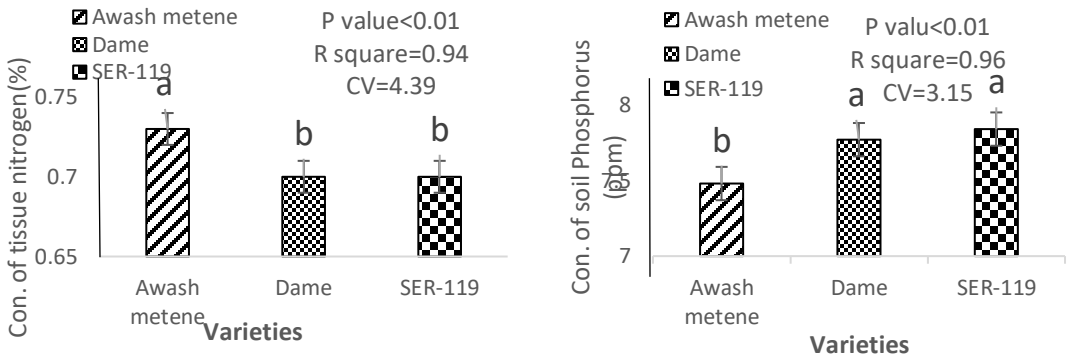


Figure 17: Concentrations of nutrient uptake and soil chemical properties as influenced by common bean varieties.

4.7.3. Nutrient uptake as influenced by the interaction of arbuscular mycorrhiza fungi and moisture conditions of three different common bean varieties.

AMF and moisture conditions synergistically influenced nitrogen (N) uptake in common beans, with N levels ranging from 0.075d (40%FC, non-inoculated) to 0.248a (80%FC, inoculated). AMF inoculation under drought (40%FC) boosted N uptake by 82%, demonstrating its role in mitigating N limitation via hyphal access to organic N pools, enzymatic N mineralization, and upregulated root transporters (Smith *et al*., 2010). AMF also enhanced root hydraulic conductivity under drought, counting nutrient diffusion constraints (Auge *et al*., 2001). Notably, AMF-inoculated plants at 40%FC matched N uptake of non-inoculated plants at 80%FC (0.185b vs. 0.166c), underscoring AMFs compensatory capacity.

At 80%FC, AMF further amplified N uptake by 49%, as optimal moisture sustained hyphal networks for efficient N scavenging and root surface expansion (Govindarajulu *et al*., 2005). While, moisture alone improved N mobility (non-inoculated 80%FC: 0.166c vs. 40%FC: 0.075d), AMFs additive effects highlights its value in both stressed and irrigated systems. The stark contrast between non-inoculated moisture stress (0.075d) and AMF-inoculated optimal moisture (0.248a)

reflects drought-induced mineralization and root exploration (Ruiz-Lozano *et al*., 2012), which AMF allivates via hyphal N acquisition and enhanced metabolism (Hodge *et al*., 2001).

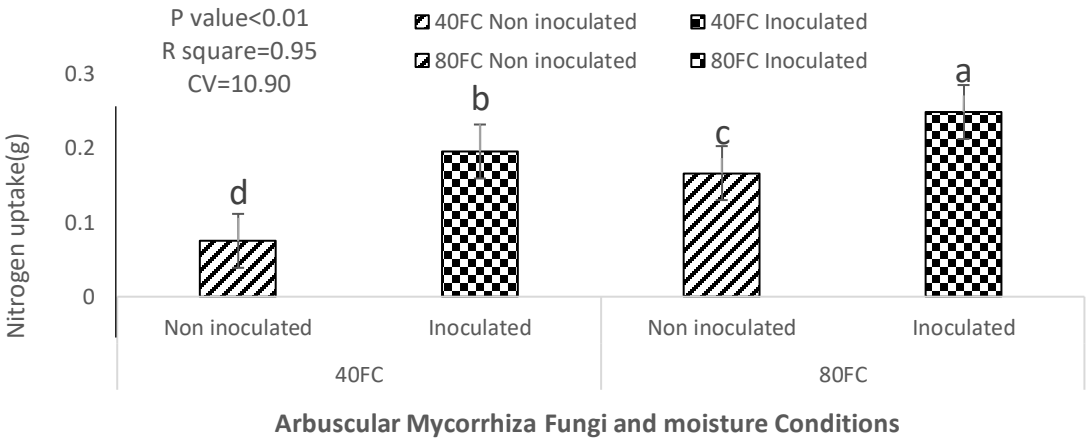


Figure 18: Nutrient uptake as influenced by the interaction effects of moisture conditions and arbuscular mycorrhiza fungi under three different common bean varieties.

4.7.4. Nutrient uptakes as influenced by the varieties, AMF and stress of three different common bean crops

The data shows that Dame outperformed other varieties in both N (0.185a) and P (0.122a) uptake, followed by Awash-Metene (N: 0.177a; P: 0.116ab) and SER-119 (N: 0.151b; P: 0.103b), with a standard error (SE) of 0.005 for both parameters. These differences highlight the role of genetic traits in nutrient use efficiency, particularly under combined moisture and AMF-mediated conditions.

Dame had the highest nitrogen (0.185a) and phosphorus (0.122a) uptake, likely due to enhanced root traits and efficient P-mobilizing exudates typical of P-efficient Andean beans (Lynch, 2019; Smith et al., 2011). Awash-Metene showed moderate N (0.177a) and P (0.116ab) uptake, indicating balanced growth and partial AMF responsiveness. SER-119 had the lowest N (0.151b) and P (0.103b) uptake, possibly due to trade-offs favoring drought survival over nutrient

acquisition and limited AMF compatibility (Rao et al., 2020; Smith & Read, 2008; Grümberg et al., 2015).

Genetic differences in N and P uptake among bean varieties highlight the need for genotype-specific breeding. Dame's high nutrient efficiency suits resource-limited systems, while SER-119's trade-offs show the importance of AMF compatibility in drought-tolerant lines. These findings support climate-resilient legume development by targeting traits that enhance nutrient uptake under moisture stress.

Table 14. Tissue nutrient uptake as influenced by the effect of three different common bean varieties.

Varieties	Tissue N uptake (g)	Tissue P uptake (g)
SER-119	0.151±0.005b	0.103±0.005b
Dame	0.185±0.005a	0.122±0.005a
Awash Metene	0.177±0.005a	0.116±0.005ab
CV	4.39	14.56
P-value<0.05	0.001	0.05
R-square	0.95	0.96

AMF-inoculated common beans had 160% higher tissue phosphorus uptake (0.164) than non-inoculated plants (0.063), reflecting AMF's ability to access immobilized soil P through hyphae and transporters like *MtPT4* (Smith et al., 2011). Under moisture stress, AMF support P uptake via phosphatase secretion and enhanced root conductivity (Smith & Read, 2008; Augé et al., 2001). While differences were not statistically significant, the low SE suggests biological relevance (Halsey, 2019). Non-inoculated plants likely faced P limitations due to reduced root exploration under drought (Marschner, 2012).

Moisture Availability Modulates P Acquisition: Phosphorus uptake at 80% field capacity (0.149) was 91% higher than at 40% FC (0.078), with both sharing statistical grouping ("a") and SE =

0.005. Higher moisture improves P solubility and diffusion (Smith et al., 2011), while drought reduces availability through fixation (Marschner, 2012). The trend reflects moisture's effect on root transporter activity (Augé et al., 2001), though variability may stem from soil heterogeneity (Lynch, 2019).

AMF inoculation supports sustainable P management in Low-P, drought-prone soils, reducing fertilizer needs. Combining AMF with 80% FC irrigation may synergistically enhance P uptake, as AMF hyphae access distant P under stress (Augé et al., 2015). Both strategies significantly improve P acquisition in beans, warranting further research on AMF strain performance and field application for climate-resilient agriculture.

In conclusion, moisture availability is a pivotal driver of phosphorus uptake in common beans, with AMF inoculation amplifying benefits under optimal conditions (80% FC).

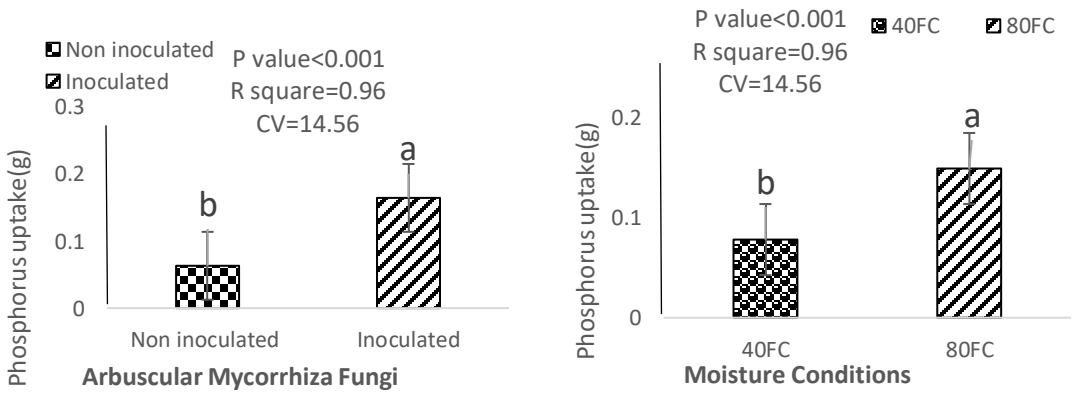


Figure 19: Nutrient uptake as influenced by the main effect of moisture conditions and arbuscular mycorrhiza fungi under three different common bean varieties.

4.8. Correlation Analysis

4.8.1. Association between morphological, physiological yield component and yield of common bean under AMF and different moisture conditions

The significant (*P<0.05*) and strong positive correlations between morphological parameters (like branch number, leaf number, number of flower) and yield components (pod length, pod number, number of seeds pod^{-1}) suggest that as these morphological traits increase, there's a notable increase in yield components. This implies that plants with more branches, leaves, and higher number of flower tend to produce more pods and seeds, contributing to higher seed yield. The strong positive correlation indicates a robust relationship between these variables, reinforcing the idea that changes in morphological traits are closely associated with changes in yield components.

Correlation analysis showed that leaf number was significantly (*P<0.05*) and strongly correlated in a positive sense with PL (r= 0.95**), NSPP (r=0.94**), 1000SW (r=0.93**), HI (r=0.94**) and SeYW(r=0.97***), as affected by AMF and soil moisture levels (Table 6). The number of flowers was also significant (*P<0.05*) and strongly correlated in a positive sense with PL (r= 0.96**), NPPP (r= 0.92*), NSPP (r=0.94**), 1000SW (r=0.93*), HI (r=0.97**) and SeYW (r=0.97***) as affected by AMF and moisture levels (Table 6).

This finding suggests that an increase in leaf number leads to higher productivity in terms of seed production for common beans. The stronger correlations observed for PL, HI, 1000SW, NSPP, and SeYW indicate that these parameters are more directly influenced by leaf number. This could be due to the fact that leaf area plays a crucial role in photosynthesis, which is essential for plant growth and development. Moreover, the positive correlation between leaf number and flower production implies that more leaves contribute to an increased number of flowers, which ultimately results in higher yields.

Table 15: Person correlation coefficient (r) among growth and morphological parameters, and yield and yield components of common bean influenced by different soil moisture and Arbuscular mycorrhizal fungi.

	BN	LN	LA	LFW	NF	RN	PL	NPPP	NSPP	1000SW	SeYW	HI
BN	1											
LN	0.98***	1										
LA	0.88ns	0.84ns	1									
LFW	0.91*	0.89ns	0.96***	1								
NF	0.97***	0.96***	0.93**	0.97***	1							
RN	0.97***	0.96***	0.90*	0.94**	0.97***	1						
PL	0.95***	0.95**	0.83ns	0.87ns	0.96**	0.90*	1					
NPPP	0.84ns	0.82ns	0.95**	0.93**	0.92*	0.82ns	0.85ns	1				
NSPP	0.96***	0.94**	0.86ns	0.88ns	0.94**	0.97***	0.89ns	0.78ns	1			
1000SW	0.93*	0.93**	0.76ns	0.82ns	0.93*	0.88ns	0.98***	0.80ns	0.89ns	1		
SeYW	0.96***	0.97***	0.84ns	0.89ns	0.97***	0.92*	0.99***	0.87ns	0.91*	0.98***	1	
HI	0.96***	0.94**	0.89ns	0.93*	0.96**	0.95**	0.94**	0.87ns	0.91*	0.90*	0.95**	1

Where, BN-number of branches, LN-leaf number, LA-leaf area, SLA-specific leaf area, LFW-leaf Fresh weight, FN-number of flowers, RN- Root Numbers, PL-pod length, NPPP-number of pods plant^{-1}, NSPP-number of seeds pod^{-1}, 1000SW- Thousand Seed Weight, and SeYW- seed yieldplant^{-1}Weight,

The person correlation analysis among physiological, yield component, and yield of common bean indicated a significant (*P<0.05*) and positive correlation. This correlation analysis suggests that optimizing physiological processes like photosynthesis and stomatal conductance, as well as maximizing yield components such as seed production, can lead to improved seed yield in common bean crops. Photosynthesis rate had a significant (*P<0.05*) and a strong positive correlation with PL (r= 0.97***), NSPP (r=0.94**), 1000SW (r=0.96***), SeYW (r=0.97***) and HI (r=0.95**), but non-significant (P>0.05) with NNPP. There was also a positive and correlation of Total chlorophyll with the PL (r= 0.94**), NSPP (r=0.94**), 1000SW (r=0.92*), SeYW (r=0.96***) and HI (r=0.96***), but non-significant (p>0.05) with NNPP as affected by AMF and soil moisture Stress. There was also a positive correlation of stomata number with PL (r= 0.91*), NPPP (r=0.90*), NSPP (r=0.94**), 1000SW (r=0.90*), SeYW (r=0.94**) and HI (r=0.92*), There was also a positive correlation of water use efficiency with PL (r= 0.96**), SeYW (r=0.90*) and HI (r=0.91*),but non- significant (P>0.05) with NPPP, NSPP and 1000SW, Likewise, there was also a positive correlation of stomata conductance with NPPP (r=0.96***), SeYW (r=0.90*) and HI (r=0.91*), but non- significant (P>0.05) with PL, NSPP and 1000SWa s affected by AMF and soil moisture Stress

Table 16: Person correlation coefficient (r) among physiological parameters, and yield and yield components of common bean influenced by different soil moisture and Arbuscular mycorrhizal fungi

	SN	SL	RLWC	T Chl	E	A	WUE	gs	PL	NPPP	NSPP	SeY W	1000S W	HI
SN	1													
SL	0.91*	1												
RLWC	0.87ns	0.78ns	1											
TChl	0.96**	0.94**	0.93**	1										
E	0.94**	0.95**	0.83ns	0.97**	1									
A	0.93*	0.92*	0.87ns	0.96**	0.96**	1								
WUE	0.86ns	0.87ns	0.87ns	0.93**	0.91*	0.98**	1							
gs	0.93*	0.84ns	0.88ns	0.92*	0.85ns	0.87ns	0.80ns	1						
PL	0.91*	0.90*	0.84ns	0.94**	0.92*	0.97**	0.96**	0.87ns	1					
NPPP	0.90*	0.83ns	0.84ns	0.87ns	0.79ns	0.83ns	0.78ns	0.96**	0.85ns	1				
NSPP	0.94**	0.83ns	0.88ns	0.94**	0.94**	0.94**	0.89ns	0.87ns	0.89ns	0.78ns	1			
SeYW	0.94**	0.93*	0.86ns	0.96**	0.95**	0.97**	0.90*	0.90*	0.99**	0.87ns	0.91*	1		
1000SW	0.90*	0.90*	0.79ns	0.92*	0.92*	0.96**	0.84ns	0.84ns	0.98**	0.80ns	0.89ns	0.98**	1	
HI	0.92*	0.87ns	0.88ns	0.96**	0.95**	0.95**	0.91*	0.91*	0.94**	0.87ns	0.91*	0.95**	0.90*	1

Where, SN- stomata numbers, SL- stomata length, RLWC-relative leaf water content, TC- total chlorophyll, A- photosynthesis, E-transpiration, WUE- water use efficiency, gs-stomata conductance, NPPP-number of pod plant-1, NSPP- number of seeds pod-1, 1000SW-thousand seed weight and SeYW- seed yield plant-1 weight

5. SUMMARY AND CONCLUSION

Common beans are a vital staple food in Ethiopia, providing essential nutrients and contributing to food security for many households. Their cultivation is widespread due to their adaptability to various agro-ecological zones. More than 60% of the world's common beans are cultivated under non-irrigated conditions. However, beans are sensitive to drought stress, which negatively impacts their growth and productivity. drought stress alters the metabolic processes of plants, slows growth, and makes it more difficult for them to utilize soil nutrients. Drought is estimated to cause up to 80% yield losses in many regions of the world. In common beans, drought stress during flowering and post-flowering causes reductions of 60–99% in yield, 25.4% in the number of pods per plant, 20.3% in the number of seeds per pod, and 11% in seed size. However, AMF form symbiotic relationships with over 80% of land plant. This symbiosis is crucial for drought adaptation, regulating various metabolites and metabolic pathways. AMF enhance survival, improve water absorption and transport, modify root morphology and affect gas exchange and water use efficiency. Additionally, AMF facilitate the uptake of minerals, primarily phosphorus and nitrogen, absorbing and transporting significant amounts of phosphates to root cells. This study investigates the effects of AMF on the growth, yield, and physiological responses of different bean varieties under moisture stress in a shade house. It also explores bio-fertilizers as a cost-effective alternative to inorganic fertilizers, addressing the low adoption of organic options among smallholder farmers due to availability and cost issues. A pot experiment was conducted to investigate the effect of AMF and soil moisture on the morpho-physiology, yield and yield component of common beans. So that the experiment was conducted with a factorial combination of three varieties, two soil moisture and two AMF (inoculated & non-inoculated) arranged in a completely randomized design with three replications.

This finding highlights the transformative role of AMF in enhancing drought resilience, optimizing growth, and improving yield in common beans, especially under moisture stress conditions.

AMF significantly enhances drought resilience and physiological performance. The symbiosis with AMF improves nutrient and water uptake, particularly phosphorus (P) and nitrogen (N), through extra radical hyphae, even in drought conditions (40% FC). This enhanced P uptake, which can increase by up to 42%, supports ATP synthesis, photosynthesis, and carbon assimilation, while improved root hydraulic conductivity aids in water transport. Moreover, AMF inoculation leads to a notable boost in photosynthetic efficiency, with a 45% increase in chlorophyll-a content under stress, a 96% increase in photosynthetic rates at 40% FC, and a 30% improvement in stomatal conductance at 80% FC. These enhancements stabilize light interception and gas exchange, helping to mitigate drought-induced photo-inhibition. Additionally, AMF optimizes biomass allocation by prioritizing reproductive structures during stress, resulting in a 40.5% improvement in the harvest index, with pod numbers increasing by 25-64% and seed yield rising by 28-62%, depending on the variety.

The responses of different common bean varieties to AMF highlight various adaptive strategies. The Awash-Metene variety excels in root biomass 89% increase in dry weight under drought conditions and maintaining balanced root-shoot growth, making it suitable for arid, low-fertility soils. Its superior nitrogen assimilation (0.73a tissue N) supports intrinsic drought tolerance while reducing reliance on AMF inputs. In contrast, the Dame variety achieves the highest seed yield (11.36 g), pod length (8.38 cm), and 1,000-seed weight (87.58 g) under optimal moisture conditions, benefiting from AMF-enhanced phosphorus mobilization. However, it exhibits high mycorrhizal dependency (MD), peaking at 134.12 under stress, indicating its suitability for drought-prone regions that require AMF support. The SER-119 variety is characterized as an

efficient phosphorus scavenger (4.76a), making it well-suited for severely phosphorus-limited environments but necessitating irrigation or AMF supplementation during drought. Its moderate MD (42.69 at 80% FC) suggests adaptability to variable climates.

From an agronomic perspective, the findings suggest several implications for policy and practice in drought-prone regions. Farmers should prioritize the Awash-Metene variety for its root-driven resilience or the Dame variety with AMF support for yield stability. Integrating AMF with organic amendments like compost can further maximize drought tolerance. In irrigated systems, using Dame can lead to high biomass and yield; however, care should be taken to avoid excessive irrigation that could delay maturity. For low-nitrogen soils, leveraging Awash-Metene's nitrogen efficiency is recommended. Sustainable agricultural practices can be enhanced by reducing synthetic inputs through AMF-driven nutrient efficiency and promoting breeding programs focused on developing AMF-compatible varieties along with field-scale inoculation protocols.

The global relevance of AMF symbiosis aligns with climate-smart agriculture initiatives by enhancing yield stability in water-limited environments (with potential yield gains of 25-40% under drought), reducing greenhouse gas emissions through lower fertilizer use, and supporting food security in climate-vulnerable regions via resilient cropping systems. However, it should be noted that this study was conducted under shade house with only three common bean varieties. Therefore, further research is necessary under field conditions with a several varieties of common bean before any generalized conclusions can be drawn.

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7. APPENDIX TABLES

Appendix Table 1: Analysis of variance (ANOVA) for days of emergence(EMER), days to flower (DTF), days to pod setting (DTPS), Days to physiological maturity (DPM),number of flower(NF) and plant height (PH)

Source of variation	DF	EMER	DTF	DTPS	DPM	NF	PH
AMF	1	2.56***	40.81**	30.25***	8.03*	1406.25***	6933.3***
Var.	2	0.73*	1.15ns	1.36ns	2.03ns	16.86*	2288.6***
MC.	1		655.96***	930.25***	406.69***	1640.25***	10650.2***
AMF*Var.	2	0.30ns	1.26ns	0.08ns	0.86ns	1.58.ns	15.7ns
AMF*MC.	1		112.61***	148.03***	51.36***	20.25*	711.1*
MC*Var.	2		7.48ns	3.25ns	2.03ns	0.25ns	138.2ns
AMF*MC*Var.			0.04ns	1.19ns	0.19ns	1.08ns	50.4ns
Error	24	0.15	2.90	1.69	1.14	3.69	128.3

*The signs *, **, and *** indicate, P<0.05, P<0.01, and P<0.001 respectively, whereas ns- indicates a non-significant difference (P>0.05). DF, AMF, Var, and MC stand for degree of freedom, arbuscular mycorrhiza fungi, variety and moisture conditions, respectively.*

Appendix Table 2:Analysis of variance (ANOVA) for leaf number (LN), leaf area (LA), specific leaf area (SLA), leaf fresh weight (LFW), leaf weight ratio (LWR) and leaf dry weight (LDW)

Source of variation	DF	LN	SLA	LA	LFW	LDW	LWR
AMF	1	4011.1***	396.63***	1027817***	532.22***	20.011***	0.006**
Var.	2	346.9***	53.86***	22044 **	0.16ns	0.204ns	0.001ns
MC	1	2635.1 ***	751.40 ***	1892193***	1022.72***	41.259***	0.035***
AMF*Var.	2	6.2ns	11.44 ns	16186*	0.96ns	0.309ns	0.0008ns
AMF*MC	1	205.4*	90.88***	93522***	12.56**	0.047ns	0.0001ns
MC*Var.	2	9.7ns	2.00 ns	3824ns	0.02ns	0.198ns	0.002ns
AMF*MC*Var.		9.7ns	7.37ns	6738ns	0.75ns	0.297 ns	0.0015ns
Error	24	33.3	4.74	2985	1.17	0.207	0.0118

*The signs *, **, and *** indicate, P<0.05, P<0.01, and P<0.001 respectively, whereas ns- indicates a non-significant difference (P>0.05). DF, AMF, Var, and MC stand for degree of freedom, arbuscular mycorrhiza fungi, variety and moisture conditions, respectively.*

Appendix Table 3: Analysis of variance (ANOVA) for Root weight ratio (RWR), stem weight ratio (SWR), leaf area ratio(LAR), leaf area index (LAI), leaf dry matter content (LDMC), stem fresh weight(SFW) and stem dry weight (SDW)

Source of variation	DF	RWR	LAR	LAI	SWR	SFW	SDW
AMF	1	0.0001ns	1310.06***	17.383***	0.001*	516.50***	10.2613***
Var.	2	0.002*	28.10 **	0.373**	0.003***	1.85ns	0.1760 ns
MC	1	0.0026*	2411.79***	32.002***	0.009***	650.25***	17.3333 ***
AMF*Var.	2	0.0001ns	20.63*	0.274*	0.0002ns	0.30ns	0.1723ns
AMF*MC	1	0.00001ns	119.20***	1.582***	0.0001ns	17.08 *	0.4489*
MC*Var.	2	0.0002ns	4.87ns	0.065ns	0.0001ns	0.62 ns	0.0041 ns
AMF*MC*Var.		0.00003ns	8.59ns	0.114ns	0.00001ns	0.09ns	0.0482 ns
Error	24	0.0004	3.81	0.050	0.0003	2.82	0.0932

*The signs *, **, and *** indicate, P<0.05, P<0.01, and P<0.001 respectively, whereas ns- indicates a non-significant difference (P>0.05). DF, AMF, Var, and MC stand for degree of freedom, arbuscular mycorrhiza fungi, variety and moisture conditions, respectively.*

Appendix Table 4: Analysis of variance (ANOVA) for branch number (BN), internode number (IN), root number(RN), root fresh weight (RFW), root dry weight (RDW) and taproot length(TRL)

Source of variation	DF	BN	IN	RN	RFW	RDW	TRL
AMF	1	920.11 ***	277.778***	324.00***	959.24***	10.0278***	1311.65***
Var.	2	34.75 ***	5.583ns	15.75***	0.35ns	0.3421 *	24.65ns
MC	1	484.00***	289.000***	300.44***	1194.97***	12.4609***	1682.37***
AMF*Var.	2	1.03ns	0.528ns	0.58ns	1.68 ns	0.0400ns	0.61ns
AMF*MC	1	11.11*	11.111*	28.44***	9.74*	0.7685 **	192.75**
MC*Var.	2	0.08ns	0.583ns	0.53ns	0.75ns	0.0648 ns	10.83ns
AMF*MC*Var		0.69ns	0.194ns	0.36ns	1.26ns	0.0740 ns	3.74ns
Error	24	1.44	2.139	1.11	1.60	0.0792	18.42

*The signs *, **, and *** indicate, P<0.05, P<0.01, and P<0.001 respectively, whereas ns- indicates a non-significant difference (P>0.05). DF, AMF, Var, and MC stand for degree of freedom, arbuscular mycorrhiza fungi, variety and moisture conditions, respectively.*

Appendix Table 5: Analysis of variance (ANOVA) for stomatal conductance (gs), photosynthesis rate (A), transpiration rate (E), chlorophyll-a (Chl. a), chlorophyll -b(Chl-b), and water use efficiency (WUE)

Source of variation	DF	A	E	WUE	gs	Chl-a	Chl-b
AMF	1	12686.3 ***	480.63 ***	10.6200 ***	2224.7***	1550.92 ***	1483.79 ***
Var.	2	105.4 **	37.88 ***	0.0983 ns	59.7ns	46.62 **	22.78ns
MC	1	5791.2***	361.51***	3.9064***	3990.0 ***	1818.88***	1989.75***
AMF*Var.	2	32.0ns	3.13ns	0.0611ns	29.4ns	1.62 ns	44.31*
AMF*MC	1	643.5***	77.03***	1.1797***	210.3*	215.55***	105.20**
MC*Var.	2	87.6*	10.93ns	0.0026ns	5.0ns	5.52ns	7.67ns
AMF*MC*Var		20.9ns	0.74ns	0.0661ns	6.2ns	5.92ns	0.19ns
Error	24	16.7	4.03	0.0462	48.1	7.19	9.47

*The signs *, **, and *** indicate, P<0.05, P<0.01, and P<0.001 respectively, whereas ns- indicates a non-significant difference (P>0.05). DF, AMF, Var, and MC stand for degree of freedom, arbuscular mycorrhiza fungi, variety and moisture conditions, respectively.*

Appendix Table 6: Analysis of variance (ANOVA) for Total chlorophyll, chlorophyll fluorescence (CF), stomata length (SL), stomata width (SW), stomata density (SD), stomata index (SI)

Source of variation	DF	T Chl	CF	SL	SW	SD	SI
AMF	1	6068.7 ***	6.38 ***	234.42 ***	149.711 ***	26042***	3709.8***
Var.	2	61.9 *	0.03 ns	41.99 ***	10.181*	2227*	11.9ns
MC	1	7613.4***	5.34 ***	348.48***	175.133 ***	39368***	6083.7***
AMF*Var.	2	48.8ns	0.001ns	5.56ns	7.606ns	485ns	8.7ns
AMF*MC	1	621.9***	2.63***	51.42 14***	7.445ns	343ns	308.9**
MC*Var.	2	25.0ns	0.005ns	17.15*	5.235ns	383ns	41.8ns
AMF*MC*Var.		6.9ns	0.022ns	0.96ns	0.329ns	306ns	8.8ns
Error	24	15.9	0.064	3.57	2.981	595	27.6

*The signs *, **, and *** indicate, P<0.05, P<0.01, and P<0.001 respectively, whereas ns- indicates a non-significant difference (P>0.05). DF, AMF, Var, and MSL stand for degree of freedom, arbuscular mycorrhiza fungi, variety and moisture conditions, respectively.*

Appendix Table 7: Analysis of variance (ANOVA) for Stomata number(SN), relative leaf water content (RLWC), pod length (PL), number of pods plant^{-1} (NPPP), number of seeds p^{-1} number of seeds plant^{-1} (NSPPL), number of seeds pod^{-1} (NSPP), and seed yield weight (SeYW)

Source of variation	DF	SN	RLWC	PL	NPPP	NSPP	NSPPL	SeYW
AMF	1	413.44***	1961.0***	67.700***	196.00***	22.0900***	20280.1***	395.08***
Var.	2	35.36*	106.4*	2.350 **	11.44ns	1.2284***	211.9ns	20.08***
MC	1	625.00***	3883.4***	33.152***	498.78***	13.3225***	26122.6***	245.55***
AMF*Var.	2	7.69ns	0.1ns	0.068 ns	1.00ns	0.4827*	84.1ns	1.01 ns
AMF*MC	1	5.44ns	187.2*	1.946 *	32.11*	0.9025*	1334.1*	11.11*
MC*Var.	2	6.08ns	74.2ns	0.087ns	3.44ns	0.1290ns	340.5ns	0.04ns
AMF*MC*Var.		4.86ns	1.4ns	0.595ns	1.44ns	0.0327ns	92.1ns	2.31ns
Error	24	9.44	31.2	0.315	7.19	0.1197	268.5	1.45

*The signs *, **, and *** indicate, P<0.05, P<0.01, and P<0.001 respectively, whereas ns-indicates a non-significant difference (P>0.05). DF, AMF, Var, and MSL stand for degree of freedom, arbuscular mycorrhiza fungi, variety and moisture conditions, respectively.*

Appendix Table 8: Analysis of variance (ANOVA) for thousand seed weight (1000SeW), total above ground biomass fresh weight (TAGBFW), total above ground biomass dry weight (TAGBDW), total below ground fresh weight (TBGFW), total below ground dry weight (TBG DW), strew yield (SY) and harvest index(HI).

Source of variation	DF	1000SeW	TAGBFW	TAGBDW	TBGFW	TBGDW	SY	HI
AMF	1	9047.8***	9169.0 ***	619.26***	104.82***	1.9928 ***	5679.9***	0.207***
Var.	2	598.2 ***	1935.5***	67.86 ***	19.61***	0.6423 ***	1639.7***	0.005ns
MC	1	3440.6***	7285.5***	337.27 ***	387.24***	23.3128***	5475.8***	0.155***
AMF*Var.	2	111.2ns	676.4***	3.00 ns	4.43*	0.0809ns	710.2***	0.006ns
AMF*MC	1	447.7**	410.1**	119.72 ***	5.56*	0.5550**	237.3*	0.004ns
MC*Var.	2	12.5ns	181.0*	6.87ns	6.51**	0.2415**	194.6*	0.003ns
AMF*MC* Var.	2	23.0ns	119.4ns	8.93 ns	3.52ns	0.0257ns	132.9ns	0.003ns
Error	24	47.1	39.7	4.28	1.11	0.0404	39.2	0.002

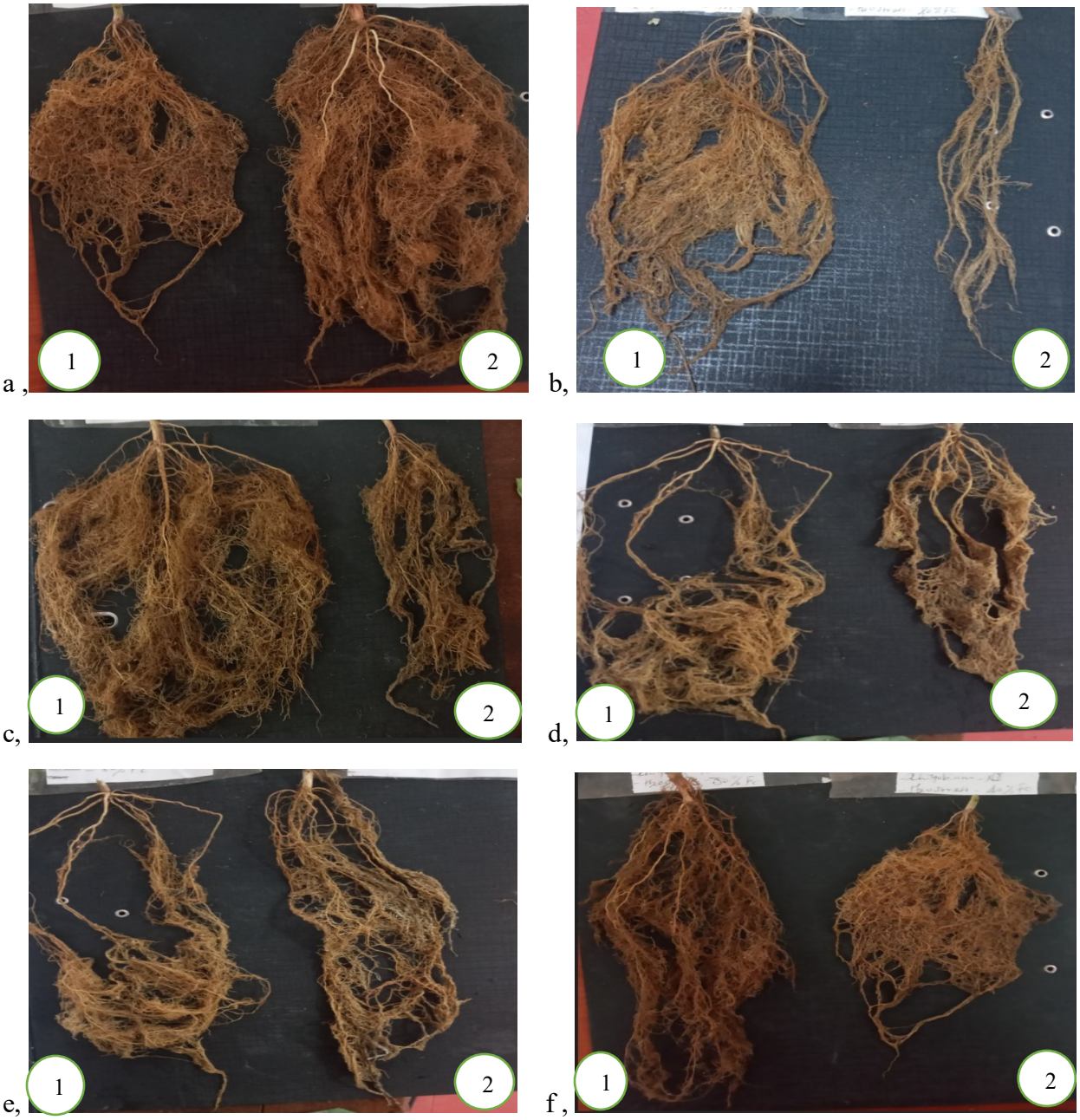
*The signs *, **, and *** indicate, P<0.05, P<0.01, and P<0.001 respectively, whereas ns-indicates a non-significant difference (P>0.05). DF, AMF, Var, and MC stand for degree of freedom, arbuscular mycorrhiza fungi, variety and moisture conditions, respectively.*

Appendix Table 9: Analysis of variance (ANOVA) for microbial traits, tissue N, tissue P, soil N, and soil P after harvest

Source of variation	DF	Root colonization	Spore density	MD	Con.Tissue N(%)	Con. tissue P(%)	Con. soil N(%)	Con. soil P(ppm)	Tissue N uptake (g)	Tissue P uptake (g)
AMF	1	95687***	6874010***	507.92***	0.24***	0.603***	0.0007***	23.06***	0.093***	0.091***
Var.	2	14ns	1503ns	680***	0.005*	0.0007ns	0.00008ns	0.45**	0.004***	0.001*
MC.	1	289*	37442**	17098***	0.109***	0.281***	0.007***	8.38***	0.047***	0.045***
AMF*Var.	2	14ns	1503ns	680***	0.0002ns	0.004ns	0.0000ns	0.006ns	0.0001ns	0.0002ns
AMF*MC.	1	289*	37442**	17098***	0.005*	0.014**	0.00025**	2.68***	0.003**	0.001ns
MC*Var.	2	1ns	1280ns	460***	0.0004ns	0.001ns	0.0000ns	0.16ns	0.0001ns	0.0001ns
AMF*MC*Var.	2	1ns	1280ns	460***	0.001ns	0.002ns	0.0000ns	0.12ns	0.0005ns	0.0004ns
Error	24	46	35.90	0	0.001	0.001	0.00003	0.06	0.0003	0.0003

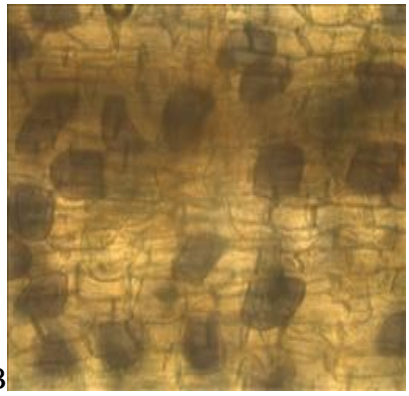
*The signs *, **, and *** indicate, P<0.05, P<0.01, and P<0.001 respectively, whereas ns-indicates a non-significant difference (P>0.05). DF, AMF, Var, and MC stand for degree of freedom, arbuscular mycorrhiza fungi, variety and moisture conditions, respectively*

8. APPENDIX FIGURES

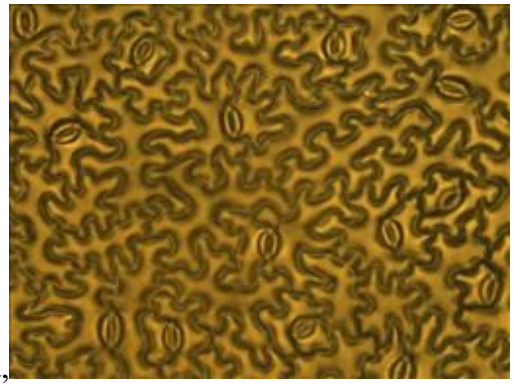


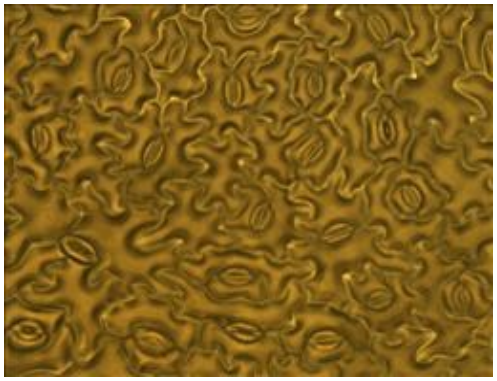
Appendix figure 1: Root pictures influenced by arbuscular mycorrhiza fungi and different moisture conditions. (a1) Awash metene by Arbuscular mycorrhiza fungi under 80% field capacity (a2) Awash metene by Arbuscular mycorrhiza fungi under 40% field capacity, (b1) SER-119 by non-inoculated with 80%FC (b2) SER-119by non-inoculated with 40%FC, (c1) Awash metene by non-inoculated with 80%FC (c2) Awash metene by non-inoculated with 40%FC (d1) Dame by Arbuscular mycorrhiza fungi under 80% field capacity (d2) Dame by Arbuscular mycorrhiza fungi under 40% field capacity

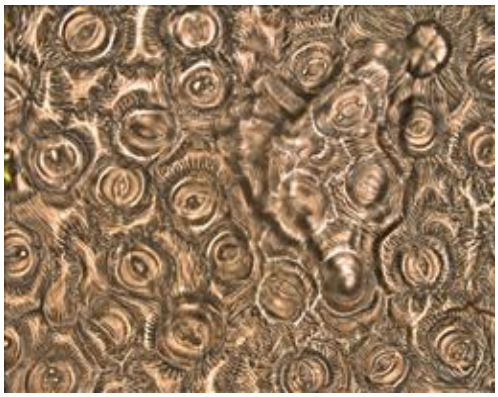
(e1) Dame by non-inoculated with 80%FC (e2) Dame by non-inoculated with 40%FC (f1) SER-119 by Arbuscular mycorrhiza fungi under 80% field capacity (f2) SER-119 by Arbuscular mycorrhiza fungi under 40% field capacity

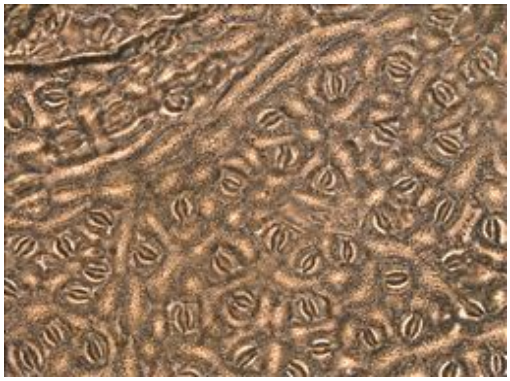
A,  B  C, 

Appendix figure 2: View of microscopic examination of common bean root under a light microscope (40X) in a work of AMF root colonization. (a) Root section not colonized by Arbuscular mycorrhiza fungi (b) root section colonized with Arbuscular mycorrhiza fungi under 80% field capacity (c) root section colonized with Arbuscular mycorrhiza fungi under 40% field capacity

a, 

b, 

c, 

d, 

Appendix figure 3: stomata anatomy of common bean under different moisture conditions and arbuscular mycorrhiza fungi inoculations. (a) stomata figure without Arbuscular mycorrhiza fungi under 40% field capacity. (b) stomata figure without Arbuscular mycorrhiza fungi under 80% field capacity. (c) stomata figure with Arbuscular mycorrhiza fungi under 40% field capacity (d) stomata picture with Arbuscular mycorrhiza fungi under 80% field capacity

a,  b, 

c,  d, 

Appendix figure 4: Common bean varieties under all experimental and treatments at the growth stages

a, 

b, 

c, 

d, 

Appendix figure 5: Sample preparation for stomata counting (b) and soil analyzing (a, & d) and morphological data measuring (c).

SKETCH OF BIOGRAPHY

The author was born in 1999 G.C at Sire Morose kebele, Hidebu Abote wereda, in the North Shoa zone, Ethiopia. She attended primary education (grade 1-8) at General Tadesse Biru primary school. She then after completing full primary school, she joined General Tadesse Biru secondary school where She attended grade 9 and 10. With scoring well result in Ethiopian national examination, she joined General Tadesse Biru preparatory school where she studied grade 11 and 12. As a result of passing Ethiopian university entrance examination, she joined Hawassa University, College of Agriculture in 2017 G.C and graduated with the Degree of Bachelor of Science in Horticulture in December 31, 2020 G.C.

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