ARBUSCULAR MYCORRHIZAL FUNGI AND SILICON EFFECTS ON NUTRIENT UPTAKE, GROWTH AND YIELD OF SORGHUM UNDER WATER STRESS IN MACHAKOS COUNTY, KENYA

BY

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OCTOBER, 2021

DECLARATION

I Kaaria Kallen Gacheri affirm that this thesis is my original work and has not been presented for the award of a degree in any other university or any other award.

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We confirm that the work reported in this thesis was carried out by the candidate under our supervision as university supervisors.

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DEDICATION

I dedicate this thesis to my mum Bridget Kaaria, my late father Stephen Kaaria, Sisters Emily and Betty, Brother Nathan, and my lovely kids Eldad and Elam.

ACKNOWLEGEMENT

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LISTS OF ACRONMYS AND ABBREVIATIONS

ANOVA	Analysis of variance
AMF	Arbuscular mycorrhizal fungi
P	Phosphorus
K	Potassium
N	Nitrogen
Ca	Calcium
Mg	Magnesium
Si	Silicon
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
GoK	Government of Kenya
NGO	Non-governmental organization
MOA	Ministry of Agriculture
pH	Potential of hydrogen
R	Statistical software

ABSTRACT

Sorghum (*Sorghum bicolour* L. Moench) is an important cereal crop ranked second after maize as a food security in Kenya. However, its production is threatened by low soil fertility and moisture content. Many studies on arbuscular mycorrhizal fungi (AMF) have shown its importance in nutrient and water uptake, resulting in better yields of crops. In addition, silicon helps in plant resistance to both abiotic and biotic stresses. The study evaluated effects of AMF and silicon on nutrients uptake, growth and yield of two sorghum varieties under different water regimes. Two field experiments were carried out in Machakos County, Kenya. A Randomized Completely Block Design (RCBD) in a factorial arrangement was used to lay out the experiment. The factors tested included: Two levels of sorghum varieties (Seredo and Machakos local red), the other factor was water regimes in three levels (20, 40 and 60%) while the third level was silicon and Mychorriza (plus and minus). Sorghum varieties and leek were used as trap plants in a greenhouse experiment. Data collection was done on sorghum growth, yield and nutrient uptake, AMF colonization percentage and AMF diversity. Analysis of variance (ANOVA) was used to analyze data using R software and significant means separated using Tukey's test at 5% significance level. The results showed that Seredo variety had the highest shoot dry weight (107 g), longest roots (44.1 cm) and longest period to 50% flowering (76.4%) while Machakos local red had tallest plants (210.9 cm) and highest number of leaves (10.8). At 60% water regime, Si amendment and AMF inoculation enhanced sorghum growth better than other treatments. Seredo variety recorded the highest grain yield (4.4 tha^{-1}). The variety also revealed various nutrient uptake as follows:- phosphorus (111.1 kg ha^{-1}), nitrogen (34.7 kg ha^{-1}), K (69.7 kg ha^{-1}), calcium (3296 kg ha^{-1}) and magnesium (172.1 kg ha^{-1}) uptake. It has recorded the best AMF root colonization. Moreover, Seredo variety had the maximum harvest index of 0.39. At 40% water regime, Seredo variety amendment with Si and AMF produced the highest grain yields, nutrients uptake and AMF root colonization. A total of 4 AMF genera (*Gigaspora, Scutellospora, Acuolospora* and *Glomus* spp) from the family Gigasporaceae, Acaulosporacea and Glomeraceae were detected from both trap culture and experimental soil. The trap culture had the highest number of spore density 57.5 (leek), 32.8 (Seredo) and 23.5 (Machakos red local) compared to the experimental soil that had 15 spores per 100g of soil. Leek plants trapped more *Glomus* (23), *Scutellospora* (15.8) and *Acaulospora* (11.8) than both sorghum varieties but Seredo variety trapped most *Gigaspora* (15.3) per 100g of soil. This study demonstrated that Si amendment and AMF inoculants have potential of improving sorghum growth and yield under water stressed conditions as indicated by the high grain yield and nutrients uptake achieved at 40% water regime. Therefore, combined use of Silicon and AMF is recommended for improving sorghum productivity in water stress areas. Such strategies could enable food production in marginal areas characterized by low rainfall and high temperatures.

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

Sorghum (*Sorghum bicolor* L. Moench) is a critical food security crop and the fifth most important cereal crop grown worldwide (Twomlow *et al.*, 2004). Sorghum is widely used in human foods mainly as processed flour, fermented porridge, feed industries and bioenergy crop (Muui *et al.*, 2013). Due to its ability to tolerate drought (Younis *et al.* 2007), it is mainly grown in the dry and semi-arid areas. Sorghum is fairly adaptable and can grow well in temperate to warm weather conditions, fairly stable rainfall pattern, and well-drained fertile soil through the developing period.

Sorghum production is constrained by soil fertility problems caused by ongoing climate change that has caused severe yield reduction and crop failure (Kabubo *et al.*, 2019: Manzi and Gweyi-Onyango, 2020; Ntiyari and Gweyi-Onyango, 2021). This growth suppression can be alleviated by incorporating beneficial micro-organisms and silicon during sorghum production. Beneficial soil microorganisms perform a great role in biodiversity and environment management in sustainable crop production. They increase tolerance to abiotic stresses and biotic stress, recycling of nutrients and mineralization of the soil organic matter (Giovannetti and Avio, 2002; Hodge and Fitter, 2010). Presence of a diverse population of microorganisms is characteristic of healthy and fertile soils (Vierheilig *et al.*, 1998).

Among the beneficial microorganisms is Arbuscular Mycorrhizal Fungi (AMF) which are essential in agricultural crops for sustainable production (Vierheilig *et al.,* 1998). Arbuscular mycorrhizal fungi form mutualistic symbioses with the roots of terrestrial plants. This association is beneficial to the host plant and the fungi, whereby the fungi obtains nutrients and shelter from the host plant while the host plant receives nutrients from the soil through the extraradical fungal hyphae (Vierheilig *et al.,* 1998). Approximately 90% of the terrestrial plant species are colonized by AMF (Gadkar *et al.,* 2001). It has been shown that mycorrhiza enhances uptake of phosphorous and nitrogen (Abdel-Fattah and Mohamedin, 2000) and it also improves uptake of immobile nutrient elements like copper and zinc (McMaster *et al.,* 2019). Effective AMF associations have been reported to reduce the amount of fertilizer needed to be applied to crop by 50% (Miyasaka *et al.,* 2003).

Silicon (Si), on the other hand has been proved as an element that is beneficial for plant growth and regulation of water utilization (Cuong *et al.,* 2017). It has been recognized as an important plant nutrient and the most second abundant component in the layers of the earth as well as one of the most abundant mineral elements in plant tissues (Gargand Bhandari, 2016a). The role of Si in plants in some cases may be equal to the essential macronutrients (Garg and Bhandari, 2016b). Silicon is taken up by plants as silicic acid [$Si(OH)_4$] and deposited within plant tissue as SiO_2 (Frew *et al.,* 2017). In addition, silicon has positive effects on plants such as increase in plant cell wall stiffness and strength, reduction of toxic absorption, reduction of plant evapotranspiration, increase in tolerance to biotic and abiotic stress and increases defense of plants against herbivores (Cuong *et al.*, 2017; Frew *et al.*, 2017 ; Garg and Singh, 2018). This is because Si deposition within or between cell walls makes cells more impact absorbent, harder to physically crush and less susceptible to fracture propagation (Hunt *et al*., 2008). In addition Si enhances Jasmonate signaling pathways which produces Jasmonic acid that attracts predators and parasitoids that inhibit insect pests from attacking plants. Although silicon is a nutrient that causes no toxicity to the environment and living organisms, its role in plant growth and functions have remained scanty (Meena *et al.*, 2014).

1.2 Statement of the problem

Sorghum yields in Kenya are below the optimal potential due to low soil fertility and drought stress among other factors. According to FAOSTAT, (2018), world sorghum yield ranges between 3.5 to 5 ton/ha. National yield per hectare in Kenya has decreased from 1.2 tons/ha in 2005 to 0.5tons/ha in 2013 (FAOSTAT, 2018). Drought is a major abiotic stress that limits crop productivity (Zhu and Gong, 2014), with climate change leading to increased drought in Eastern Africa, (Ngugi *et al.*, 2015). Moreover, soil fertility depletion has also affected crop productivity leading to food insecurity. Furthur, soil fertility depletion has been recognized as a major production constraint affecting sorghum in Eastern Africa (Wortmann *et al.*, 2006).

To this end sustainable solutions are required to improve sorghum yield. One of the possible solutions is the use of fertilizers. However, inorganic fertilizers are very expensive in Kenya and similar regions since they are imported and not affordable to small scale farmers, not forgetting the associated negative human and environmental health challenges. Soil inoculation with AMF helps to increase nutrient uptake (Rouphael *et al*., 2015) and alleviate effects of soil acidity for better crop growth (Kumar *et al*., 2015). However, most soils have low native AMF populations and few AMF species, yet AMF effectiveness is highly influenced by their abundance and diversity and the crop grown. A combination of silicon amendment and AMF inoculation could solve the impact of drought and low soil fertility challenges hindering sorghum production in Kenya. However, there is inadequate information on the best water regime for effective performance of silicon and AMF for optimum sorghum growth and yield in drought stressed areas of Kenya.

1.3 Research objectives

1.3.1 General objective

To improve sorghum production using arbuscular mycorrhiza and silicon for increased growth, yield and uptake of nutrients in water stressed soils.

1.3.2 Specific objectives

i. To determine the influence of silicon and AMF inoculation on sorghum root colonization under different levels of soil water status.

ii. To determine the effects of AMF and silicon on growth and yield of sorghum grown under different watering regimes.

iii. To evaluate the effects of AMF and Silicon on nutrient uptake by sorghum grown under different water regimes

iv. To assess the native arbuscular mycorrhizal diversity of the experimental soil.

1.4 Research hypotheses

- **i.** AMF and Si influences root percentage colonization increase under increase soil water stress.
- ii. Arbuscular mycorrhiza and silicon affects growth and yield of sorghum under different watering regimes.
- iii. Nutrient uptake in sorghum is affected by AMF and silicon under differing soil watering status
- iv. The experimental farm soil have variations in native AMF species diversity.

1.5 Significance of the study

This study will provide strategies for designing affordable and sustainable technologies for improved sorghum production. Improving sorghum production will improve food security and improve livelihood of people by creating employment along the value chain and consequently increase the national income (Muui *et al.,* 2013). The knowledge generated will help in developing succinct recommendations that will be used to advice farmers on use of AMF and silicon in production of sorghum and cereal crops. Results will be used by research institutions, extension, policy makers and other stakeholders to inform and train farmers on the importance of AMF and silicon in sorghum production. The research will also be important to the county government, scholars, NGO and national government. Higher yields for farmers with low inputs, steady market supply and stable market prices will be realized. Farmers will get high returns which will help them improve their livelihoods.

1.6 Justification of the study

Drought and low soil nutrient are some of the key restraints of crop output. As a mitigation measure, planting tolerant crop species such as sorghum is recommended. Sorghum is a critical food security crop that adapts to a wide range of climate. Studies by Muui *et al.,* (2013) indicate that a large population of people in Kenya largely depend on sorghum as food especially the poor and those living in the marginalized areas. It is also used in industries for making beer and processed flour thus improving livelihood of people by creating employment and growing the economy of the country (Muui *et al.,* 2013). According to research by Younis *et al.* (2007), sorghum is mainly grown in the dry and semi-arid zones due to its ability to tolerate drought. However, its production has been declining worldwide. Therefore there is a need to seek sustainable solutions to improve and increase sorghum production.

This study focuses on the enhancement of nutrient uptake by use of microbial inoculants (AM fungi) and incorporates the use of silicon. Silicon enhances plant growth (upright growth) and yield, encourages leaves favorable exposure to light, avoids lodging and provides plant defense to diseases caused by fungi and bacteria, while AMF mobilizes nutrient uptake by plants. The findings of the study will add to knowledge on enhancement of sorghum yields. This will bridge the gap of low sorghum production especially in small-scale farms.

1.7 Conceptual framework

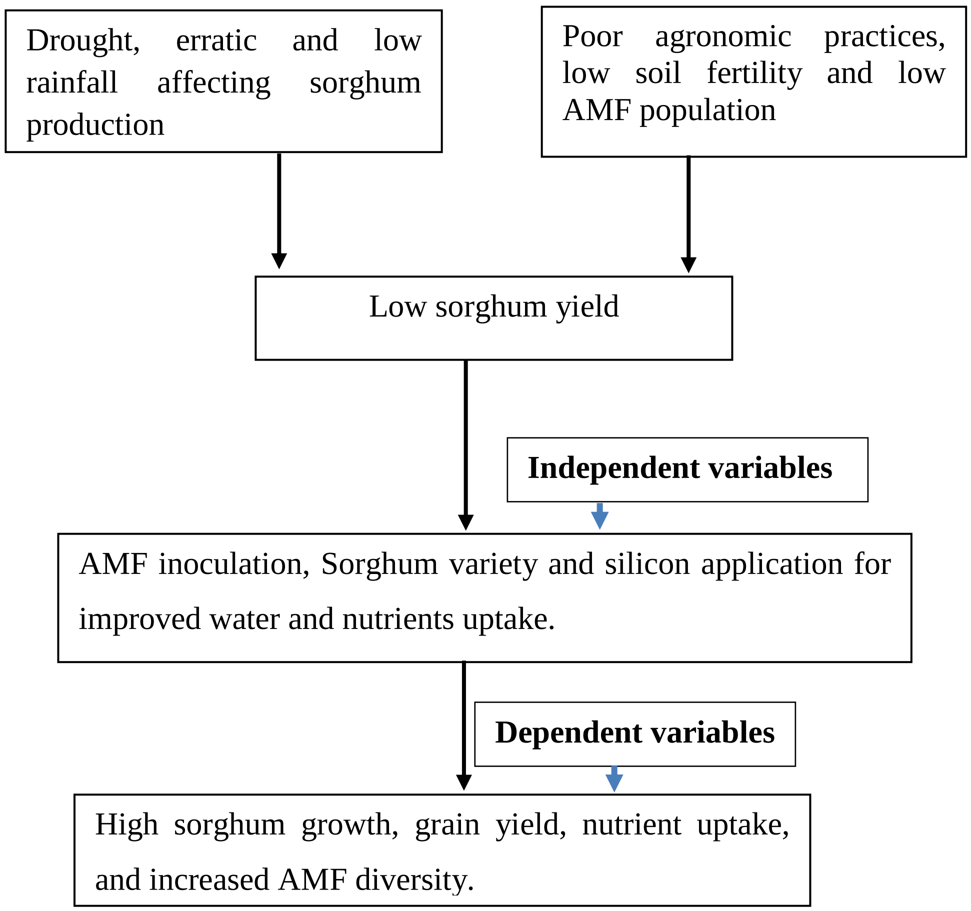


Figure 1.1: Conceptual framework

CHAPTER TWO: LITERATURE REVIEW

2.1 Origin and diversity of sorghum

Sorghum (*Sorghum bicolor* L. Moench) also known as milo, kafir and guinea corn is a crop of worldwide importance. According to Mar *et al.* (2019), sorghum was domesticated from great diversity of both wild and cultivated species that originated in North-Eastern Africa. It was domesticated in Ethiopia about 500 years ago. Millions of people especially in Asia and Africa use sorghum as an important diet in their food (Reddy, 1987) where over 90% of the sorghum produced is used for human food. According to Dicko *et al.* (2006) it is categorized as the fifth greatest main cereal crop (in terms of production), after barley, maize, rice, and wheat. According to Vila-Real *et al.* (2017), about 58 million tons grain is produced from 42.6 million ha of land worldwide.

In Kenya it is considered to be the second most significant cereal crop after maize. Current sorghum total production in Kenya is about 229,000 MT grown in about 226 ha, while human consumption is over 50% of the sorghum produced. This crop is majorly cultivated for its seeds, although it does well as livestock fodder. Northern Rift valley, Western, Eastern and parts of Central province are the major regions that grow sorghum in Kenya. Sorghum has the ability to regrow after harvesting and this reduces the cost of land preparation and replanting. Its ability to tolerate diverse climates has led to its widespread cultivation.

2.2 Taxonomy and description of sorghum

According to Bosch *et al.* (2017) sorghum belongs to the Graminea grass family and it is grown for its grain. Fuller and Stevens, (2018) reviewed the nomenclature of cultivated sorghum, wild and weedy relatives. Cultivated sorghum resembles grass with diverse morphology (Reddy, 1987). It has a shoot height that ranges from 0.5 metres (m) to 6 m with erect, slender and stout stems. Adventitious stems called tillers originate from plant base and have leaf blades that are smooth or hairy, varying from linear to lanceolate. Sorghum inflorescence consists of a single panicle that may be either compact or open with many racemes. It is a self-pollinated plant but sometimes wind pollination can occurs.

2.3 Ecological adaption of sorghum

Sorghum is mainly produced in the more marginal and water deficit regions of dry and semi-arid areas, mostly by small scale farmers. According to Mar *et al.* (2019), the crop can tolerate high temperature throughout its growth cycle and it is widely grown in such areas experiencing high temperatures. Rainfall requirements for sorghum production are between 450 and 650 mm depending on the climate. Optimum temperatures are between 15 °C to 35 °C. However, some sorghum varieties can tolerate high temperature of up to 38 °C.

2.4 Importance of sorghum

Sorghum is a very key source of food and farm revenue for smallholder farmers, which can be boosted particularly if allied to new markets. In semiarid regions of East African, sorghum is important to a substantial number of farm families. On account of sorghum being a drought resistant crop (MOA, 2012). Also it is taken as a major poverty eradicating crop especially in marginal regions (MOA, 2012). Sorghum is important in ensuring food security and it largely constitutes the major food items for many households. According to Tesso (2005), it has many characteristics such as resistance to salinity, tolerance to water lodging and resistance to drought. It is also cheap to establish since it does not require much inputs and can grow in degraded lands hence increasing agriculture production. Sorghum is consumed as food by humans and as forage fed for animals. In addition, the stem is used as building material and after harvesting the plant remains are used as fuel. Report by Mar *et al.* (2019) shows that it is also used in industrial production of alcohol and lager beer.

2.5 Role of AMF in nutrients uptake

Presence of a diverse population of microorganisms in the soil shows a good characteristic of healthy and fertile soils (Vierheilig *et al.,* 1998). Arbuscular Mycorrhizal fungi are part of the vital component of soil microorganisms that are important in sustainable production of agricultural crops (Vierheilig *et al.,* 1998). Arbuscular mycorrhizal fungi forms a mutualistic symbiosis with the roots of terrestrial plants. This association is beneficial for host plant and the fungi, where fungi obtains food from the host plant while the host plant receives nutrients from the soil through the extraradical fungal hyphae (Vierheilig *et al.,* 1998). The occurrence of the AMF association is elicited by a signal exchange between mycorrhiza and the host plant roots (de Oliveira *et al*., 2020). The roots of the host plants elicit release of strigolactones that induce mycorrhiza spore germination and mycelia branching (MacLean *et al*., 2017).

Theses strigolactones have been isolated and known in root exudates of different crops species involved in AMF colonization (Ejeta *et al*., 2017; MacLean *et* al., 2017). However, mycorrhiza may also produce lipo-chitooligosaccharides which activates the symbiosis signaling pathway in the roots (Vergara *et al*., 2019).

Inoculation of AMF can enhance the concentration of various macro-nutrients and micro-nutrients significantly, which leads to increased photosynthate production and hence increased biomass accumulation (Chen *et al*., 2017; Mitra *et al*., 2019). It has been shown that mycorrhizal enhances the uptake of phosphorous and nitrogen (Abdel-Fattah and Mohamedin, 2000). Mycorrhiza also improves uptake of immobile nutrient elements like copper and zinc (Clark and Zeto, 2000). Besides, AMF is very effective in helping plants to take up nutrients from the nutrient-deficient soils (Kayama and Yamanaka, 2014). The most imperative benefit that AMF provides to their host plant is improved P uptake and the leading regulatory factor in the plant-fungal relationship (Graham, 2000) is status of P in plants. Apparently, P uptake usually controls AMF relationship with the host plants though can play a great role in the uptake of other nutrients by the host plant. Mycorrhiza plays a pivotal role in the nitrogen cycle by its ability to take a substantial amount of N from dead and decomposing material that increase their fitness to grow and stay alive rendering them the main stakeholder of global N pool that is equivalent in scale to fine roots (Hodge and Fitter 2010).

Moreover, different reports have shown enhanced activity of a K+ transporter in the mycorrhizal roots of *Lotus japonicas* (Guether *et al*., 2009; Berruti *et al.*, 2016). Apart from the macronutrients, AMF association has been reported to increase the phytoavailability of micronutrients like zinc and copper and improve the surface absorbing capability of host roots (Smith and Read, 1997). This is done by use of AMF mycelium acting as extensions of plant root systems. The hyphae exist both within the host roots called intraradical hyphae and outside of it called extraradical hyphae that range from the roots up to the surrounding rhizosphere (Hodge and Storer, 2015; Battini *et al.,* 2017; Turrini *et al.,* 2018; Battini *et al.,* 2017). AMF absorbs nutrients by use of extensive mycelium network which spreads hooked on the soil and supplies the acquired nutrients to their host plants (Van Der Heijden, 2002). In addition, roots diseases caused by several soil borne pathogens can be reduced by use of Arbuscular mycorrhiza symbiosis (Wu and Xia, 2006).

Mycorrhiza inoculation in sorghum increases dry matter, grain yield and nutrient content (Abdelhalim *et al.,* 2019). The fungi increase the absorption area of the sorghum roots system by 20-folds; increasing surface area for nutrient absorption by the plant (Liu *et al.,* 2018). The mutual relationship between the AMF and roots of the host plant is known to increase nutrients, for instance, P uptake in sorghum (Bernardino *et al.,* 2019; Wen *et al.,* 2019). Under P deficiency, sorghum plants produce strigolactones such as 5- deoxstrigol, sorgomol and orobanchol that triggers AMF colonization thus more P and other nutrients acquisition (Borghi *et al.,* 2016).

2.6 The role of silicon in plant's drought tolerance

Regardless of silicon being the second component in the layers of the earth after oxygen, it is not essential in plant growth but beneficial to plants growth and development (Tubana *et al.,* 2016). This is because most of the silicon in the soil is insoluble and unavailable to the plants (Alsaeedi *et al.,* 2019). It has beneficial roles in plants growth especially resistance to drought and low soil fertility (Hamayun *et al.,* 2010). Silicon is beneficial to the development of many healthy growing plant species such as barley, cotton, and maize (Ali *et al.,* 2013; Farooq *et al.,* 2013; Malčovská *et al.,* 2014). Research by Guntzer *et al.* (2012 and Ma, (2004), show that silicon increased the resistance to metal toxicity, salinity, heat, freezing, drought and UV radiation to growing crops. Plants take up silica in different amounts depending on species (Puppe *et al.,* 2019). Silicon is absorbed by plants as mono silicic acid [$Si(OH)_4$] that is deposited within plant tissue as SiO_2 (Frew *et al.,* 2017). According to Ouellette *et al.* (2017) , it is taken up in the plants through transporter Lsi1 and Lsi2 while its distribution in the plant is carried out by Lsi3 and Lsi6. It also gives the plant a better control over transpiration and thus a greater resistance to stress conditions (Ouzounidou *et al.,* 2016; Frew, *et al.,* 2018). Silicon amendments have attributed to the reduction of water loss by cuticular transpiration caused by the formation of deposits of Si under the cuticle, reduced absorption of toxic, increased stiffness and strength of plant cell walls according to Garg and Singh (2018).

Most silicon studies show more benefit in stressed plants than in non-stressed plants (Ouellette *et al.,* 2017). For instance, report on sorghum by Meharg and Meharg, (2015), showed that silicon improved the root water uptake in stressed plants and had no effect on the non-stressed plants. Plant water status is modulated by silicon through enhancing water absorption and reducing the rate of transpiration thus low water loss via crop leaves (Chen *et al.,* 2018). This mechanism for the improvement of water uptake by crops supplied with silicon fertilizers is due to the ability of silicon to increase the activities of aquaporin in the cell membrane, therefore, regulating the aquaporin genes, improves osmosis of root xylem sap via increasing the buildup of osmoregulators such as amino acids and soluble sugars and improvement of root/shoot ratio due to inducing root growth thus more surface capacity is increased for the uptake of water by the plants (Chen *et al.*, 2018; Kafi *et al.* (2011).

Reduction of water loss by the plant as a result of silicon use is attested by the presence of a precipitated well-thickened layer of silicon in the epidermal cell walls in form of phytoliths (Ma, 2004) and improves stomatal conductance which modifies transpiration rate (Chen *et al.,* 2016). Through these mechanisms, the high relative water content in the plant tissues is maintained, leading to high rate of photosynthesis that improves plant development under low soil moisture (Alsaeedi *et al.,* 2019).

CHAPTER THREE: MATERIALS AND METHODS

3.1 Description of the study area

The field experiment was carried out at the Yatta National Youth Service field station in Machakos County during the dry period as shown in figure 3.1. It lies between Latitude – 1.088439 south and Longitude 37.476116 east. The rainfall pattern is bimodal having two rainy periods between March and May (long rains) and October and December (short rains). Average temperature ranges between 29 °C and 36 °C while the average rainfall received is 450-800 mm per year. The experiment was carried out in two cycles (December 2019 to March 2020) and (May to August 2020).

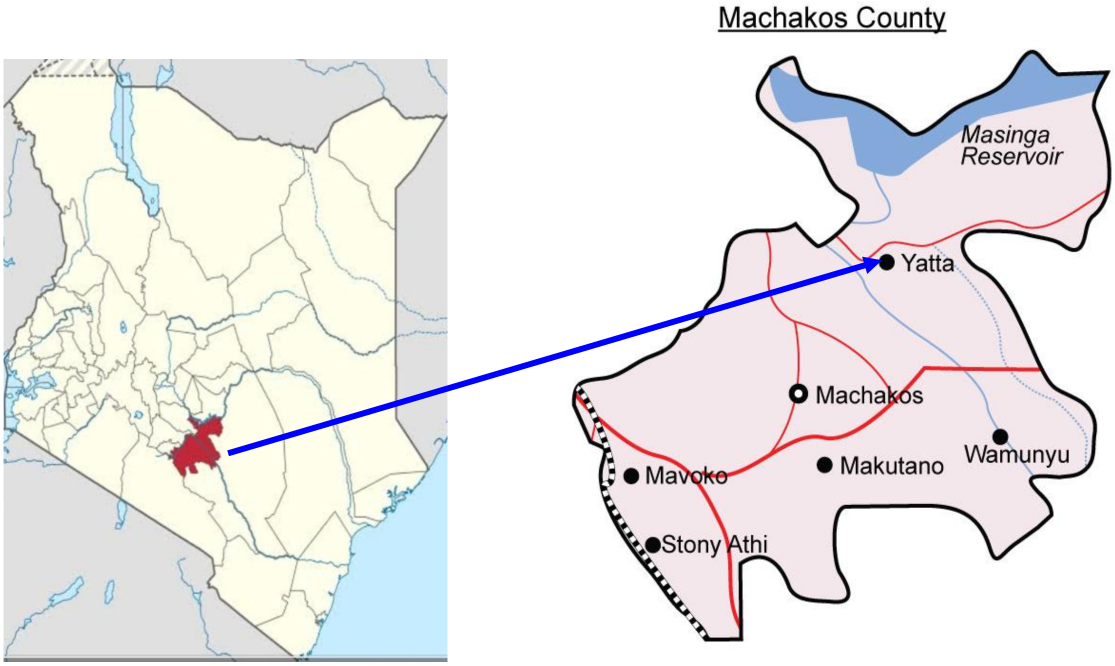


Figure 3.1: Map of Yatta NYS field station location in Machakos County

Source; https://learn.e-limu.org/topic/view/?c=468&t=1507

Before land preparation, soil samples were collected for determination of soil texture, soil bulky density, water field capacity, total organic carbon, total nitrogen (N), exchangeable cations potassium (K), calcium (Ca) and magnesium (Mg), available phosphorus (P), pH and electroconductivity using procedures by Okalebo *et al.* (2002) and the results are as shown in Table 3.1. Initial soil microorganism's population was assessed using serial dilution and pour plate method as described by Noverizaa and Quimio (2016) and AMF according to Bencherif *et al.* (2019).

Table 3.1: Selected physical and chemical characteristics of the soil at the experimental site

Parameter	**Mean value**
pH (1:2.5, soil: water)	6.33
Total organic carbon (%)	0.18
Soil organic matter (%)	0.31
Total nitrogen (%)	0.06
Available phosphorus (%)	0.01
Exchangeable potassium (%)	0.07
Exchangeable magnesium (%)	0.44
Exchangeable calcium (%)	1.26
EC (mhos/cm)	0.023
Bulky density (g/cm^3)	1.56
Field water capacity (%)	22.70
Sand (%)	76.00
Silt (%)	14.00
Clay (%)	10.00
Soil textural class	Loamy sand

3.2 Field experiment

3.2.1 Materials used in the study

Sorghum variety Machakos local red was sourced from farmers in Machakos County while Seredo variety was sourced from Kenya seed (www.kenyaseed.com). These varieties were selected since Machakos local red is commonly grown by local farmers because of its high yields and good adaptation, while Seredo variety is an improved variety with characteristics of tolerance to insects and pests, high yields as well as its adaptation to low moisture.

Commercial inoculant (AMF) (Rhizatech) was sourced from Dudutech and it consisted of four mixed strains: *Claroideoglomus claroideum* strain Ddt03; *Claroideoglomus etunicatum* strain Ddt04; *Rhizophagus irregularis* strain Ddt07 and *Funneliformis mosseae* strain Ddt05. Silicon in form of Silicic acid was sourced from Lentera Limited Kenya.

3.2.2 Experimental design and treatments

A Randomized Complete Block Design (RCBD) in a factorial arrangement replicated three times was used to lay out the experiment in the field. The experimental factors were; Sorghum varieties (Machakos local red and Seredo), water regimes {60% Field capacity (FC), 40% Field capacity (FC) and 20% Field capacity (FC), Silicon (Si) levels (with or without) and AMF (with or without)}. This gave a total of 24 experimental treatments as shown in (Table 3.2).

Table 3.2: Experimental treatments

No	Treatments	No	Treatments
1	V1+L1+Si1+AMF1	13	V2+L1+Si1+AMF1
2	V1+L1+Si1+AMF0	14	V2+L1+Si1+AMF0
3	V1+L1+Si0+AMF1	15	V2+L1+Si0+AMF1
4	V1+L1+Si0+AMF0	16	V2+L1+Si0+AMF0
5	V1+L2+Si1+AMF1	17	V2+L2+Si1+AMF1
6	V1+L2+Si1+AMF0	18	V2+L2+Si1+AMF0
7	V1+L2+Si0+AMF1	19	V2+L2+Si0+AMF1
8	V1+L2+Si0+AMF0	20	V2+L2+Si0+AMF0
9	V1+L3+Si1+AMF1	21	V2+L3+Si1+AMF1
10	V1+L3+Si1AMF0	22	V2+L3+Si1AMF0
11	V1+L3+Si0+AMF1	23	V2+L3+Si0+AMF1
12	V1+L3+Si0+AMF0	24	V2+L3+Si0+AMF0

Key; V1- Machakos local red, V2- Seredo, L1-water level one (60% FC), L2-water level two (40% FC), L3-water level three (20% FC), Si1-with silicon, Si0-without silicon-with AMF1-with inoculant, AMF0-without inoculant.

3.2.3 Crop establishment and management

The land was prepared; thereafter it was demarcated into three blocks each consisting of 24 plots measuring 3 m by 3 m, whereas a spacing of 1m and 0.5m was maintained between the blocks and between the plots respectively as shown in Plate 3.1.

Healthy sorghum seeds were planted as recommended at a spacing of 75 cm between the rows and 25 cm within the rows. Additionally, each experimental plot had five plant rows, each with 12 plants. This gave a total of 60 plants per experimental plot.

Plate 3.1: Land measuring and demarcation

AMF inoculum was applied during planting at the rate of 25 g per planting hole while Silicon was drenched two weeks after planting at the rate of 0.1 mg per plant. Later on, three water levels were introduced at floral initiation (four weeks after planting). Field water capacity was measured daily to check on depletion of water in the soil using a moisture meter. Thereafter the three irrigation levels were applied in their specific plots when soil water content fell below field capacity (60% FC, 40% FC and 20% FC) of initial values. This was done throughout the experiment period. The crops grew in the prevailing day and night weather conditions that were held constant. Inorganic fertilizers were applied with P as (TSP) being added at 45 Kgha^{-1} P (3.44 g P per plant) during planting, while N as Urea at 180 Kg ha^{-1} N (5.87g N per plant) was introduced as a top dressing (Galal, 2016) four weeks after planting.

All agronomic practices were applied uniformly throughout the experimental period. Insect pests such as cutworms, aphids and fall armyworm, Rust disease, monkeys and birds were some of the challenges. Insect pests were managed using an integrated pest management strategy; rust disease was managed at different plant stages using products such as hexaconazole, difenconazole and propiconazole while monkeys and birds were kept away using scarecrows. These activities helped the crops to grow well as shown (Plate 3.2)

Plate 3.2: Sorghum varieties growing in the field

3.3 Trap culture experiment

The native AMF spore diversity and abundance in the soil were determined by establishing a trap culture experiment. The experiment was set and maintained in a greenhouse at Yatta NYS field station for five months. The experimental design was CRD replicated four times. The treatments were two sorghum varieties (Machakos local red and Seredo varieties) and leek crop. Soil sampling was done at a depth of 0-20 cm from different locations of the experimental site before land preparation. The collected soil was sieved, homogenized and put in twelve 250 g pots where ten healthy leek seeds, Seredo sorghum variety and Machakos local red sorghum variety were planted as a trap crop. Soil moisture was maintained at 80% of water field capacity which was done by weighing the pots before water was added. Plants were maintained for five months, while reducing watering in the last month to enhance sporulation of the AMF (Plate 3.3). The spores were then extracted using the centrifugal method, counted, mounted on slides and observed under the microscope for characterization and identification.

Plate 3.3: Trap culture experiment in the greenhouse at five months after planting

3.4 Data collection

Different plant growth parameters were assessed from planting up to harvesting of the crop. These parameters included; plant height, leaf count, tiller numbers, shoot biomass, root biomass and days to 50% flowering. Three plants from each experimental plot were tagged and were used to determine tillers, leaf number and height of the plant. Destructive sampling was done on the second outer on each experimental plot in a stratified manner. Furthermore, three plants on each experimental plot were uprooted and were used to measure shoot and root biomass.

3.4.1 Determination of plant growth parameters

i. **Plant height:** This was measured from the top of the soil (base of the plant) to tip of the youngest leave by use of meter rule from the three tagged plants in each experimental plot. This was done from the sixth week after planting and thereafter biweekly until grain filling stage using a meter rule (Plate 3.4).

ii. **Number of Leaves:** Leaves were counted on the main stem from the three tagged plants in each experimental plot. This was recorded from the sixth week after planting and thereafter biweekly until grain filling stage.

iii. **Tillers count:** Total number of tillers was counted from the three tagged plants**.** This was done from the sixth week after planting and thereafter biweekly until grain filling stage.

iv. **Plant weight:** Three plants on each experimental plot were uprooted and weighed to get shoot and root fresh weight. This was done biweekly from the sixth week until grain filling. The samples were oven dried at 60 **°C** for 72 hours till they reached a constant weight. Shoot and root dry weights were measured using an electronic weighing balance from the three plants from each experimental plot and average recorded.

v. **Days to 50% flowering:** The day when fifty per cent of plants had flowered in each experimental plot was noted**.**

Plate 3.4: Plant growth data collection

3.4.2 Yield and yield components determination

i. **Stover fresh and dry weight**: During harvesting, the above-ground biomass without the panicle for each experimental net plot was weighed and recorded. The Stover samples were oven dried at 60 **°C** for 72 hours till they reached a constant weight and weighed.

ii. **Panicle weight:** Soon after harvesting panicle weight of three plants from each experimental plot was determined and recorded. Later, the weight of dry grains plus the weight of dry panicle residue from three plants in each experimental plot was used to determine the dry weight of panicle.

iii. **Grain yield:** Yield data was determined after harvesting of the net plot where the total weight of grains per each experimental plot in kilogram was taken after threshing and transformed to Kgha^{-1}. The grains were later oven dried at

60 **°C** for 72 hours till the moisture content was at 12 **°C** and thereafter the weight was determined by use of a weighing balance.

iv. **Harvest index:** Harvest index for each experimental unit was determined by dividing grain weight by the total of the above-ground biomass multiplied by 100. The harvest index (HI) was calculated according to Leport *et al.* (2006).

3.4.3 Determination of arbuscular mycorrhizal colonization

Arbuscular mycorrhiza fungi root colonization of sorghum was estimated at the vegetative stage, flowering, grain filling and harvesting stages. Three plants from the two outer rows in each experimental plot were uprooted, roots were cleaned with clean running water then preserved in 70% ethanol and later assessed for mycorrhizal colonization (Silva *et al.,* 2017). Subjective visual technique (Füzy *et al.* 2015) commonly referred to as the slide method was used to estimate percentage root colonization intensity. The roots were autoclaved at 121 °C for 15 minutes in 2.5% potassium hydroxide and washed under running water.

Removal of phenolic constituents was done using alkaline hydrogen peroxide (60 ml of 28-30% NH_4OH, 90 ml of 30% H_2O_2 and 840 ml distilled water) and the roots were left standing in a hood for one hour. Thereafter, the roots were washed under tap running water followed by acidification with 1% hydrochloric acid and left standing for 30 minutes. Hydrochloric acid was decanted from the roots and 0.05% trypan blue in acid glycerol (500 ml glycerol, 450 ml water, 50 ml of 1% HCI and 0.5 g Trypan blue) a staining reagent was added without rinsing the roots (Vierheilig *et al.,* 1998). The stained roots were later autoclaved for 5 minutes at 121 °C. A de-staining solution containing acid glycerol (500 ml glycerol, 450 ml water, and 50 ml of 1% HC1) was added after decantation of the stain. The intensity of arbuscular mycorrhizal fungi was determined using 1cm long segments of fine roots where thirty pieces of root segment were randomly picked, mounted on slides and observed under a compound microscope (Silvana *et al.,* 2018). The presence of AMF features like intraradical and extraradical mycelia, arbuscules, vesicles and coils were examined. The AMF percentage cover of infective propagules in each 1cm root parts was recorded as AMF colonization intensity.

3.4.4 Plant nutrient content determination

Plant samples and grains from the experimental plots were collected at the harvesting stage and taken to Kenyatta University Agricultural Science and Technology laboratory for nutrient analysis. The plant stover samples collected were washed, rinsed with deionised water, chopped and dried at 70 °C for 48 hours while the grains were only washed, rinsed and dried. A blender was used to ground the dried plant stover and grains and the materials stored ready for analysis.

Nutrient extraction was done by acid digestion of the samples followed by spectrometry analysis (Okalebo *et al*., 2002). Zero point three grams (0.3 g) of ground plant tissue sample and grain sample from each experimental plot was weighed and put into a clean dry digestion tube. A volume of 10 ml of digestion mixture that consisted of 3.2 g of salicylic dissolved in 100 ml of sulphuric acid- selenium mixture were added to each sample and reagent blank tubes. The samples were digested by heating at 110 °C for 1 hour. The temperature was raised to 360 °C for 4 hours until the solution was colourless. The sample digestates were then allowed to cool. After cooling, the content was topped to the 50 ml mark with distilled water and used for analysis of N, P, K, Ca and Mg concentrations following procedures described below.

3.4.4.1 Total pphosphorus and phosphorus uptake

The colorimetric method was used to determine plant tissue and grains P following the procedure by Okalebo *et al*. (2002). Five ml of the digestate solution was pipetted into a volumetric flask (50 ml) and to each flasks starting with the standards 10 ml ascorbic acid was added. The content was topped to the 50 ml mark with distilled water stopped, agitated well and left to stand for 1 hour for colour development. Standards and sample absorbance were measured using u/v spectrophotometer at the wavelength of 880 nm. Calibration curve of the standards series, concentration against the absorbance was plotted. The slope was to calculate P concentration as shown in equation 1. Phosphorus uptake was calculated using equation 2.

$$\%\ \mathrm{P} = \frac{(a-b)\times V\times f\times 100}{1000\times W\times 1000} \qquad (1)$$

$$\mathrm{P\ uptake\ (kg\ ha^{-1})} = \frac{\%P\times dry\ matter(kg\ ha^{-1})}{100} \qquad (2)$$

(Okalebo *et al*., 2002)

3.4.4.2 Nitrogen concentration and uptake

Kjeldahl distillation method following protocols defined by Okalebo *et al*. (2002) was used to determine the total nitrogen in the digestate.

Ten millilitres of the digested sample solution was transferred to a reaction chamber of the distiller and 10 ml of 1% sodium hydroxide added. Immediately, steam distillation into 5 ml 1% boric acid containing 4 drops of the mixed indicator was done and distillation continued until the indicator turned green. The distillate was titrated with hydrochloric acid up to the endpoint that when the indicator change to pink. Percentage N in the plant tissue and N uptake in grain samples were calculated using equations 3 and 4, respectively.

$$\%N = \frac{(a-b)\times V\times 100}{1000\times W\times al\times 100} \qquad (3)$$

$$\text{N uptake (kg ha}^{-1}) = \frac{\%N\times dry\ matter(kg\ ha^{-1})}{100} \qquad (4)$$

3.4.4.3 Potassium, Calcium and Magnesium concentration and uptake

Nutrient extraction was done by acid digestion of the samples followed by spectrometry analysis (Okalebo *et al*., 2002).

Flame photometry following (Okalebo *et al.* 2002) procedures was used to determine potassium concentration in the digestate samples. Here, into a volumetric flask measuring 50 ml, 2 ml of the digested sample solution was pipetted. The mixture was topped to the 50 ml mark using distilled water, shaken well and the amount of K measured starting with the standards, the sample, and the blank solutions. The accumulation of the K in the plant tissue and grain samples was expressed into percentage using equation 5 while K uptake was determined using equation 6 (Okalebo *et al*., 2002).

$$\%\text{K, Ca, Mg} = \frac{(a-b)\times V\times f\times 100}{1000\times W\times 1000} \qquad (5)$$

$$\text{K, Ca, Mg uptake (kg ha}^{-1}) = \frac{\%K\times dry\ matter\ (kg\ ha^{-1})}{100} \qquad (6)$$

The concentration of total Ca and Mg in the digestate was determined using the atomic absorption spectrophotometry. For calcium, into a 50 ml volumetric flask 10 ml of the digested sample solution was pipetted. Ten ml of 0.15 % lanthanum chloride added and the mixture toped to the mark using distilled water. The content was shaken and measurements absorbance of Ca in samples at 422.7 nm. The concentration and uptake of Ca were determined using equation 5 and 6, respectively.

For magnesium, 5ml of previously digested sample solution was pipetted into a volumetric flask measuring 50 ml where distilled water was used to fill to the mark and the content was agitated well. Magnesium standard series, blank and sample were sprayed into the flame of atomic absorption spectrophotometer and magnesium concentration determined using equation 5 while uptake was calculated using equation 6.

3.4.5 Determination of Arbuscular mycorrhiza fungi diversity

Extraction and quantification of the original soil and trap cultures spores was done as reported by Bencherif *et al.* (2019). This was through the wet-sieving and decanting method where reproductive structures of AMF were extracted from 300 grams of farm soil and trap soil. In the traps, 100 g of soil was drawn from each pot and suspended in 200 ml water in a 500 ml flask. The solution was stirred allowing sediments to settle down for a few minutes. Thereafter, the suspension was decanted through 710 µm and 45 µm mesh sieves arranged one over another in descending order. Into 100 ml tubes containing 25 ml of water filled from the bottom, the filtrates were added and centrifuged at 2700 rpm for five minutes.

The supernatant solution was poured keeping the pellet at the bottom of the tubes. A fifty per cent sucrose solution (vol/vol) was added in the tubes up to 30 ml and centrifuged at 2700 rpm for one minute. Through a 45 µm sieve, the supernatant was rinsed to reduce the concentration of the sucrose and spores isolation done from concentrated supernatants using a dissecting microscope. Thereafter, the spores were mounted in Polyvinyl Alcohol, Lactic acid Glycerol (PVLG) according to Stefanowicz *et al.* (2019), Zubek *et al.* (2016) and Melzer's reagent (1:1) using soft forceps. A compound microscope was used for the identification of spores based on original keys, synoptic, descriptions, and, specialized websites

(www.zor.zut.edu.pl/Glomeromycota;invam.caf.wvu.edu).

Percentage abundance of each genus was calculated as

$$Ap = \frac{n}{N} \times 100$$

In which, n represent number of spores of each genus and N is the sum of all spores present in a treatment (Lukow *et al*., 2000).

3.5 Data analysis

One-way analysis of variance (ANOVA) test was used to analyze data on AMF root colonization, sorghum growth parameters, grain and stover yields, nutrient uptake and AMF diversity. Amendment treatments and sampling time were kept as fixed effects, while replication was a random effect. Data for each cycle and experiment was analyzed separately. R software, version 4.0.2 was used to perform all statistical analyses. Significant means were separated using Tukey's test at 5% significance level.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Influence of varieties, water regimes, silicon and AMF on sorghum root colonization

Arbuscular mycorrhiza fungi (AMF) colonization intensity on sorghum roots were characterized using specialized AMF features namely appressoria, hyphae, vesicles, intercellular hyphae coils and arbuscules (Plate 4.1).

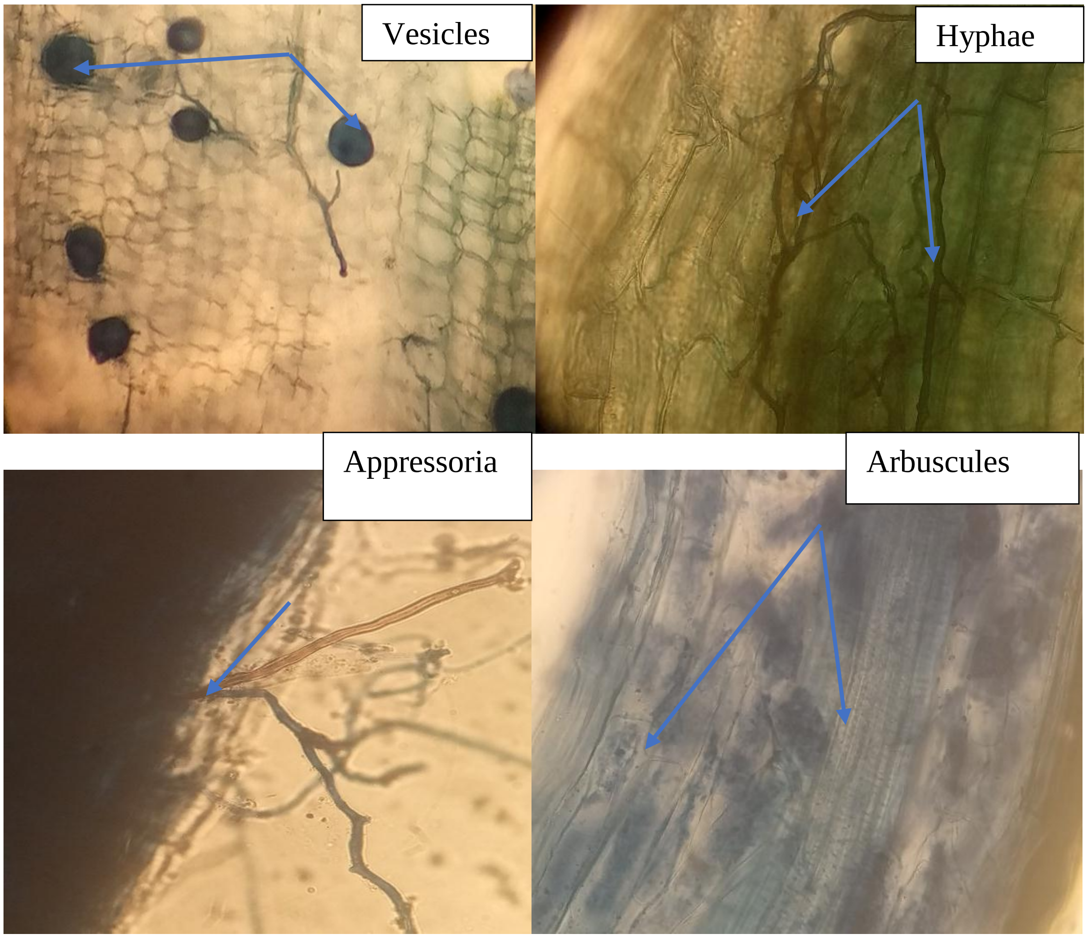


Plate 4.1: Features of arbuscular mycorrhiza fungi

The results obtained on these features comprehensively revealed that there was an increase in the intensity of sorghum root colonization throughout the growth period in both cycles. There was major variance at $p<0.001$ reported for the varieties in both cycles (Table 4.1). Seredo variety recorded the highest root colonization throughout the study period and in both cycles, with an. intensity of 61.84% being recorded in Seredo at week 15 cycle of one while the lowest intensity of 11.80% was recorded in Machakos local red variety in week 6 of cycle two. Variation in the amount of applied water significantly ($p<0.001$) affected sorghum roots colonization intensity by AMF in both cycles, with 40% of water field capacity giving the highest root colonization intensity throughout the study period in the two growing cycles. Maximum root colonization intensity was observed under 40% water field capacity in week 15 of cycle 1 which had 61.44% while lowest root colonization intensity of 9.53% was recorded under 60% water field capacity in week 6 of cycle two as shown in Table 4.1.

Silicon application significantly enhanced symbiotic efficiency at $p<0.001$ since the AMF root colonization intensity increased tremendously with silicon application throughout the cycles compared to the control in both cycles. The highest root colonization intensity (56.34%) was measured in silicon amended treatments week 15 of cycle one while the control recorded the lowest root colonization intensity (11.27%) in week 6 of cycle 2 (Table 4.1). Further, AMF inoculation significantly ($p< 0.001$) affected roots colonization such that the AMF efficiency to colonize was enhanced compared to the control in all the weeks of study in both cycles. AMF root colonization intensity was high at 64.18% in the inoculated plants in week 15 cycle one while lowest

6.32% root colonization intensity was observed in the control in week 6 cycle two (Table 4.1).

Table 4.1: Root colonization intensity as affected by sorghum varieties, water levels, Silicon and AMF in experimental cycle 1 and 2

Root colonization intensity (%)								
Weeks	**Week 6**		**Week 9**		**Week 12**		**Week 15**	
Cycles	**C 1**	**C 2**	**C 1**	**C 2**	**C 1**	**C 2**	**C 1**	**C 2**
Variety								
Mlr	12.73^b	11.80^b	28.60^b	24.36^b	37.86^b	36.15^b	47.10^b	45.13^b
Srd	15.82^a	13.61^a	32.36^a	27.11^a	48.34^a	45.78^a	61.84^a	55.75^a
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Water regimes (%)								
60Wr	11.05^c	9.53^c	25.07^c	20.32^c	34.65^c	32.18^c	48.74^c	45.47^c
20Wr	13.71^b	12.19^b	28.82^b	24.07^b	46.02^b	43.47^b	53.21^b	48.83^b
40Wr	18.07^a	16.39^a	37.57^a	32.82^a	48.63^a	47.24^a	61.44^a	57.01^a
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Silicon								
Control	12.74^b	11.27^b	28.96^b	24.21^b	41.68^b	39.37^b	52.59^b	48.93^b
Si+	15.81^a	14.13^a	32.01^a	27.26^a	44.52^a	42.55^a	56.34^a	51.95^a
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Inoculation								
Control	8.06^b	6.32^b	22.39^b	17.64^b	33.74^b	31.57^b	44.76^b	41.20^b

AMF+	20.50^{a}	19.09^{a}	38.58^{a}	33.83^{a}	52.46^{a}	50.36^{a}	64.18^{a}	59.68^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Seredo(Srd) sorghum variety; Machakos local red(Mlr) sorghum variety; C= Experiment cycle.

Results of this study indicates that, interaction between sorghum varieties, water stress, silicon application and AMF inoculation on root colonization intensity of sorghum throughout the growth period in both cycles results was significant (p<0.001) (Table 4.2). Interactions presented positive influence on roots colonization intensity. Seredo variety irrigated to 40% field capacity in combination with silicon and AMF exhibited the highest root colonization intensity and the trend held throughout the season in both cycles. Similar results were recorded in Machakos red variety at 40% water field capacity in combination with silicon and AMF. The highest root colonization intensity (79.66%) at 40% FC was observed in Seredo variety in week 15 of cycle one, while control gave the lowest root colonization intensity and the trend was consistently across the weeks in the two cycles. Nevertheless, the controls of all the interaction remarkably lagged in terms of root colonization intensity and the least 1.22% were noticed in Machakos local red under 60% water field capacity in week 6 cycle 2 (Table 4.2). AMF colonization intensity was low under 20% water field capacity compared to 40% water field capacity.

The results were in agreement with (Kaya e*t al.* (2003) who stated that low soil moisture reduced mycorrhiza infection in watermelon. However, root colonization in sorghum supplied with water at 20% field capacity increased with plant growth. This confirmed the benefits of osmotic adjustment in plants and soil by the AMF (Wu and Xia, 2006**;** Bitterlich *et al.*, 2018)**.** Moreover, AMF may also have improved the soil structures through the aggregation of soil particles by mechanical actions of fungal extraradical hyphae and extraction of glycoprotein and glomalin that attributed to maintaining soil moisture for longer periods (Moreira e*t al.*, 2018; Gianinazzi *et al.*, 2010).

Table 4.2: Interactive effects of sorghum varieties, water stress, silicon and AMF inoculation on root colonization intensity both experimental cycles

			Root colonization intensity (%)							
			Week 6		**Week 9**		**Week 12**		**Week 15**	
Variety	**Water regime (%)**	**Amendments**	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**
Srd	60	Si+AMF	21.25^{e}	20.00^{e}	35.23^{g}	33.48^{e}	52.25^{de}	61.02^{b}	71.21^{d}	67.40^{c}
	60	AMF	18.19^{h}	16.31^{i}	32.19^{i}	26.88^{h}	50.23^{e}	38.92^{jk}	68.27^{e}	46.61^{m}
	60	Si	6.33^{r}	4.42^{q}	20.20^{q}	15.58^{m}	26.97^{n}	21.68^{q}	47.48^{m}	35.66^{w}
	60	control	3.32^{t}	1.39^{s}	17.20^{t}	12.50^{o}	24.13^{o}	18.67^{r}	43.35^{n}	32.66^{x}
	40	Si+AMF	29.27^{a}	27.17^{a}	53.19^{a}	47.94^{a}	66.99^{a}	64.19^{a}	79.66^{a}	73.66^{a}
	40	AMF	26.06^{b}	23.96^{b}	50.26^{b}	45.01^{b}	58.07^{c}	61.10^{b}	76.63^{b}	70.63^{b}
	40	Si	14.32^{k}	13.16^{j}	29.63^{k}	23.83^{j}	46.08^{fg}	35.92^{m}	59.60^{h}	43.59^{o}
	40	control	11.35^{m}	9.31^{m}	26.61^{m}	17.98^{l}	43.30^{hi}	32.38^{n}	56.70^{i}	41.29^{q}
	20	Si+AMF	23.08^{c}	20.99^{c}	38.73^{e}	29.98^{g}	64.26^{b}	50.13^{d}	73.40^{c}	65.21^{d}
	20	AMF	20.19^{f}	18.09^{g}	35.63^{f}	30.38^{f}	64.22^{b}	58.00^{c}	70.35^{d}	64.35^{e}
	20	Si	9.66^{o}	7.86^{n}	26.30^{m}	21.05^{k}	42.32^{hij}	41.20^{hi}	49.27^{l}	43.27^{p}
	20	control	6.90^{q}	4.80^{p}	23.26^{o}	18.01^{l}	41.3^{ij}	38.18^{kl}	46.17^{m}	40.17^{s}
Mlr	60	Si+AMF	17.33^{i}	16.11^{i}	31.12^{j}	26.81^{h}	40.92^{j}	42.37^{gh}	49.67^{l}	48.78^{l}
	60	AMF	14.18^{k}	12.2^{k}	28.07^{l}	21.05^{k}	38.14^{k}	36.80^{lm}	46.17^{m}	44.32^{n}
	60	Si	5.44^{s}	4.36^{q}	19.82^{r}	14.97^{n}	23.93^{o}	29.22^{o}	38.09^{p}	35.96^{v}

	60	control	2.41^{u}	1.22^{s}	16.74^{u}	11.95^{p}	20.67^{p}	20.85^{q}	25.75^{q}	37.35^{u}
	40	Si+AMF	21.52^{d}	20.50^{d}	48.25^{c}	44.01^{c}	53.56^{d}	51.56^{d}	65.53^{f}	62.47^{f}
	40	AMF	18.54^{g}	17.52^{h}	45.11^{d}	40.87^{d}	50.34^{e}	48.55^{e}	62.77^{g}	59.46^{h}
	40	Si	13.22^{l}	11.24^{l}	25.29^{n}	24.38^{i}	36.33^{kl}	43.18^{g}	46.38^{m}	53.60^{i}
	40	control	10.33^{n}	9.25^{m}	22.22^{p}	21.36^{k}	34.38^{l}	40.18^{ij}	44.30^{n}	50.70^{k}
	20	Si+AMF	20.26^{f}	19.24^{f}	34.18^{h}	29.94^{g}	46.40^{f}	45.44^{f}	54.86^{j}	51.80^{j}
	20	AMF	16.13^{j}	16.09^{i}	31.05^{j}	26.94^{h}	44.15^{gh}	47.11^{e}	51.64^{k}	62.27^{g}
	20	Si	8.12^{p}	7.10^{o}	22.23^{p}	17.99^{l}	34.33^{l}	29.22^{o}	41.04^{o}	38.98^{t}
	20	control	5.38^{s}	2.63^{r}	19.21^{s}	14.95^{n}	31.22^{m}	24.22^{p}	39.01^{p}	40.48^{r}
P-value	**V*Wr*A**									
			<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= Experiment cycle.

Decreased AMF root colonization was observed as the watering increased (60% water field capacity). These results agree with those of Deepika and Kothamasi (2015) who stated that roots of plants in flooded soils have low AMF colonization compared to those in non-flooded soils. Low AMF colonization may have been due to decrease in aeration that leads to lack of oxygen thus decreasing the activities of aerobic AMF (Stürmer and Siqueira, 2006). Furthermore, the high soil moisture content have been reported to favour the growth of AMF parasites which exert an inhibitory effect on spore germination and fungal hyphae growth (Moreira e*t al.*, 2018), thus reducing AMF effectiveness.

The study also found out that non-inoculated plants were colonized and that the colonization increased immensely across all weeks in both cycles. This indicates that the soil generally had viable AMF propagules an argument similar to those of Sakah *et al.*, (2019). Similar observations were made by Moreira *et al.* (2018) who reported that plants that were not inoculated were still infected by AMF since natural soil contain native fungal spores and other propagules like infected plant roots and hyphae. Synergistic effect between silicon and AMF was manifested on root colonization even in non-inoculated plots with colonization intensity being enormous under silicon application compared to those treatments without silicon. This synergistic effect may be due to silicon induced stimulation of root growth that may have promoted mycorrhiza colonization thus increasing its efficiency (Hajiboland *et al.*, 2018).

4.2 Effects of varieties, water regimes, silicon and AMF on growth and yield of sorghum

4.2.1 Plant Height

The experimental results revealed that sorghum varieties were significantly ($p < 0.001$) different from each other in terms of plant height throughout growth in both cycles (Table 4.3). Machakos local red recorded the highest plant height of 210.92 cm and 190.92 cm in week 15 cycle of one and two respectively whereas Seredo variety recorded the lowest plant height 24.36 cm and 19.36 cm in week 6 both cycles.

Water application influenced plant height significantly ($p < 0.001$) in both growing cycles and across all weeks (Table 4.3). Maintaining soil moisture at 60% water field capacity was superior across all weeks in both cycles recording the highest plant height 193.67 cm, 173.67 cm in week 15 of cycle one and two, respectively. Furthermore, silicon addition significantly ($p < 0.001$) affected plant height in the two cycles (Table 4.3). Treatments with silicon showed superior plant height across all weeks in both cycles. Maximum plant heights of 194.06 cm and 174.06 cm was recorded in week 15 in cycles one and two, respectively. However, it was observed that treatments without silicon had the lowest plant height across the weeks in the two cycles.

Table 4.3: Plant height as affected by sorghum varieties, water levels, Silicon and AMF inoculation experimental cycle 1 and 2

	Plant height (cm)							
Weeks	**Week 6**		**Week 9**		**Week 12**		**Week 15**	
Cycles	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**
				Variety				
Srd	24.36^b	19.36^b	72.97^b	57.97^b	119.64^b	106.64^b	159.64^b	139.64^b
Mlr	30.64^a	20.64^a	91.08^a	76.08^a	163.31^a	150.31^a	210.92^a	190.92^a
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
				Water regimes (%)				
20wr	22.46^c	14.96^c	71.00^c	56.00^c	130.58^c	117.58^c	174.88^c	154.88^c
40wr	28.08^b	20.58^b	81.88^b	66.88^b	141.75^b	128.75^b	187.29^b	167.29^b
60wr	31.96^a	24.46^a	93.21^a	78.21^a	152.08^a	139.08^a	193.67^a	173.67^a
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
				Silicon				
control	24.22^b	16.64^b	73.78^b	58.78^b	129.31^b	116.31^b	176.50^b	156.50^b
Si	30.78^a	23.28^a	90.28^a	75.28^a	153.64^a	140.64^a	194.06^a	174.06^a
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
				Inoculation				
control	24.14^b	16.64^b	74.06^b	59.06^b	123.78^b	110.78^b	172.44^b	152.44^b
AMF	30.86^a	23.36^a	90.00^a	75.00^a	159.17^a	146.17^a	198.11^a	178.11^a
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05.Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= Experiment cycle.

Arbuscular mycorrhiza inoculation gave the highest plant height in all the weeks studied in both cycles, and the data was significant at $p < 0.001$ as shown in Table 4.3. The highest plant height of 198.11 cm was recorded in inoculated treatments at week 15 of cycle one. Further, there were significant ($p < 0.001$) interactions between sorghum varieties, water regimes, silicon and AMF inoculation on plant height of sorghum (Figure 4.1, 4.2). To illustrate this effect, combined AMF inoculation with silicon addition encouraged vigorous plant growth despite being supplied with the lowest water regime (20%) as shown in Figure 4.1a, 4.2a. Machakos local red variety recorded the highest plant height of 246.3 cm on the 86th day after planting in cycle one under 60% water field capacity when both silicon and AMF inoculation was amended (Figure 4.1 c). Lowest plant heights of 132.7 cm and 112.7 cm were realized at low water regime (20%), in Seredo variety without silicon and AMF in both cycles respectively (Figure 4.1a and 4.2a). Among abiotic factors, drought stress is considered a main detrimental issue affecting crop progression and enlargement. The findings from the study showed that low soil moisture negatively affected plant height of sorghum (Table 4.3).

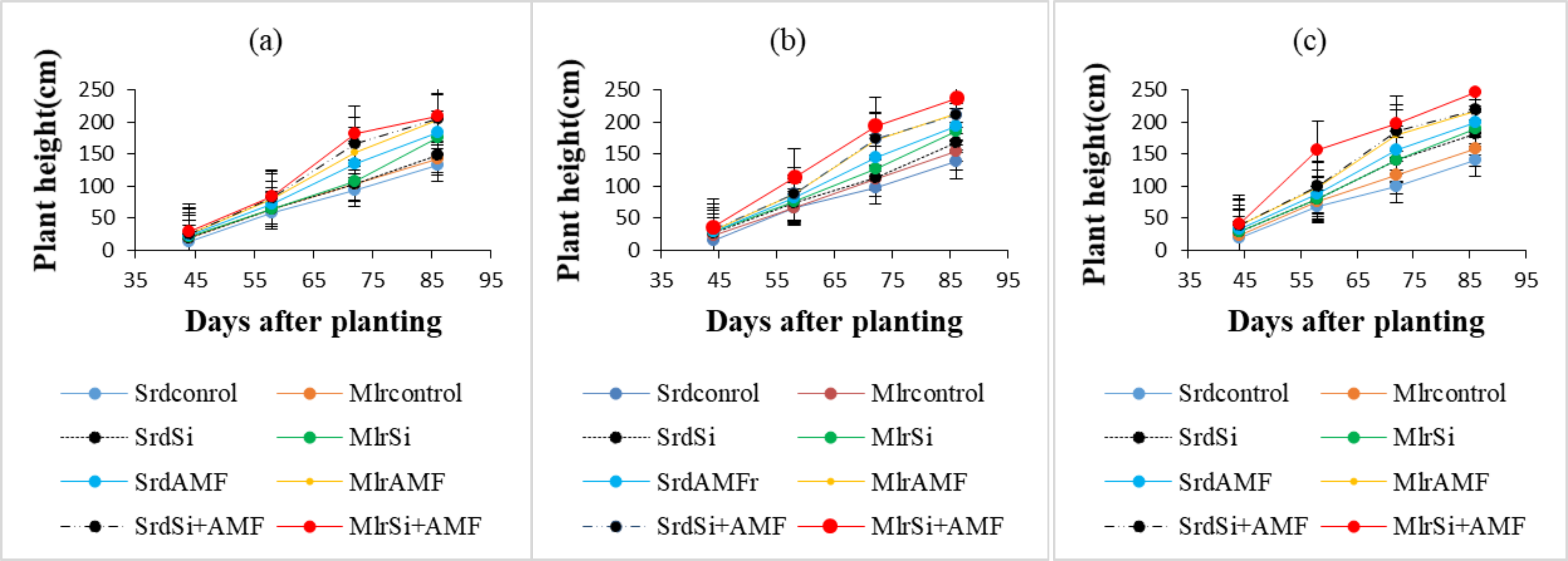


Figure 4.1a, b, and c: Interactive effects between varieties, water levels, Silicon and AMF inoculant on sorghum plant height cycle 1

Srd= Seredo variety; Mlr= Machakos local red variety Si= With Silicon; AMF= With AMF inoculant; Wr= Water regime (20%, 40% and 60% field capacity); (a)=20%wr, (b)=40%wr and (c)= 60%wr

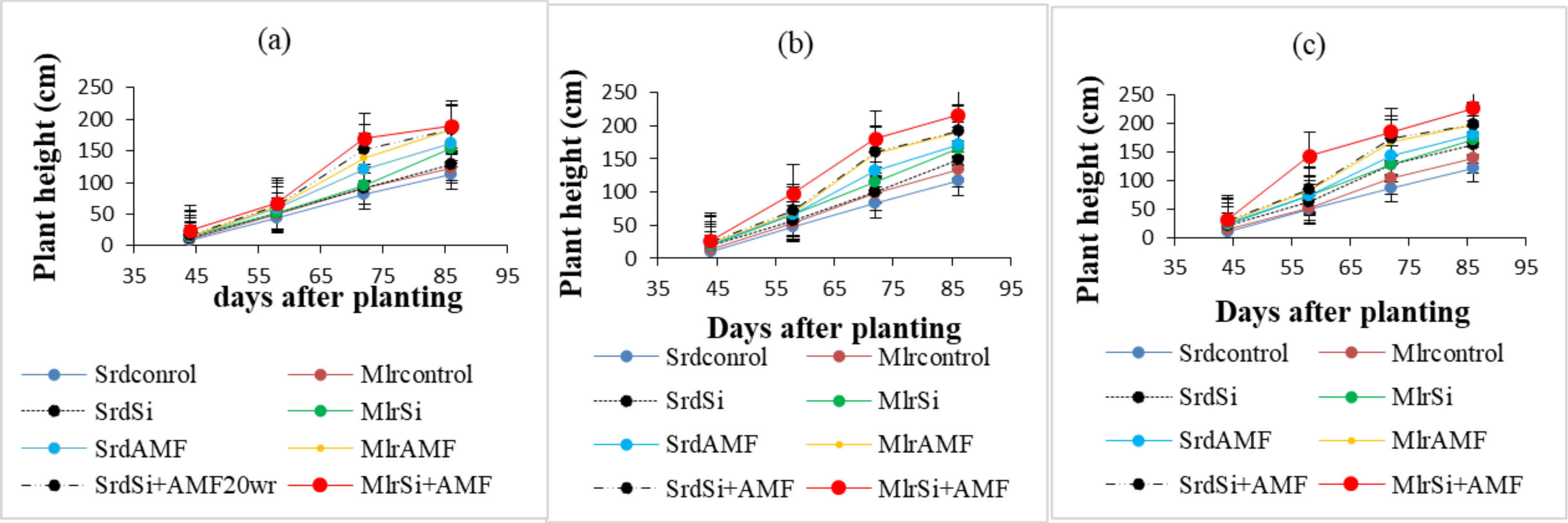


Figure 4.2a, b and c: Interactive effects between varieties, water levels, Silicon and AMF inoculant on sorghum plant height cycle 2

Srd= Seredo variety; Mlr= Machakos local red variety Si= With Silicon; AMF= With AMF inoculant; Wr =Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

Bhatt and Rao (2005) confirmed the deleterious effect caused by drought in Okra, while Cakir (2004) indicated that low soil moisture lessened elevation of the plant, stem diameter, nodes number as well as biomass of cotton plants. Cheruth *et al.,* (2009) also reported a reduction of soybean stem length under low soil moisture. Wu *et al.*, (2008) and Jaleel *et al.* (2009) reported that under water stress scenario up to 25% height of citrus seedlings were negatively affected. Besides, Jaleel *et al.* (2009) reported noticeably decrease in stem length of crops such as Okra (*Abelmoschus esculentus),* parsley (*Petroselinum crispum*), potato tuber (*Solanum tuberosum*), soybean (*Glycine max*), plus cowpeas (*Vigna unguiculata*) under drought. Similar results were reported in black night shade under different watering regimes (Okello *et al*., 207a,b).

Plant height of both improved and the local variety of sorghum increased considerably with the use of silicon and AMF inoculum with Machakos red a local variety exhibiting better results than Seredo an improved variety (Table 4.3). May *et al.* (2014) in his study concluded that plant height varies from one variety to another due to variation in the adaptation to weather conditions or due to genetic differences. Similar results were obtained by Mwamahonje and Maseta (2018) who indicated significant variation of plant height of between local and improved sorghum genotypes where the local gave the highest plant height (279.8 cm) while improved variety Macia showed the shortest (122.4 cm).

Silicon application resulted in increased plant height. This is in line with of different researchers (Ahmad *et al*., 2007; Kaaria *et al*., 2021) who reported that it extensively enhanced plant height under water strain than well-watered conditions**.** The earlier report conforms towards the results of this study. Silicon is reported to improve leaf water potential of plants under low soil moisture due to its phytoliths that thickens the cuticle of the plant forming cuticle double layer on the epidermal leaf tissue (Ahmad *et al.,* 2007). Silicon is also recognized to enhance plants tolerance to drought by means of improving activities of photosynthesis, sustaining water stability of the crops and improving xylem vessel and leaf structures when transpiration rates are high (Ahmad *et al.,* 2007).

Sorghum plants supplied with AMF inoculum exhibited increased growth in plant height than the plants which had no AMF inoculum. These results correlated with those of Xie *et al.* (2018) who observed that mycorrhiza inoculated plants have more growth and better physiological status (stomatal conductance, water use efficiency and photosynthetic rate) compared to crops without inoculum. In addition, where soil moisture is reduced, plants with AM fungi inoculum show greater plant height than non-inoculated. This could be because of the adjustment of abscisic acid levels and regulation of stress responsive genes in the plant caused by AMF (Chitarra *et al.,* 2016; Moreira *et al*., 2018). Also, AMF is also a natural symbiont that can provide essential nutrients to the host plants, thereby increasing growing of the plant under well water and stressed soils (Begum et al., 2019).

4.2.2 Shoot dry weight

There were significant (p <0.001) differences in plant shoot dry weight in both growing cycles between the two sorghum varieties (Table 4.4). The lowest shoot dry weights of 107.29 g and 87.29 g at week 15 was recorded in the Machakos local red variety during cycles one and two respectively while Seredo variety recorded the highest shoot dry weight of 133.06 g and 113.06 g during the same period, respectively. The results also reveal that water regimes in both cycles affected shoot dry weight significantly ($p < 0.001$) (Table 4.4). Under the lowest soil moisture content (20% water regime) in week 15, the shoot dry weight was significantly reduced recording 113.77 g compared with the highest water level (60%) recording 123.61 g in cycle one. This trend held in cycle two (Table 4.4.)

Silicon treatment caused significant ($p < 0.001$) increases in shoot dry weight. Maximum shoot dry weight of 138.29 g was recorded in treatments supplied with silicon in week 15 of cycle one (Table 4.4). A similar trend was observed in cycle two with silicon application leading to the highest shoot dry weight (118.29 g) compared to treatments without silicon. Additionally, AMF inoculation significantly ($p < 0.001$) influenced shoot dry weight in both cycles. Inoculated treatments had the highest shoot dry weight 134.55 g, 114.55 g in week 15 of cycle one and two respectively. Non inoculated plants displayed significantly low shoot dry weight (21.07 g) and (19.57 g) of cycle one and two respectively at week 6 (Table 4.4). Interaction among sorghum varieties, water stress, silicon and mycorrhiza inoculation was evident ($p < 0.001$) on shoot dry weight. All factors combined resulted in high shoot dry weight (183 g and 163 g) on the 86th day after planting in cycles one and two respectively, suggesting a synergistic effect between Seredo variety, AMF and Silicon under irrigation to 60% field capacity (Figure 4.3c and 4.4c). Seredo sorghum variety produced the highest shoot dry mass than the Machakos local red variety even though it was shorter than Machakos local red, (Table 4.3), which proves differences of plant height does not influence the final yield. Since

Seredo is an improved variety to drought it grew faster even under low soil moisture resulting to increase in shoot dry weight.

In the present study, results show that reduction of water supply to plants led to reduced shoot dry mass implying that plants were affected by low water availability to the cells. Findings by Zuccarini and Savé (2016) reported that insufficient water to plants cause stomatal closure leading to reduced photosynthesis, hence causing growth inhibition. Silicon amendment caused a significant increase in shoot growth, and weight a factor attributed to the plants response to silicon supplementation through increased photosynthesis, better tissue strength and low plant transpiration (Ali and Hassan, 2016). The results show that silicon nutrition was able to increase the accumulation of shoot dry matter. Noticeably, the positive influence of silicon nutrition was relatively more on shoot dry matter than on root dry matter. The findings on the effects of silicon conform to those of Ma *et al*. (2004), Chen *et al*. (2011) for rice, and Pilon *et al.* (2013) for potato.

Table 4.4: Mean shoot dry weight (g) as affected by sorghum varieties, water stress, AMF inoculation and silicon in both experiment cycles

Shoot dry weight (g)								
Weeks	**Week 6**		**Week 9**		**Week 12**		**Week 15**	
Cycles	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**
Variety								
Mlr	15.59^{b}	14.59^{b}	19.43^{b}	17.43^{b}	63.41^{b}	48.41^{b}	107.29^{b}	87.29^{b}
Srd	17.37^{a}	15.37^{a}	27.37^{a}	22.37^{a}	78.17^{a}	63.17^{a}	133.06^{a}	113.06^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Water regimes (%)								
20wr	15.11^{c}	13.61^{c}	22.11^{c}	18.61^{c}	67.24^{c}	52.24^{c}	113.77^{c}	93.77^{c}
40wr	16.33^{b}	14.83^{b}	22.84^{b}	19.34^{b}	71.42^{b}	56.42^{b}	123.15^{b}	103.15^{b}
60wr	18.00^{a}	16.50^{a}	25.27^{a}	21.77^{a}	73.71^{a}	58.71^{a}	123.61^{a}	103.61^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Silicon								
Control	10.26^{b}	8.76^{b}	17.37^{b}	13.87^{b}	58.86^{b}	43.86^{b}	102.06^{b}	82.06^{b}
Si	22.71^{a}	21.21^{a}	29.44^{a}	25.94^{a}	82.71^{a}	67.71^{a}	138.29^{a}	118.29^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Inoculation								
Control	11.90^{b}	10.40^{b}	18.37^{b}	14.87^{b}	61.33^{b}	46.33^{b}	105.80^{b}	85.80^{b}
AMF	21.07^{a}	19.57^{a}	28.43^{a}	24.93^{a}	80.24^{a}	65.24^{a}	134.55^{a}	114.55^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr = Machakos local red sorghum variety; C= Experiment cycle.

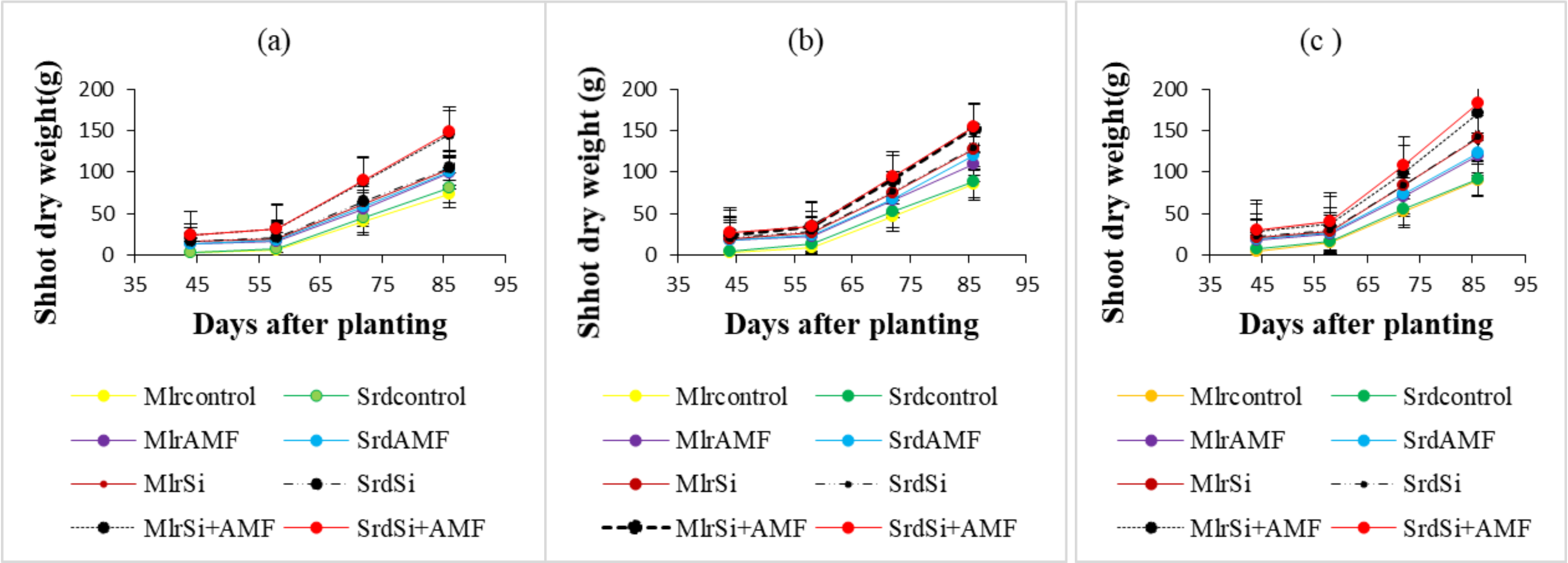


Figure 4.3a, b and c: Interactive effects between varieties, water levels, Silicon and AMF inoculant on sorghum shoot dry weight cycle 1

Srd= Seredo sorhugm variety; Mlr = Machakos local red sorghum variety; Si= With Silicon; AMF= With AMF inoculant; Wr= Water regime (20%, 40% and 60% field capacity); (a)= 20%wr, (b)= 40%wr and (c)= 60%wr

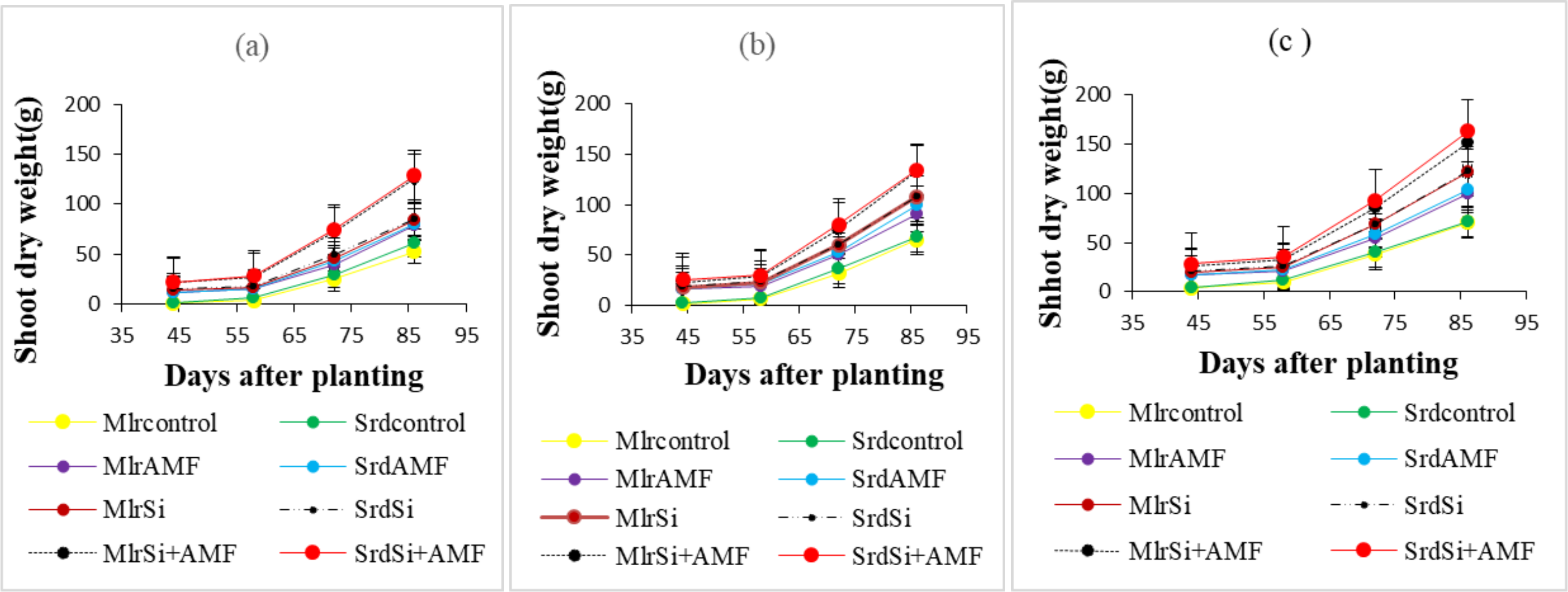


Figure 4.4a, b and c: Interactive effects between varieties, water levels, Silicon and AMF inoculant on sorghum shoot dry weight cycle 2

Srd= Seredo sorhugm variety; Mlr = Machakos local red sorghum variety; Si= With Silicon; AMF= With AMF inoculant; Wr =Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

Maximum shoot dry weight was observed when sorghum varieties were inoculated with AMF under both favorable and low water conditions. High shoot dry weight were observed on the infected plants than those not colonized can be owing to dynamics like hydraulic conductance that are improved (Sánchez-Blanco *et al.* 2004, Chelangat *et al.*, 2021a,b), improved AMF root absorption area (Khalvati *et al.* 2005) and enhanced osmotic adjustment (Wu and Xia, 2006).

Furthermore, it shows that AMF infection enhances status of water in the plant by improving its moisture absorption ability accordingly enhancing growth even under low soil moisture conditions. On the other hand, the improved growth effects of the AMF inoculated plants is regularly linked to the enhancement of phosphorus and other nutrient uptake (Abdel-Salam *et al.*, 2018). In support of the above statement, Giri *et al.* (2007) indicated enhancement of phosphorus nutrition in the soil is the major mechanism for improving tolerance to drought in AM fungi inoculated crops.

A significant interaction was seen among all the factors on shoot dry weight. Effect of combined silicon application and AMF inoculation resulted in a higher shoot dry weight under 60% water regime and 40% water regime as well as 20% water regime conditions suggesting synergistic effects between silicon and arbuscular mycorrhiza fungi. The results showed that the maximum growth improvement was seen in plants under optimal water condition in the combination of silicon application and AMF inoculation. This is in accordance with Moradtalab *et al.* (2019) whose report indicated that silicon induced shoot growth is associated with arbuscular mycorrhiza fungi mediated increase in the root growth. Also, Hajiboland *et al.* (2018) reported various mechanisms such as increased net photosynthetic rate and protein concentrations and C and N metabolism that could have been involved in improving dry matter production in strawberry plants when Si was combined AMF. Moradtalab *et al.* (2019) observed that AMF inoculation considerably increased biomass production by the plant through improving water in the plants and enhancing the rate of photosynthesis.

4.2.3 Root dry weight

There were significant differences ($p < 0.001$) in the dry weight of root among sorghum varieties, soil moisture stress, silicon and AMF inoculation. Seredo variety had superior root dry weight 107.00g and 94.75g in week 15 in cycle one and two respectively (Table 4.5). Root dry weight increased with the amount of water applied such that 60% water field capacity recorded the highest root dry weight throughout the growth period and this trend applied to both cycle one and two. Generally, 20% of water field capacity had the lowest root dry weight 95.00 g and 80.41 g in week 15 cycle one and two respectively as illustrated in Table 4.5. Nevertheless, the application of silicon significantly increased root dry weight in both cycles. Silicon applied treatments recorded maximum root dry weight 115.20 g, 102.92 g cycle one and two in week 15 while lowest root dry weight 68.26 g was observed in treatments without silicon in cycle two as shown in Table 4.5. Inoculation of AMF to sorghum in general lead to significant ($p < 0.001$) rise in dry weight of root in both cycles. Greater root dry weight 123.10 g was observed in week 15 cycle one in inoculated treatments whereas the lowest root dry weight 3.05 g was recorded in non-inoculated week 6 cycle two (Table 4.5).

Further, there was significant (p <0.001) interaction in the influence of the varieties, water levels, Silicon and AMF inoculant on root dry weight of sorghum cycle 1 and 2 (Figure 4.5 and 4.6). Seredo variety amended with Silicon and AMF exhibited higher root dry weight 154.8 g in cycle one under 60% water field capacity (Figure 4.5c). Controls among the water regime treatments recorded the lowest root dry weight in cycle one and two (Figure 4.5 and 4.6). The study demonstrated that improved variety (Seredo) performed better than local variety (Machakos local red) in terms of root dry weight. As stated earlier, this could be due to their differences in genetic makeup.

Increased moisture levels resulted in increased root dry weight. This observation was in support of previous studies such as Blum and Arkin (1984) who recognized soil moisture as a key factor affecting sorghum root distribution in the soil profile, and Cakir (2004) who reported that total dry matter accumulation was affected by soil water deficit. Ndiso *et al.* (2016) designated that a reduced root and plant growth could be attributed to reduced cellular expansion and deterioration in photosynthesis resulting from water stress conditions. The findings from the study also indicate that silicon application leads to more superior root biomass accumulation than those not amended. These confirmations signify that silicon has an enhancing influence on plant production (Guntzer *et al.*, 2012). Sivanesan and Park (2014); Khenizy and Ibrahim, (2015) reported that Si improves growth and yield of various crops by alleviating different stresses and nutrients imbalance. The current findings are consistent with (Moreira *et al.* 2018) who reported higher yield root dry masses in inoculated plants an those not inoculated. Also, this could be attributed to enhanced root hydraulic conductance and improved water absorption and nutrient by plants through extended extraradical mycelia (Hajiboland *et al.*, 2018)**.**

Table 4.5: Mean root dry weight (g) as affected by sorghum varieties, water stress, AMF inoculation and silicon both experimental cycles

Root dry weight (g)								
Weeks	**Week 6**		**Week 9**		**Week 12**		**Week 15**	
Cycles	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**
Variety								
Mlr	7.83^{b}	6.92^{b}	10.63^{b}	9.63^{b}	54.57^{b}	44.57^{b}	91.40^{b}	76.42^{b}
Srd	8.87^{a}	5.83^{a}	17.83^{a}	12.83^{a}	60.04^{a}	50.04^{a}	107.00^{a}	94.75^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Water regimes (%)								
20wr	6.29^{c}	4.69^{c}	12.73^{c}	9.47^{c}	52.66^{c}	42.31^{c}	95.00^{c}	80.41^{c}
40wr	7.59^{b}	6.02^{b}	13.89^{b}	10.75^{b}	57.31^{b}	46.89^{b}	99.60^{b}	84.33^{b}
60wr	9.66^{a}	8.42^{a}	16.08^{a}	13.48^{a}	61.95^{a}	52.72^{a}	103.00^{a}	92.02^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Silicon								
control	5.58^{b}	3.97^{b}	12.01^{b}	8.74^{b}	49.19^{b}	38.67^{b}	83.20^{b}	68.26^{b}
Si	10.12^{a}	8.79^{a}	16.46^{a}	13.73^{a}	65.42^{a}	55.94^{a}	115.20^{a}	102.92^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Inoculation								
control	4.33^{b}	3.05^{b}	10.67^{b}	7.93^{b}	42.74^{b}	33.26^{b}	75.30^{b}	62.94^{b}
AMF	11.37^{a}	9.70^{a}	17.80^{a}	14.53^{a}	71.87^{a}	61.35^{a}	123.10^{a}	108.23^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr = Machakos local red sorghum variety; C= Experiment cycle.

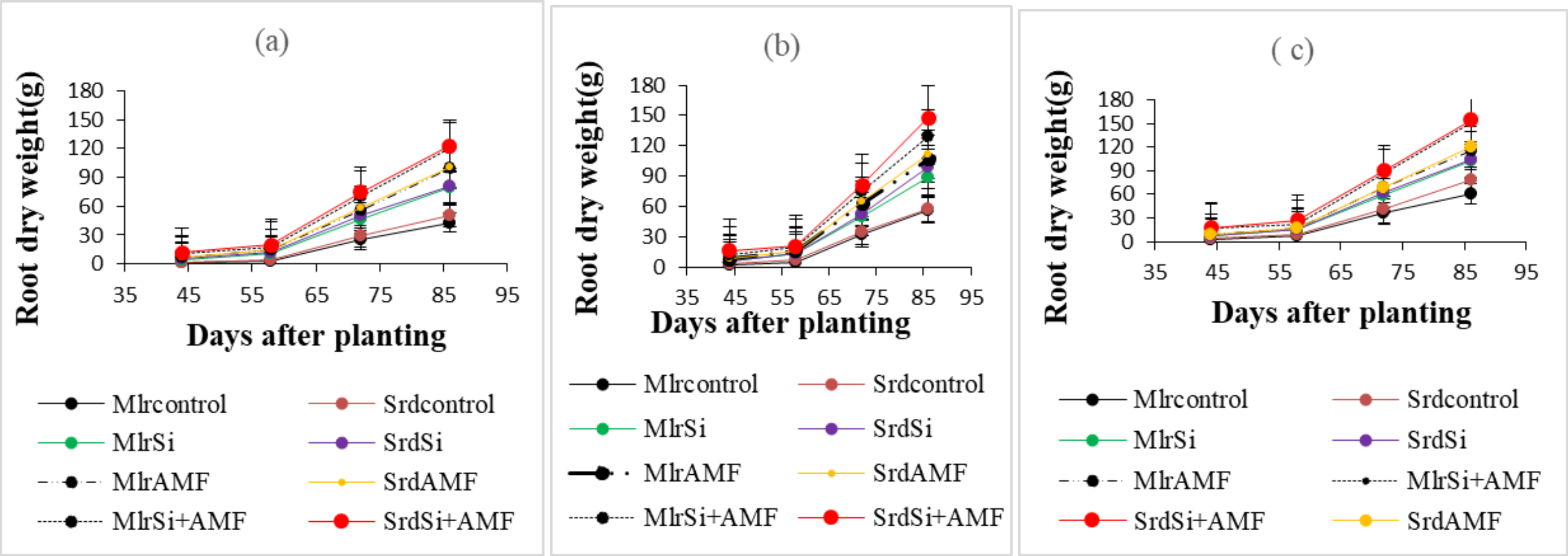


Figure 4.5a, b and c: Interactive effects between varieties, water levels, silicon and AMF inoculation on sorghum root dry dry weight cycles 1

Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); (a)= 20%wr, (b)= 40%wr and (c)= 60%wr.

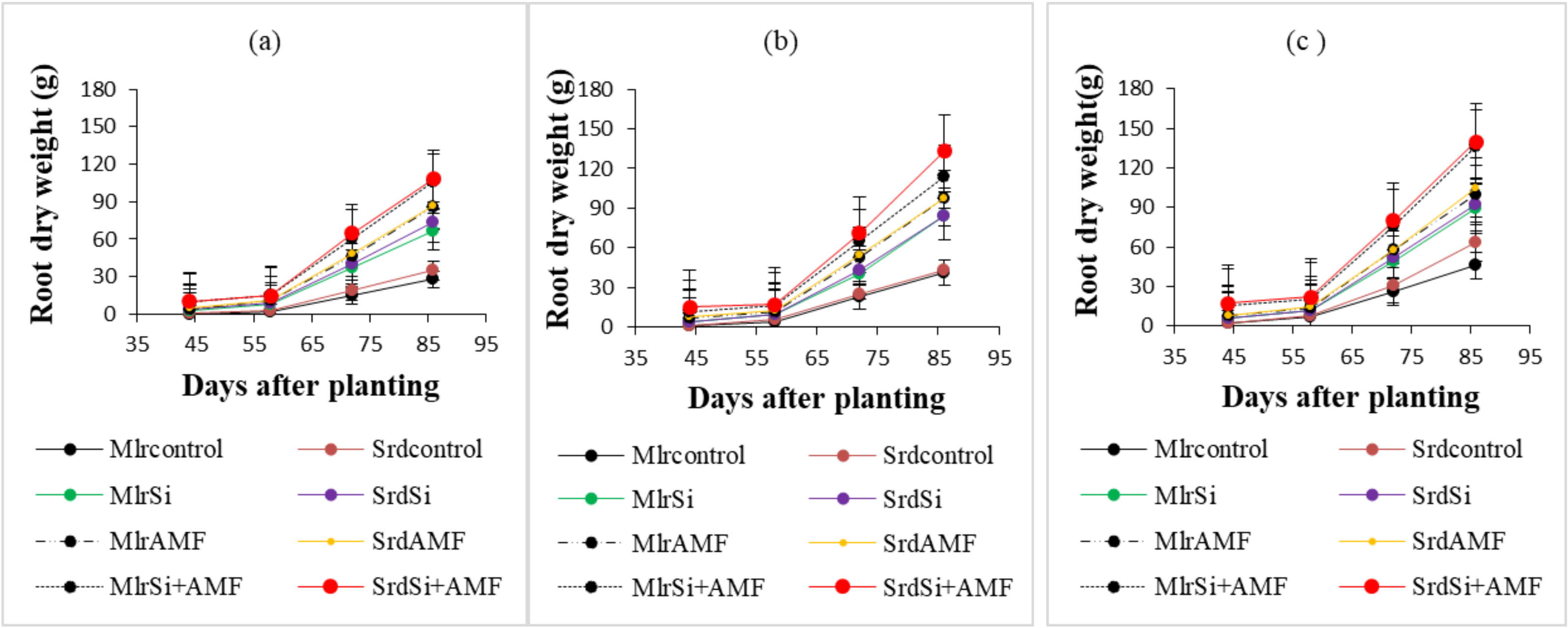


Figure 4.6a, b and c: Interactive effects between varieties, water levels, silicon and AMF inoculation on sorghum root dry dry weight cycles 2

Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

Interaction between silicon and AMF improved sorghum growth under optimum and depressed water conditions. Addition of silicon and AMF led to high accumulation of root dry weight. These results indicate the potential of silicon and AMF in enhancing plant growth. The mycorrhizal association is known to improve absorption of water by the plant thus reducing more expenses of root apparatus (Zuccarini and Savé, 2016). The Superior effects observed on root dry weight when improved variety Seredo was subjected to silicon and AMF in both cycles could be attributed to their synergistic effects. Hajiboland *et al.* (2018) also found out that strawberry dry matter production, root colonization rate, photosynthesis rate and water relation parameters were all improved by Si in combination with AMF, and these achieved the highest amounts in the study.

4.2.4 Root length

Results of this study revealed that sorghum varieties were significantly varied ($p < 0.001$) in terms of the root length in both cycles. Seredo variety recorded the highest root length of 44.05 cm in cycle one week 15 (Table 4.6). Water regimes significantly influenced roots growth of sorghum plant at $p < 0.001$. The highest root length of 47.10 cm and 40.10 cm was observed in cycle one and cycle two week 15 respectively and this happened in the plants under high moisture level (60%). As well 60% water regime gave maximum root length across the weeks in the two seasons (Table 4.6). Application of silicon significantly triggered ($p < 0.001$) increase in the root length of sorghum in the two cycles as compared with treatments without silicon. Maximum root length 46.00 cm and 39.00 cm was recorded in week 15 in cycle one and two respectively (Table

4.6). AMF caused a significant ($p < 0.001$) increase in the root length of sorghum, such that the treatments without AMF recorded the lowest root length across the weeks in the two cycles. The highest root length of 48.74 cm was recorded in inoculated treatments at week 15 of cycle one (Table 4.6).

As shown in Figure 4.7 and 4.8 the interaction of varieties, water regimes, Silicon and AMF inoculation was significant ($p < 0.001$) across the experimental period. Machakos local red had the lowest root length of 54.2 cm, 47.9 cm when interacted with silicon and AMF under 60% water level compared to Seredo variety that showed superiority in root length recording 56.9 cm and 50.2 cm at 86 day after planting in the two cycles respectively. Seredo variety recorded the highest root length and a similar trends were observed in all the weeks in the two cycles. The results also showed similar trend with those of root dry weight (Table 4.5), an indicator that high root length also elicits high root dry weight.

The findings of the study revealed that low moisture in the soil (20 %) compromised the root length of the sorghum plant since root length in the treatment ragged behind. According to Moreira *et al.* (2018) lack of water indirectly or directly affects several cellular physiological processes in plants. Also, Abdel-Salam *et al.* (2018) reported that water deficit is a universal problem that decreases plant growth, flower yield and other physiological processes of the majority of the field and ornamental economical crops. Increased root length on silicon treatments showed the benefits of silicon in improving cell turgor, cell wall metabolism and enhancement of cell enlargement as reported by

(Ramy and Atef, 2019). Findings of this study also indicated that AMF inoculation promoted vibrant growth of roots when compared to non-inoculated plants.

Table 4.6: Mean root length as affected by sorghum varieties, water levels, silicon and AMF inoculant cycle1 and 2

Root length (cm)								
Weeks	**Week 6**		**Week 9**		**Week 12**		**Week 15**	
Cycles	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**	**C1**	
Variety								
Mlr	9.82^{b}	9.62^{b}	31.32^{a}	24.32b	35.19^{b}	30.69^{b}	42.52^{b}	34.05^{b}
Srd	11.62^{a}	9.77^{a}	27.88b	20.88^{a}	38.69^{a}	32.19^{a}	44.05^{a}	38.52^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Water regimes (%)								
20wr	8.81^{c}	7.79^{c}	26.47^{c}	19.47^{c}	33.93^{c}	31.37^{b}	40.00^{c}	33.00^{c}
40wr	10.27^{b}	9.24^{b}	29.24^{b}	22.24^{b}	36.87^{b}	28.43^{c}	42.76^{b}	35.76^{b}
60wr	13.07^{a}	12.05^{a}	33.09^{a}	26.09^{a}	40.02^{a}	34.52^{a}	47.10^{a}	40.10^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Silicon								
control	8.91^{b}	7.88^{b}	26.54^{b}	19.54^{b}	34.17^{b}	28.67^{b}	40.57^{b}	33.57^{b}
Si	12.53^{a}	11.50^{a}	32.66^{a}	25.66^{a}	39.71^{a}	34.21^{a}	46.00^{a}	39.00^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Inoculation								
control	7.30^{b}	6.28^{b}	23.98^{b}	16.98^{b}	31.73^{b}	26.23^{b}	37.84^{b}	30.84^{b}
AMF	14.14^{a}	13.11^{a}	35.22^{a}	28.22^{a}	42.15^{a}	36.65^{a}	48.74^{a}	41.74^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C=experiment cycle.

Janos (2007) reported that mycorrhizal fungus effectiveness is represented by the difference in growth between plants with and without mycorrhiza as a property of the interaction between plant and fungus species. This indicated that sorghum plant responded positively to AMF resulting in enhanced root growth. Interactions demonstrated that Seredo variety interacting with Silicon amendment in combination with AMF inoculation recorded the highest root length in all the weeks of both cycles. Tawaraya (2003) reported that different factors may influence mycorrhizal effectiveness including plant species and genotype.

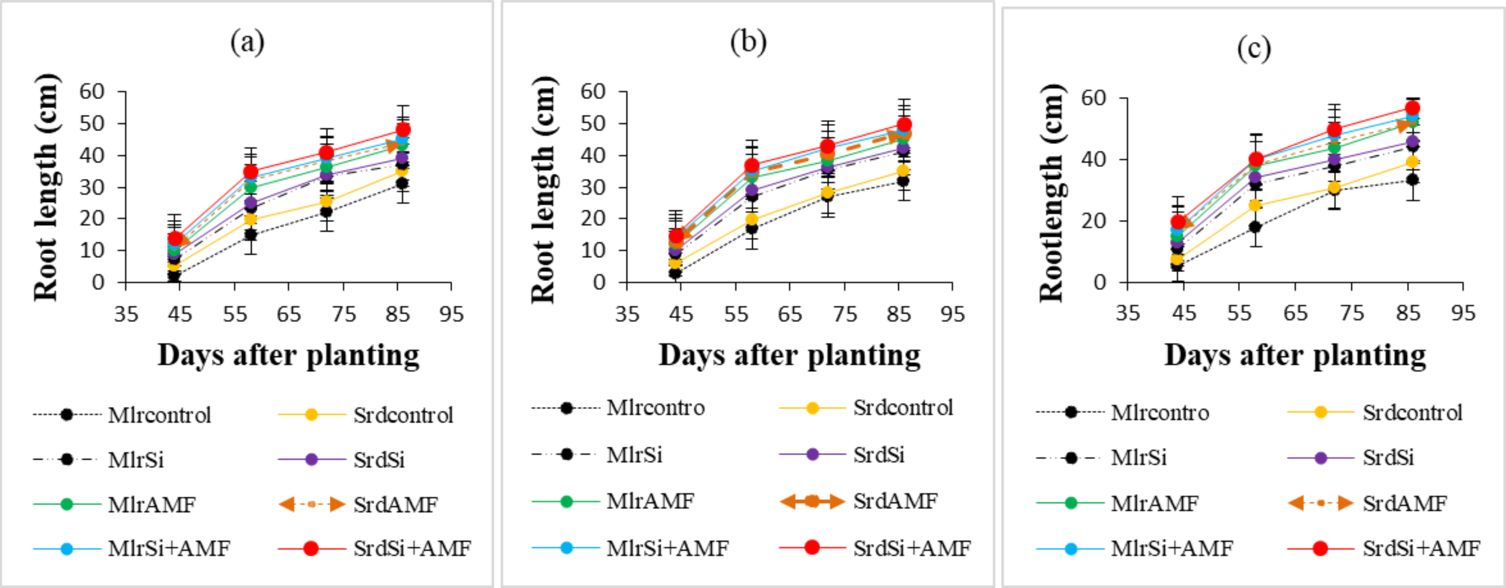


Figure 4.7a, b and c: Interactive effects between varieties, water levels, silicon and AMF inoculation on sorghum root length cycle 1

Srd= Seredo sorhugm variety; Mlr = Machakos local red sorghum variety, Si= With Silicon; AMF= With AMF inoculant; Wr =Water regime (20%, 40% and 60% field capacity); (a)= 20%wr, (b)= 40%wr and (c)= 60%wr.

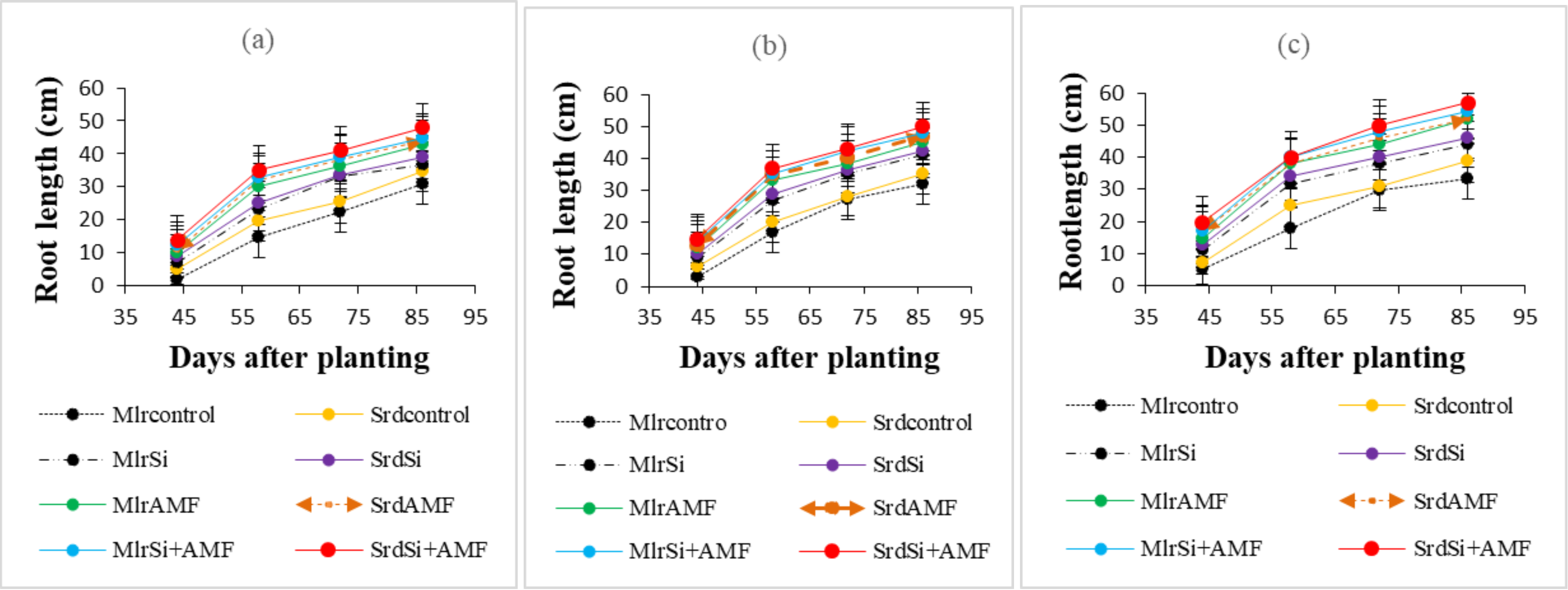


Figure 4.8a, b and c: Interactive effects between varieties, water levels, silicon and AMF inoculation on sorghum root length cycle 1.

Srd= Seredo sorhugm variety; Mlr = Machakos local red sorghum variety, Si= With Silicon; AMF= With AMF inoculant; Wr= Water regime (20%, 40% and 60% field capacity); (a)= 20%wr, (b)= 40%wr and (c)= 60%wr.

Seredo variety outperformed Machakos local red variety possibly due to their genetic makeup variation and therefore their effectiveness with which they associated with AMF differed. Besides that, inoculated plants were able to maintain their growth even in low moisture soils due to their well-developed and distributed root system that enhanced uptake of water (Moreira *et al.*, 2018). The study discovered that a combination of the silicon and mycorrhiza resulted in higher root length. This is because their synergistic effect influenced root length that that silicon played an important role in enhancing water uptake and adequate nutrients supply (Ramy and Atef, 2019), while AMF extraradical hyphae enhance nutrient uptake therefore improving plant growth (Lehmann and Rillig, 2015).

4.2.5 Number of leaves

Sorghum varieties, water regimes, silicon amendment and AMF inoculation influenced significantly (p <0.001) the number of leaves per plant in both cycles (Table 4.7). The number of leaves was significantly different in all the weeks in cycle one and two. Machakos local red variety had the highest number of leaves across the weeks and the trend remained the same in both cycles. In week 15 it 10.77 cycle one and 8.77 cycle two respectively. Plants under 60% water regime recorded the highest number of leaves compared to the lowest 20% water regime in both cycle one and two (Table 4.7). The results showed that the maximum number of leaves 11.16 and 9.33 were recorded in plants that were irrigated with 60% water level in cycle one and two respectively in weeks 15.

Silicon applied treatments exhibited significantly higher number of leaves of 11.16 and 9.27 in week 15 in both cycles respectively as shown in table 4.7. On the other hand, treatments without silicon had the lowest number of leaves across the weeks and the trend remained so in cycle one and two. AMF inoculated sorghum plants exhibited a significantly higher number of leaves in cycle one and two compared to plants that were not inoculated. The maximum number of leaves recorded in cycle one, week 15 was 10.80. As well the number of leaves were significantly ($p <0.001$) affected by the interaction between varieties, water levels, Silicon and AMF inoculant. Results revealed that the maximum number of leaves of 15.3 and 13.3 were recorded in cycle one and two respectively 86 days after planting under 60% water regime, Silicon and mycorrhiza interacting with Machakos local red variety. The lowest number of leaves of 3 and 2 were recorded under 20% water field capacity, Silicon and AMF interacting with Seredo variety in both cycles 44 days after planting (Figure 4.9 and 4.10). Machakos local red variety which had tallest plants recorded the highest number of leaves as compared with the improved Seredo variety. This shows a variety with high plant height can also give the highest number of leaves. Such results indicate that there is a difference in genetic bases with variation in the gene action expressing phenotypes among varieties tested (Mwamahonje and Maseta, 2018). Similarly, Muhammad *et al.* (2020) reported that sorghum variety Quetta *Sorghum* which had 208.89 cm plant height was also ranked among those that produced the highest number of leaves (13.78) per plant.

Silicon amendment elicited a higher number of leaves per plant than non-amended plants and as reported by Ahmad *et al.* (2007) that silicon application increased plant growth significantly, therefore the increase in number of leaves in the study was owed to silicon effects. Considering the higher number of leaves in silicon supplied plants than non-silicon applied plants, it is expected that the photosynthesis of silicon applied sorghum plants was higher than that of plants not supplied with silicon.

Table 4.7: Number of leaves as affected by sorghum varieties, water levels, silicon and AMF inoculant cycle1 and 2

Number of leaves								
Weeks	**Week 6**		**Week 9**		**Week 12**		**Week 15**	
Cycles	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**	**C1**	
Variety								
Srd	4.16^{b}	3.72^{b}	5.55^{b}	5.38^{b}	7.80^{b}	7.27^{b}	8.80^{b}	8.02^{b}
Mlr	4.75^{a}	4.88^{a}	6.38^{a}	6.72^{a}	9.77^{a}	7.77^{a}	10.77^{a}	8.77^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Water regimes (%)								
20wr	3.50^{c}	3.54^{c}	4.75^{c}	5.04^{c}	7.54^{c}	6.66^{c}	8.54^{c}	7.54^{c}
40wr	4.20^{b}	4.20^{a}	5.70^{b}	6.04^{b}	8.66^{b}	7.45^{b}	9.66^{a}	8.33^{b}
60wr	5.66^{a}	5.16^{a}	7.45^{a}	7.08^{a}	10.16^{a}	8.45^{a}	11.16^{a}	9.33^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Silicon								
control	3.36^{b}	3.55^{b}	4.58^{b}	5.22^{b}	7.41^{b}	6.52^{b}	8.41^{b}	7.52^{b}
Si	5.55^{a}	5.05^{a}	7.36^{a}	6.88^{a}	10.16^{a}	8.52^{a}	11.16^{a}	9.27^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Inoculation								
control	3.66^{b}	3.58^{b}	4.94^{b}	5.33^{b}	7.77^{b}	6.75^{b}	8.77^{b}	7.58^{b}
AMF	5.25^{a}	5.02^{a}	7.00^{a}	6.77^{a}	9.80^{a}	8.30^{a}	10.80^{a}	9.22^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= experiment cycle.

It can be reported that silicon regulates gene expression directly and plant metabolism through cascading effect (Moradtalab *et al*., 2019). Sorghum plant inoculation by AMF was found to raise the leaves number of the host plant. The results are corroborated with those of Wang *et al.* (2019) who conveyed that AM sorghum plants of both cultivars they worked with had improved plant biomass.

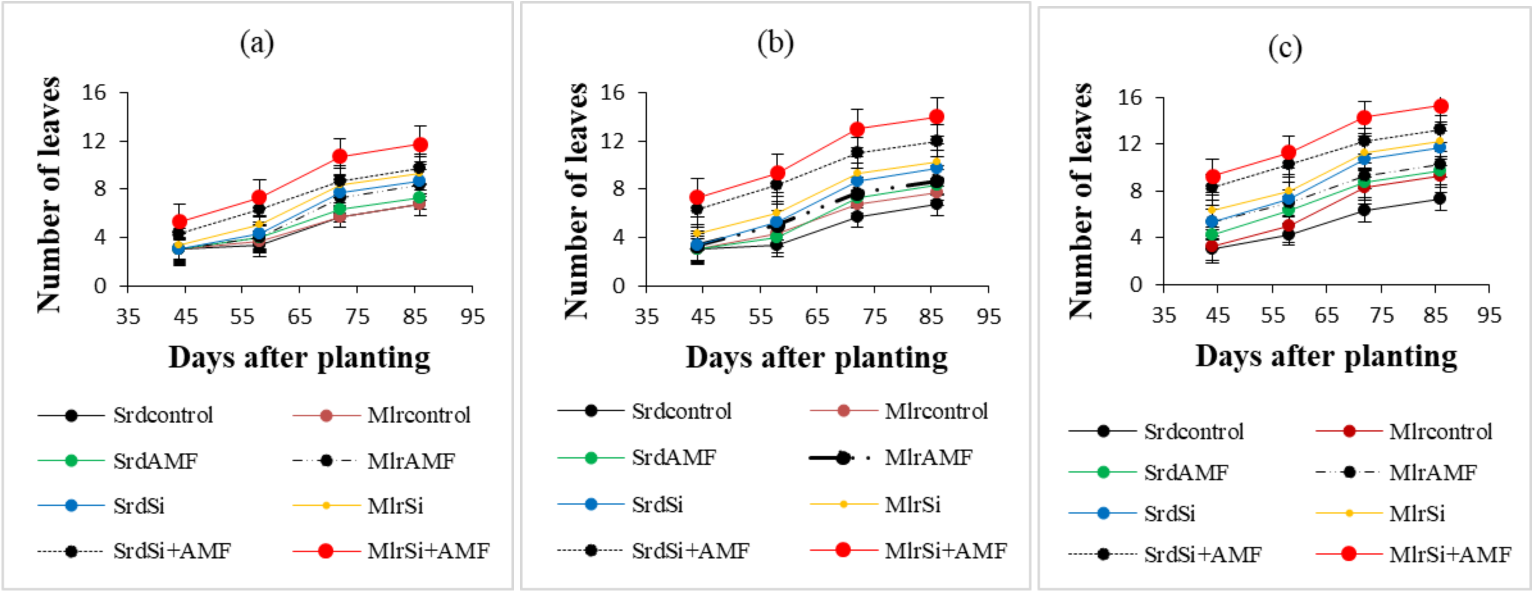


Figure 4.9a, b and c: Interactive effects between varieties, water levels, Silicon and AMF inoculant on the number of leaves of sorghum cycle 1

Srd= Seredo sorhugm variety; Mlr = Machakos local sorghum variety; Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

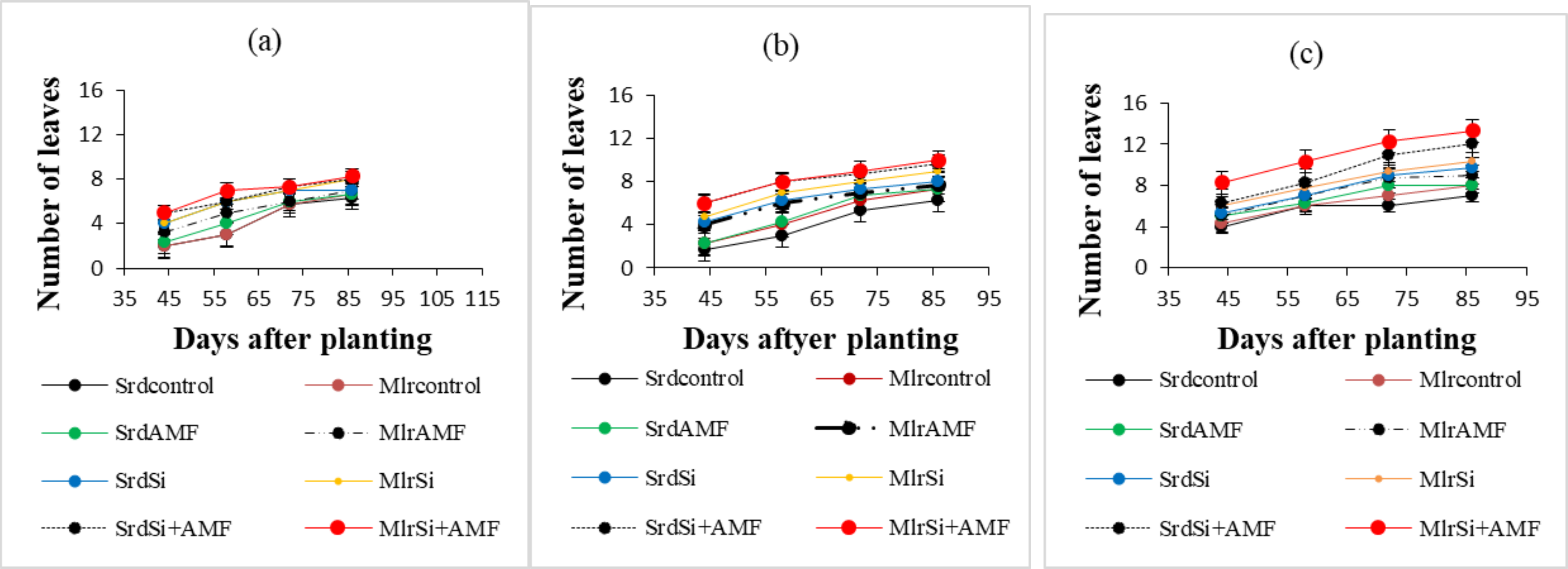


Figure 4.10a, b and c: Interactive effects between varieties, water levels, Silicon and AMF inoculant on the number of leaves of sorghum cycle 1

Srd= Seredo sorhugm variety; Mlr = Machakos local sorghum variety; Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

Furthermore, interactions showed that Machakos local red in combination with Silicon, AMF performed well under all the moisture levels. Previously the synergistic effect of AMF and Silicon was reported where results showed that AMF improved the uptake of Si and P compared to non-colonized *Brachypodium sylvaticum* plants (Haskell, 2017). These increments were attributed to the beneficial effect of AMF in enhancing symplastic water transport through regulation of aquaporins genes expression, therefore, helping in the transport of water as well as solute thereby improving water and nutrient status of plants (Zuccarini and Savé, 2016) and also improving the uptake of silicon an important element. Other research by Moradtalab *et al.* (2019) show that infection by AMF considerably increased leaf area, chlorophyll content, photosynthesis rate and photochemical efficiency of plants under drought.

4.2.6 Number of tillers

Tillers number per plant was considerably influenced ($p < 0.05$) by sorghum varieties only in week 6 in both cycles though the highest number of tillers 3.97 and 3.78 were recorded in cycle one and two respectively in week 15 (Table 4.8). Water regimes elicited a significant difference ($p < 0.001$) on the number of tillers only in week 6 in all the cycles. The maximum number of tillers at 4.21 were recorded in cycle one week 15 (Table 4.8). Addition of silicon and AMF significantly ($p < 0.01$) affected the number of tillers only in week 6 in both cycles. In Silicon treated plants, the highest number of tillers at 4.11 was observed in week 15 of cycle one while AMF inoculated treatments gave the greatest at number of tillers at 4.25 week 15 of cycle one (Table 4.8).

Table 4.8: Mean number of tillers as affected by sorghum varieties, water stress, AMF inoculation and silicon in both experiment cycles

	Number of tillers							
Weeks	**Week 6**		**Week 9**		**Week 12**		**Week 15**	
Cycles	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**	**C1**	
				Variety				
Srd	1.47^{b}	0.16^{b}	3.36^{a}	1.36^{b}	3.78^{a}	2.78^{a}	3.78^{a}	2.78^{a}
Mlr	1.80^{a}	0.86^{a}	3.53^{a}	2.36^{a}	3.97^{a}	3.78^{a}	3.97^{a}	3.78^{a}
P-value	0.04	0.01	0.72	0.41	0.69	0.06	0.68	0.71
				Water regimes (%)				
20wr	1.25^{c}	0.25^{c}	3.08^{b}	1.50^{b}	3.46^{a}	2.67^{a}	3.46^{a}	2.67^{a}
40wr	1.45^{b}	0.50^{b}	3.42^{ab}	1.67^{ab}	3.96^{a}	3.33^{a}	3.96^{a}	3.33^{a}
60wr	2.20^{a}	0.79^{a}	3.83^{a}	2.42^{a}	4.21^{a}	3.83^{a}	4.21^{a}	3.83^{a}
P-value	<0.001	<0.001	0.41	0.26	0.43	0.19	0.44	0.20
				Silicon				
control	1.30^{b}	0.38^{b}	3.25^{a}	1.67^{a}	3.64^{a}	2.89^{a}	3.64^{a}	2.89a
Si	1.97^{a}	0.63^{a}	3.64^{a}	2.06^{a}	4.11^{a}	3.67^{a}	4.11^{a}	3.67^{a}
P-value	<0.001	0.002	0.40	0.50	0.33	0.14	0.23	0.15
				Inoculation				
control	1.38^{b}	0.44^{b}	3.33^{a}	1.78^{a}	3.50^{a}	2.89^{a}	3.50^{a}	2.89^{a}
AMF	1.88^{a}	0.58^{a}	3.56^{a}	1.94^{a}	4.25^{a}	3.67^{a}	4.25^{a}	3.67^{a}
P-value	0.004	0.036	0.63	0.72	0.13	0.14	0.12	0.15

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= experiment cycle.

The interactive effects of sorghum varieties, water levels, and silicon and mycorrhiza inoculation were not significant (Appendix 1). The number of tillers showed a significant difference in the early weeks of growth (vegetative growth phase of sorghum) in the two cycles as influenced by all the treatments. The outcome of this study is similar to previous findings of Myers *et al.* (1989) who reported that sorghum tillering was most rapid between emergence and floral initiation, after which tiller number declined owing to rate of senescence exceeding the rate of appearance. Reduction of the number of tillers with 20% water regime exhibiting higher decline than control which was under 60% water field capacity. Varietal differences occurred such that Machakos local red variety had the highest number of tillers during this period. The study results agree with those of Siddique *et al.* (2000); Farooq *et al.* (2009) that stated that when plants are exposed to water stress they decreases water content and leaf water potential considerably thus consequently affect progression and expansion of the plant. Further, this study demonstrated that plant leaf area, rate of emergence and tiller development is reduced when soil water potential was low. Shen *et al.* (2010) found that low soil moisture affects soybean by significantly decreasing relative water content (RWC) thus interfere with crop development. In the present study, Silicon use improved the number of tillers per plant under water stress as well as under well-watered treatments**.** This is in collaboration with findings from research by Ahmad and Haddad, (2011); Ming *et al.* (2012) who indicated that silicon application led to increase in leaf water potential and water content in the plant, therefore, enhancing crop growth. A similar study by Gunes *et al.* (2007) and Shen *et al.* (2010) also demonstrated that Si use improved water contents in chickpea. Further, Zhang *et al*. (2017) informed that silicon application may perhaps sustain a high relative water capacity besides stomatal conductance.

There was a considerable increase in the number of tillers in AMF inoculated treatments than those non-inoculated under well-watered conditions as well as under drought conditions. Tillering is a factor of growth influenced by nutrient availability, temperature and soil moisture. Since high tillers were reported under 20% water regime with inoculum, therefore, this result put forward a substantial proof that arbuscular mycorrhiza fungi are capable of improving host plant tolerance to water deficit in the soil (Davies *et al.*, 2002; Auge´, 2004). This is possible through different mechanisms enhanced by AM fungi, for instance, osmotic adjustment increased hydraulic conductivity of the host plant, improved stomatal regulation and binding effect of the roots to the soil particles that enables more water to be absorbed from smaller poles (Auge´, 2004). Nonetheless, reports by Srivastava *et al.* (2002) indicated that water and nutrients uptake is high in water-stressed Mycorrhiza crops than in non-mycorrhiza crops. The support by AMF resulted in an increased number of tillers.

4.2.7 Number of days to 50% flowering

Fifty per cent days to flowering was significantly ($p < 0.001$) influenced by sorghum varieties, water levels, and silicon and AMF inoculation in all cycles (Table 4.9). Machakos local red variety took the shortest time to flower in cycle one with a mean of 67.92 days while Seredo variety took the longest time with a mean of 76.41 days cycle two. The treatments under 60% water regime conditions took the shortest period to flower with a mean of 66.83 days compared to those underwater stress that took a mean of 70.62 days in cycle one. The same trend was revealed in cycle two. Silicon application led to a reduced number of days to flowering recording 63.44 and 71.25 compared to the control that recorded 74.22 and 79.75 more days in cycle one and two, respectively. Similarly, the same trend was observed with AMF inoculation (Table 4.9). The findings of this study led to significant ($p < 0.001$) differences in the interaction between sorghum varieties, water levels, silicon amendment and AMF inoculation on days to 50% flowering (Figure 4.11a and b and 4.12c) in cycle one. Machakos local red variety took the shortest time to reach 50% days to flowering than Seredo variety. According to Yang *et al.* (2000), days to flowering is controlled by both genetic and environmental factors a confirmation that the two varieties in the present study differed in terms of their genotypic makeup.

Table 4.9: Days to 50% flowering as affected by sorghum varieties, water stress, AMF inoculation and silicon in both experiment cycles

50% days to flowering		
Cycles	**C1**	**C2**
	Variety	
Mlr	67.92^{b}	74.58^{b}
Srd	69.75^{a}	76.41^{a}
P-value	<0.001	<0.001
	Water regimes (%)	
60wr	66.83^{c}	73.29^{c}
40wr	69.04^{b}	75.91^{b}
20wr	70.62^{a}	77.29^{a}
P-value	<0.001	<0.001
	Silicon	
Si	63.44^{b}	71.25^{b}
control	74.22^{a}	79.75^{a}
P-value	<0.001	<0.001
	Inoculation	
AMF	65.31^{b}	73.00^{b}
control	72.36^{a}	78.00^{a}
P-value	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= experiment cycle.

Okumoto and Tanisaka (1997) reported different genes involved in flowering time in rice and this genetic differentiation created a broad variation in days to flowering among rice cultivars. The results from this study showed that silicon enhanced the appearance of the flowers decreasing the days to flowering as compared with the non-amended plants.

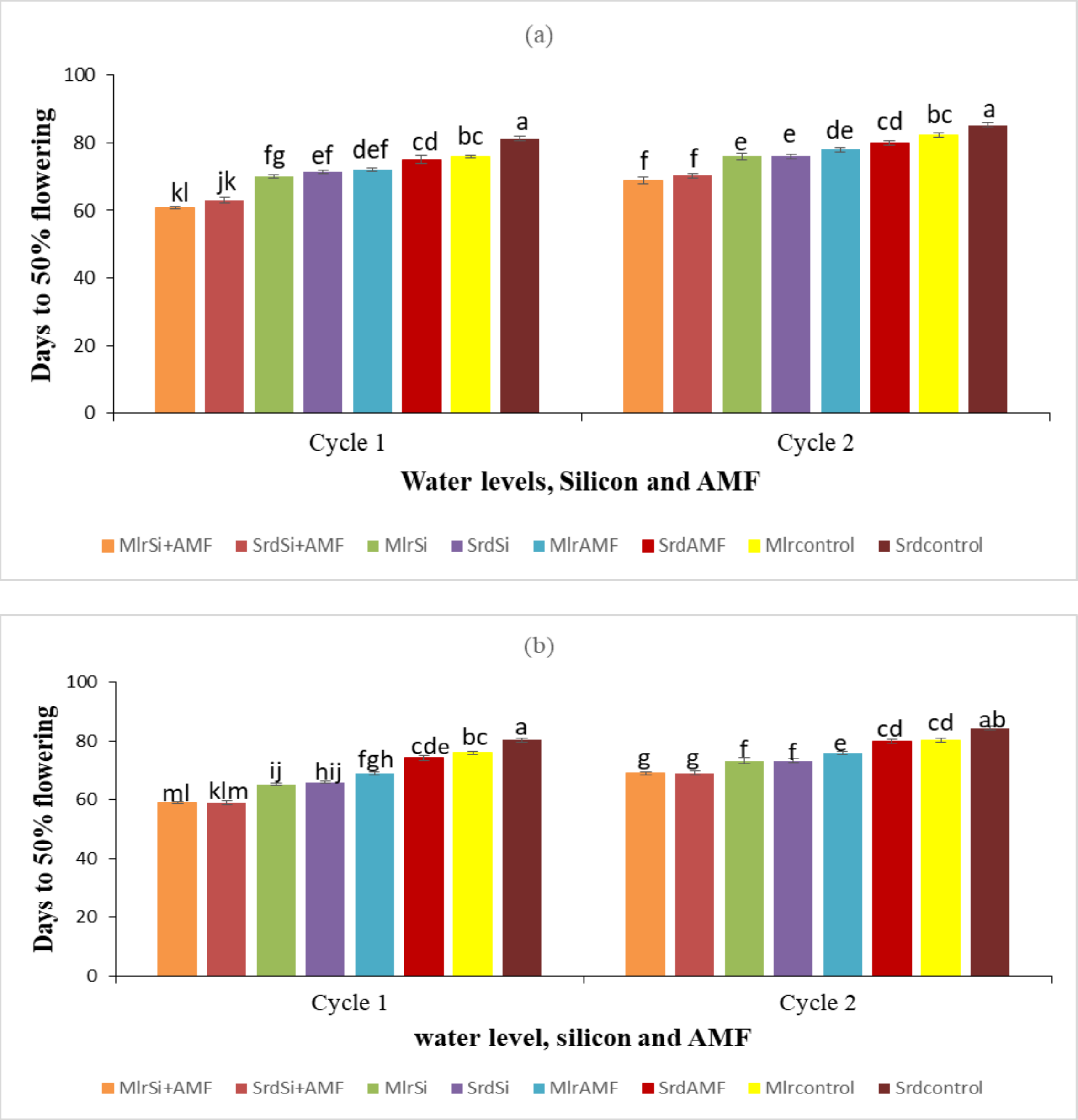


Figure 4.11a and b: Interactive effects between varieties, water levels, Silicon and AMF inoculation on days to 50% flowering cycle 1 and 2

Srd= Seredo sorhugm variety; Mlr = Machakos local red sorghum variety, Si= With Silicon; AMF= With AMF inoculant.

This could be attributed to silicon ability to improve photosynthesis; reduction of transpiration and hormones changes thus leading to accelerated flowering (Ma and Takahashi, 2002). Similarly, Ali and Hassan, (2016); Idou *et al.* (2010) reported the same trend in gerbera. AMF inoculant reduced the number of days to flowering as revealed by this study. These findings are not in agreement with Hidayat *et al.* (2019) who indicated that AMF inoculation had no effects on flowering but confirms that Inoculation with AMF increases P uptake by the rice plant which increases flowering and reducing the days to flowering (Okonji *et al.,* 2018).

Treatment interaction showed that Machakos local red variety when amended with silicon and AMF inoculant took the shortest days at 56.3 and 61.3 to flower under 60% water field capacity compared to control that took 74 and 78.3 days to flowering cycle one and two respectively. Low soil moisture had a significant influence on the number of days to flowering (Table 4.9). The results from this study revealed that water stress increased the number of days to flowering. The findings are similar to those of Martínez-Cuenca *et al.* (2020) who demonstrated that low soil moisture at vegetative and flowering stage increases days to flowering. Studies by (Lilley and Fukai, (1994) and Lafitte *et al*. (2006) in rice showed that water stress increased days to flowering for some varieties while others it reduced. This could be due to flowering time genes that have different genetic make-up (Cho *et al*., 2017). However, studies on *Brassica* stated that drought reduces days to flowering (Franks *et al*. (2007) while in *Mimulus guttatus* it increases (Jordan *et al.*, 2015).

4.2.8 Yield and yield components

Stover yield, grain yield and harvest index were significantly ($p < 0.001$**)** affected by sorghum varieties in both cycles (Table 4.10). Seredo variety recorded the highest stover yield (8.0 tha^{-1}), grain yield (4.4 t ha^{-1}) and harvest index (0.39) respectively in cycle one. Also, results obtained from this study showed that stover yield, grain yield and harvest index were significantly ($p < 0.001$**)** affected by water regimes. Both the stover and grain yields of plants exposed to water stress (20%) were significantly inferior resulting in 6.5 t ha^{-1}, 3.3 t ha^{-1}and 4.6 t ha^{-1}, 2.5 t ha^{-1}cycle one and two respectively as compared with water regime 40% that accumulated 8.5 t ha^{-1}, 4.8 t ha^{-1}and 6.1 t ha^{-1}and 3.5 t ha^{-1}in cycle one and two respectively. Although the water regime 20% recorded the highest harvest index of 0.36 and 0.35 in cycle one and two (Table 4.10). However, 60% water regime recorded low stover and grain yield and harvest index compared to 40% water regime (Table 4.10).

Silicon application led to significant differences ($p < 0.001$**)** in sorghum stover yield, grain yield, and harvest index (Table 4.10). In the two cycles, silicon non amended treatments had the lowest stover yields recording 6.1 t ha^{-1}and 4.3 t ha^{-1}in cycle one and cycle two. On the other hand, the highest stover yield was obtained in silicon amended treatments recording 9.0 t ha^{-1}, 6.3 t ha^{-1}in cycle one and two respectively. The lowest grain yields of 2.9 t ha^{-1}2.2 t ha^{-1}were recorded in non-amended treatments in cycle one and two respectively. Silicon amended treatments recorded the highest yield with 5.1 t ha^{-1}3.7 t ha^{-1}in cycle one and two respectively.

Table 4.10: Yield and yield components as influenced by sorghum varieties, water stress, AMF inoculation and silicon in both experiment cycle

	Stover yield (t ha^{-1})		**Grain yield (t ha^{-1})**		**Harvest index**	
Cycles	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**
			Variety			
Mlr	7.2^{b}	5.0^{b}	3.6^{b}	2.2^{b}	0.30^{b}	0.33^{b}
Srd	8.0^{a}	5.6^{a}	4.4^{a}	3.7^{a}	0.39^{a}	0.35^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
			Water regimes (%)			
20Wr	6.5^{c}	4.6^{c}	3.3^{c}	2.5^{c}	0.36^{a}	0.35^{a}
60Wr	7.8^{b}	5.3^{b}	4.0^{b}	2.9^{b}	0.34^{c}	0.33^{c}
40Wr	8.5^{a}	6.1^{a}	4.8^{a}	3.5^{a}	0.35^{b}	0.34^{b}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
			Silicon			
control	6.1^{b}	4.3^{b}	2.9^{b}	2.2^{b}	0.33^{b}	0.33^{b}
Si	9.0^{a}	6.3^{a}	5.1^{a}	3.7^{a}	0.36^{a}	0.35^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
			Inoculation			
control	6.4^{b}	4.4^{b}	3.1^{b}	2.4^{b}	0.34^{b}	0.33^{b}
AMF	8.8^{a}	6.3^{a}	4.9^{a}	3.5^{a}	0.35^{a}	0.34^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= Experiment cycle.

The highest harvest index was observed on treatments supplied with silicon (0.36 t ha^{-1}, 0.35 t ha^{-1}) while the treatments without silicon had the lowest recording (0.33 t ha^{-1}, 0.33 t ha^{-1}) in cycle one and two as illustrated in Table 4.10. AMF inoculation significantly (p <0.001) affected all the variables. Highest stover yield 8.8 tha^{-1}, grain yield 4.9 t $ha^{-1}$and 0.35 harvest index were recorded in inoculated treatment in cycle one. However, the lowest grain yields 2.4 t ha^{-1}, stover yield 4.4 t $ha^{-1}$and harvest index 0.33 were recorded in treatments that were not inoculated in cycle two respectively (Table 4.10).

There was significant (p <0.001) interactive effects between varieties, water regimes, silicon amendment and AMF inoculant on the grain yield where Seredo variety under 40% water level amended with silicon and AMF resulted to highest stover weight (11.26 t ha^{-1}) and grain yield (8.40 t ha^{-1}) in cycle one, although the highest harvest index (0.42) was observed under Seredo interacting with 20% water regime in combination with silicon amendment and AMF inoculation as shown in Table 4.11. Machakos local red variety recorded the lowest stover yield (2.06 tha^{-1}) and grain yield (1.11 tha^{-1}) under 20% water field capacity without silicon amendment and AMF inoculation cycle two, while the lowest harvest index (0.25) was observed under the same interactive treatment but in cycle one (Table 4.11). Highest stover and grain yields and harvest index were recorded in Seredo variety than Machakos local red in both seasons (Table 4.10). This variation could be due to Seredo being an improved variety. Seredo variety gave the highest harvest index (Table 4.10) although it was shorter than

Machakos local red variety. The results corroborated with those of (Prihar and Stewart, 1991) who reported that the harvest index was independent of plant size.

Table 4.11: Interactive effects between sorghum varieties, water stress, AMF inoculation and silicon on plant Stover yield (tha^{-1}), grain yield (tha^{-1}) and harvest index

			Stover yield (t ha^{-1}**)**		**Grain yield (** t ha^{-1}**)**		**Harvest index**	
Variety	**Water regime (%)**	**Amendments**	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**
Srd	60	Si+AMF	10.77^{b}	7.17^{b}	6.23^{b}	4.97^{b}	0.37^{abcd}	0.41^{a}
	60	AMF	8.22^{fgh}	5.69^{fg}	4.64^{cdef}	3.85^{cd}	0.35^{abcd}	0.40^{a}
	60	Si	7.91^{ghi}	5.54^{fgh}	3.67^{efghij}	3.52^{de}	0.32^{cdef}	0.39^{abc}
	60	control	5.88^{lm}	3.98^{lm}	2.84^{ijklm}	2.22^{hijkl}	0.33^{bcdef}	0.36^{bcd}
	40	Si+AMF	11.26^{a}	8.87^{a}	8.40^{a}	6.36^{a}	0.36^{abcd}	0.41^{a}
	40	AMF	8.57^{efg}	6.39^{cde}	4.41^{cdefg}	4.42^{bc}	0.35^{abcde}	0.41^{a}
	40	Si	8.65^{defg}	6.25^{de}	5.10^{bcd}	2.91^{efgh}	0.34^{bcde}	0.41^{a}
	40	control	6.87^{ijkl}	4.29^{kl}	3.22^{hijkl}	2.41^{ghijk}	0.41^{ab}	0.39^{abc}
	20	Si+AMF	9.73^{bcd}	6.84^{bc}	5.50^{bc}	4.80^{b}	0.43^{a}	0.42^{a}
	20	AMF	7.24^{hij}	5.06^{hij}	3.54^{fghij}	2.66^{fghi}	0.32^{bcdef}	0.38^{abc}
	20	Si	7.57^{ghij}	4.72^{jk}	3.49^{fghij}	2.98^{fg}	0.31^{cdef}	0.34^{cde}
	20	control	2.77^{n}	2.62^{o}	2.07^{lmn}	1.89^{jklm}	0.30^{cdef}	0.35^{bcd}
Mlr	60	Si+AMF	9.50^{cde}	6.87^{bc}	5.56^{bc}	3.34^{def}	0.36^{abcd}	0.31^{defgh}
	60	AMF	7.76^{ghij}	5.34^{ghi}	3.75^{efghi}	2.05^{ijklm}	0.33^{bcdef}	0.27^{hi}
	60	Si	7.36^{hij}	5.04^{ij}	3.28^{ghijk}	1.78^{klmn}	0.34^{bcdef}	0.26^{i}
	60	control	6.07^{kl}	3.73^{m}	2.13^{klmn}	1.45^{mn}	0.27^{ef}	0.29^{fghi}
	40	Si+AMF	10.40^{abc}	7.10^{b}	6.19^{b}	3.62^{de}	0.37^{abc}	0.33^{defg}

	40	AMF	8.63^{efg}	5.97^{ef}	4.57^{cdef}	2.57^{ghij}	0.35^{abcde}	0.30^{efghi}
	40	Si	6.83^{ijkl}	5.64^{fg}	4.24^{defgh}	2.28^{ghijkl}	0.36^{abcd}	0.28^{ghi}
	40	control	4.96^{m}	3.22^{n}	1.87^{mn}	1.33^{mn}	0.32^{cdef}	0.31^{defgh}
	20	Si+AMF	9.02^{def}	6.56^{cd}	4.82^{cde}	4.58^{bc}	0.37^{abc}	0.33^{def}
	20	AMF	7.04^{ijk}	4.57^{jk}	2.86^{ijklm}	1.81^{klmn}	0.29^{def}	0.28^{ghi}
	20	Si	6.77^{jkl}	4.33^{kl}	2.51^{jklm}	$1.56l^{mn}$	0.27^{ef}	0.26^{i}
	20	control	2.23^{n}	2.06^{p}	1.19^{n}	1.11^{n}	0.25^{g}	0.27^{hi}
P-value	**V*Wr*A**		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; V= varieties, A= amendements, Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= Experiment cycle.

Water stress decreased the grain yields, above-ground biomass and harvest index (Etabo *et al.*, 2019). The harvest under 20% water field capacity was lower than the yield under 40% field water capacity which recorded the highest yield. This study agrees with the results of Cakir (2004) who reported that the occurrence of low soil moisture during development stages of corn may reduce final grain and above-ground biomass. Also, Moreira *et al.* (2018) reported that plants under water stress close their stomata to reduce water loss through transpiration, this causing restriction of carbon dioxide into the plant reducing photosynthesis performance hence low production. Low soil moisture can also attribute to chlorophyll degradation and reducing the rate of its synthesis thus reducing the performance of the crop up to the yield (Marenco and Lopes, 2005). Besides, the harvest index was low due to moisture stress. The results are similar to those of Wenzel and Van Rooyen, (2001) who reported that severe moisture stress resulted in an average yield loss of 44% thus affecting the harvest index and on average, resistant varieties to moisture stress and intermediately resistant varieties were reported to have been resistant to harvest index loss.

The study discovered that supplementation of soil with silicon ameliorates effects of drought stress in sorghum by significantly improving the growth and its productivity. Plants supplied with silicon and its interaction with the other factors (Seredo variety, water regime and AMF) had high grain and stover yield even under the lowest water level in the soil. These results concur with the report by Shen *et al.* (2010) that showed that silicon could alleviate soybean damage under low soil moisture due to increased chlorophyll contents and photosynthesis. Also, Fawaz *et al.* (2013) highlight that silicon helps in the maintenance of water status in water-stressed chickpea.

Zhang *et al.* (2017) also reported that silicon improves physiohormonal attribute of soybean that help in the mitigation of water stress as a result of improving the yield. Also, Emam *et a*l. (2014) studies have shown silicon amelioration potential in drought stress and its mechanism in the alleviation of low soil moisture that leads to high yield production. Furthermore Liu *et al*. (2015) study showed the ability of silicon to regulate aquaporins genes that are responsible for water uptake in sorghum under drought thus enhances water stress resistance. Silicon can also help in retaining water in plant tissues by reducing transpiration and partial blocking the transpiration bypass flow (Gunes *et al*. 2008) which improves water economy of plant and maintain an efficient absorption of mineral elements, therefore, improving yield.

Results on AMF inoculation and its interaction with the other factors (Seredo variety, Silicon amendment) revealed positive effects on the grain and stover yields. These positive effects were observed even under low soil moisture content. Stressed sorghum inoculated with AMF yielded more than the control. This could be because of the large volume of soil explored by roots and extraradical mycelia of AMF increasing plant tolerance to drought (Zhang *et al.*, 2016, Chelangat et al., 2021a,b)). Nevertheless, Yooyongwech *et al.* (2016) and Moradtalab *et al.* (2019) research showed evidence of AMF alleviating problems of low water to crops such as wheat, maize, onions, strawberry, barley and soybean. Physical, biological and chemical processes in plants like regulation of osmotic adjustment, ABA metabolism, enhanced accumulation of proline and increase glutathione level are known to be regulated by the mutual relationship between the host plants and mycorrhiza (Begum *et al.*, 2019) and consequently maintaining and improving water content in the soil hence high crop yield. As well, Le Pioufle and Declerck (2018) stated that AMF had the capability of address the issue of reduced crop production under water stress conditions.

4.3 Effects of varieties, water levels, silicon and arbuscular mycorrhiza fungi inoculation on sorghum nutrient uptake

4.3.1 Phosphorus uptake

On sorghum P uptake by the varieties, water levels, Silicon and AMF inoculation substantial differences ($p < 0.001$) was observed. Seredo variety resulted in the highest 111.1 kg ha^{-1} and 102.6 kg ha^{-1} phosphorus uptake per plant compared to Machakos local red in the two cycles respectively (Table 4.12). Water regimes significantly decreased P uptake by the sorghum in the two cycles whereas optimum P uptake 126.7 kg ha^{-1} was observed under 40% water level cycle one while the lowest was recorded under 20% water level cycle two. Arbuscular mycorrhiza inoculant significantly increased P uptake by the plant in both cycles as well as Silicon amendment compared to the control (Table 4.12). Interactive effects between varieties, water regimes, silicon and AMF on sorghum P uptake at maturity stage was significant ($p < 0.001$) in the two cycles (Figure 4.12a, b and c). Application of AMF and silicon amendments under 40% water level significantly increased uptake of P by the plant in both cycles (Figure 4.12b). High P uptake observed under AMF inoculation than silicon application indicated that AMF inoculant was more effective in improving P uptake than silicon supplementation. Seredo variety under 40% water level showed more response P uptake due to silicon and AMF amendments exhibiting high P uptake 59.1 kg ha^{-1} (Figure 4.12b) than Machakos local red 52.9 kg ha^{-1} in the cycle one.

Table 4.12: Mean phosphorus uptake by plant as affected by sorghum varieties, water levels, Silicon and AMF inoculation experimental cycle 1 and 2

P uptake (kg ha^{-1})		
Cycles	**C1**	**C2**
Variety		
Mlr	100.3^{b}	70.9^{b}
Srd	111.1^{a}	102.6^{a}
P-value	<0.001	<0.001
Water regimes (%)		
20Wr	84.7^{c}	76.9^{c}
60Wr	105.6^{b}	86.3^{b}
40Wr	126.7^{a}	97.2^{a}
P-value	<0.001	<0.001
Silicon		
control	80.1^{b}	68.4^{b}
Si	131.2^{a}	105.1^{a}
P-value	<0.001	<0.001
Inoculation		
control	63.0^{b}	55.6^{b}
AMF	148.3^{a}	117.9^{a}
P-value	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= Experiment cycle.

The superiority of Seredo variety in P uptake could be attributed to its better ability to be colonized by AMF which resulted in dense and prolific roots compared to Machakos local red. The study also showed that low water considerably, decreased P uptake by the plants. Its factual that water stress has been reported to decrease P concentration in plant this is as a result decreased P mobility due to reduction of soil pore diameter Celiktopuz *et al.* (2020). Correspondily, Hosseinzadeh and Ahmadpour (2018) study indicated that farmlands facing moisture stress generally had reduced levels of availabilty of nutrients such as N, P, Ca and K. Therefore Silicon supplementation and AMF inoculation led to better uptake of P reducing the injurious effects of the water stress. According to Hajiboland *et al.* (2018), most prominent synergistic effects of combined AMF and silicon application are higher root colonization and greater mycorrhizal effectiveness of silicon amended plants compared to plants without silicon amendments

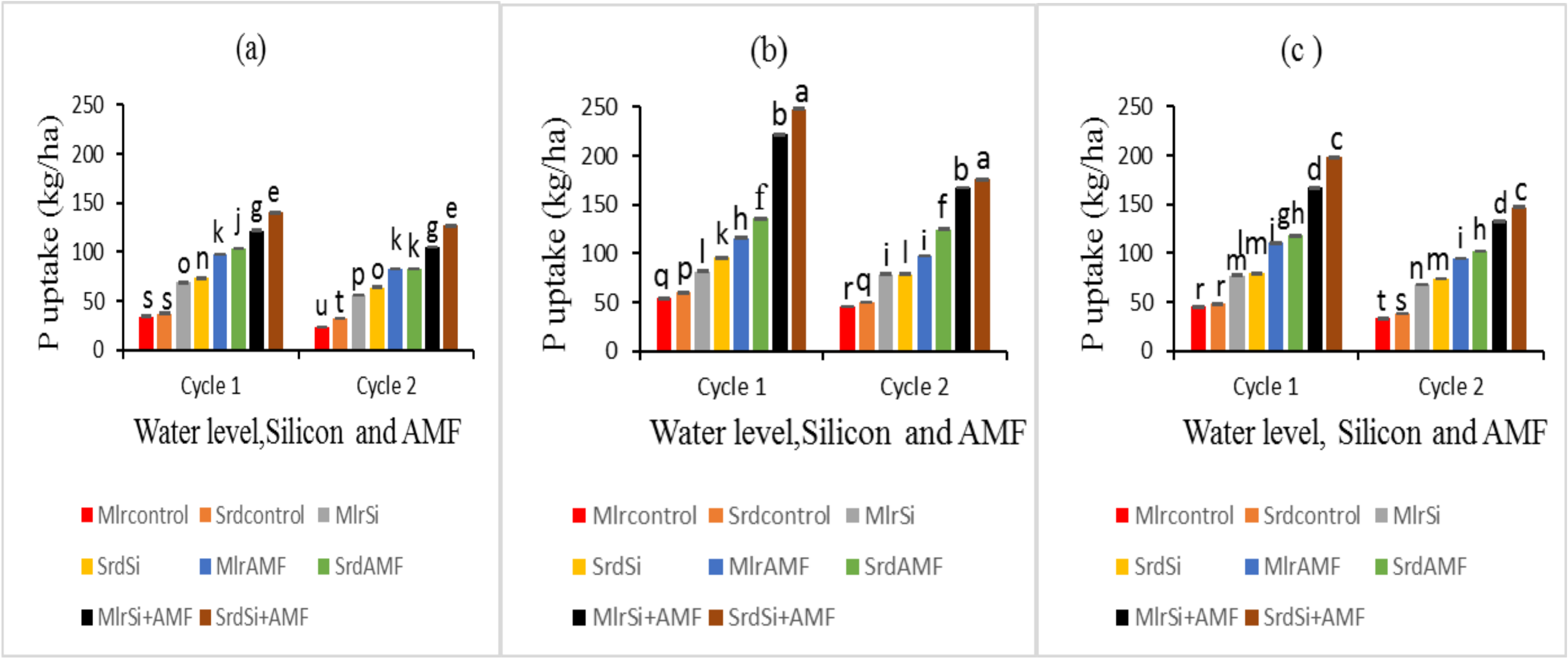


Figure 4.12a, b and c: Interactive effects between varieties, water levels, Silicon and AMF inoculant on sorghum phosphorus uptake cycle 1and 2

Srd= Seredo variety; Mlr= Machakos local red variety Si= With Silicon; AMF= With AMF inoculant; Wr= Water regime (20%, 40% and 60% field capacity); (a) =20%wr, (b) =40%wr and (c) = 60%wr

The findings of this study corraborate those obtained by Anda *et al*. (2016), who found that plants grown in Silicon and AMF ammendments had higher total P in shoots as well as roots. Results on AMF inoculation showed that inoculant had higher P uptake. This could be attributed to mycorrhiza extensive hyphae nertwork which explores more soil volume increasing P acquisition thus reducing P depletion in the rhizosphere (Garg and Pandey, 2015). Also, AMF produces arbuscules which assist in exchange of nutrients imparting a significant vigor to host plants (Li *et al.* 2016b; Prasad *et al.* 2017) thus considerably enhances P concentration in both shoots and roots (Al-Hmoud and Al-Momany, 2017).

It has been witnessed that AMF maintain P uptake at higher and lower P levels in soils with low moisture (Liu *et al.,* 2014; Liu *et al.*, 2018). This supports the results from this study that revealed that AMF was significantly effective on low soil moisture. For instance, AMF colonization increased concentration of P in *pelargonium graveolens* L (Amiri *et al.*, 2017) under drought conditions. Mbusango *et al*. (2019) indicated that, AMF inoculation increased P accumulation in deficieny water in the soil. In addition, according to Porcel *et al.* (2012) report, mycorrhiza assocition is known to increase host nutrient aquition particulary P uptake by the plants. Further, Helgason and Fitter, (2010) stated that acquirement of P through the symbiotic pathway down regulates direct P uptake by the plants. However, Abdel-Salam *et al. (*2018) reported that AMF performance depends on the uptake and transport of water for better uptake of nutrients especially P.

4.3.2 Nitrogen uptake

The amount of N accumulated by the sorghum exhibited significant variations ($p < 0.001$) due to varieties, water levels, silicon and AMF inoculant (Table 4.13). Highest N uptake of 34.7 kg ha^{-1} and 23.1 kg ha^{-1} was observed under Seredo variety in both cycles respectively compared to Machakos local red. Total above-ground N of sorghum under 20% water field capacity was the lowest 28.9 kg ha^{-1}, 17.9 kg ha^{-1} in the two cycles respectively. Maximum N uptake of 37.2 kg ha^{-1} cycle one was recorded under 40% water field capacity higher than that obtained at 60% water field capacity 33.2 kg ha^{-1}. Sorghum grown in soil amended with AMF and Silicon accumulated higher N levels than the controls that were significant at ($p < 0.001$) in the two cycles as shown in Table 4.13. There was significant ($p < 0.001$) interactive effects between varieties, water regimes, Silicon and AMF inoculant in Nitrogen accumulation by sorghum at maturity stage (Figure 4.13a, b and c). Application of 40% water field capacity and silicon in combination with AMF inoculum resulted to Seredo variety accumulating the greatest N 59.1 kg ha^{-1}, 05 45.9 kg ha^{-1} in above-ground biomass in the two cycles respectively.

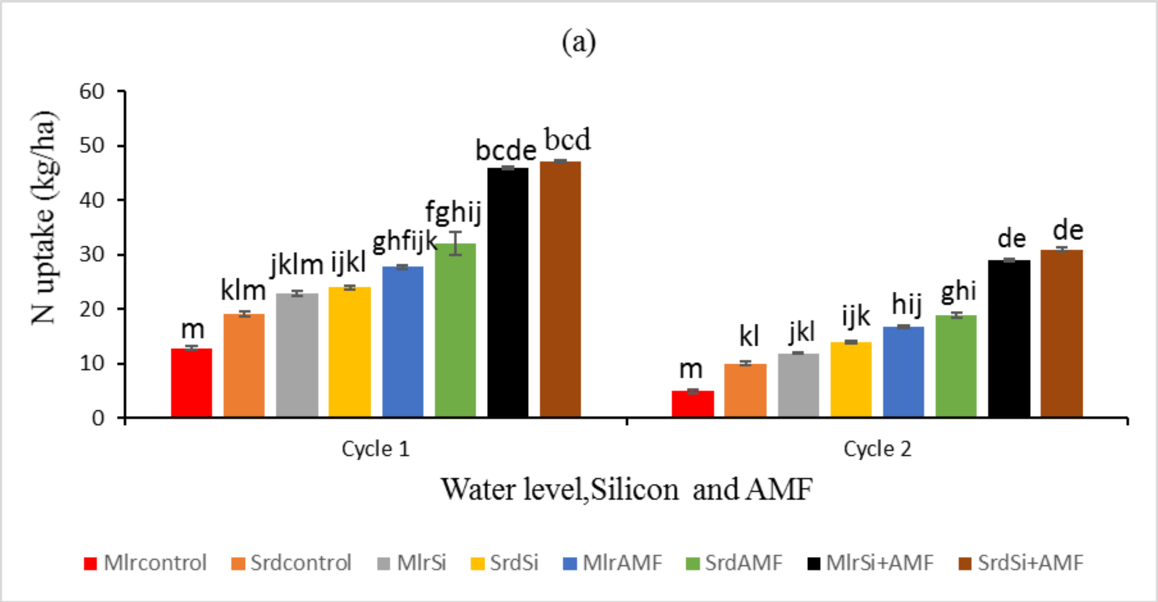
The results show that nitrogen uptake differed broadly among the varieties of the sorghum used. This shows that the varieties differed in their ability to utilize the amendments (silicon and AMF) supplied during the experiment and this is not only limited to sorghum but other crops (Ntinyari and Gweyi-Onyango, 2018; Njinju *et al.*, 2018; Gweyi Onyango 2006; Gweyi-Onyango *et al.*, 2021; Gweyi-Onyango *et al.*, 2010; Ochieng *et al.*, 2021). Sorghum grown under the lowest water level (20% water field capacity) had the lowest N uptake. This is in support of findings by Celiktopuz *et* *al.* (2020) who indicated that the occurrence of nitrogen deficiency is linked to water deficit in the soil. Additional, Tadayyon *et al.* (2018) described that availability of water increases absorption of micronutrients in the plant tissues due to accessibility of N in the soil.

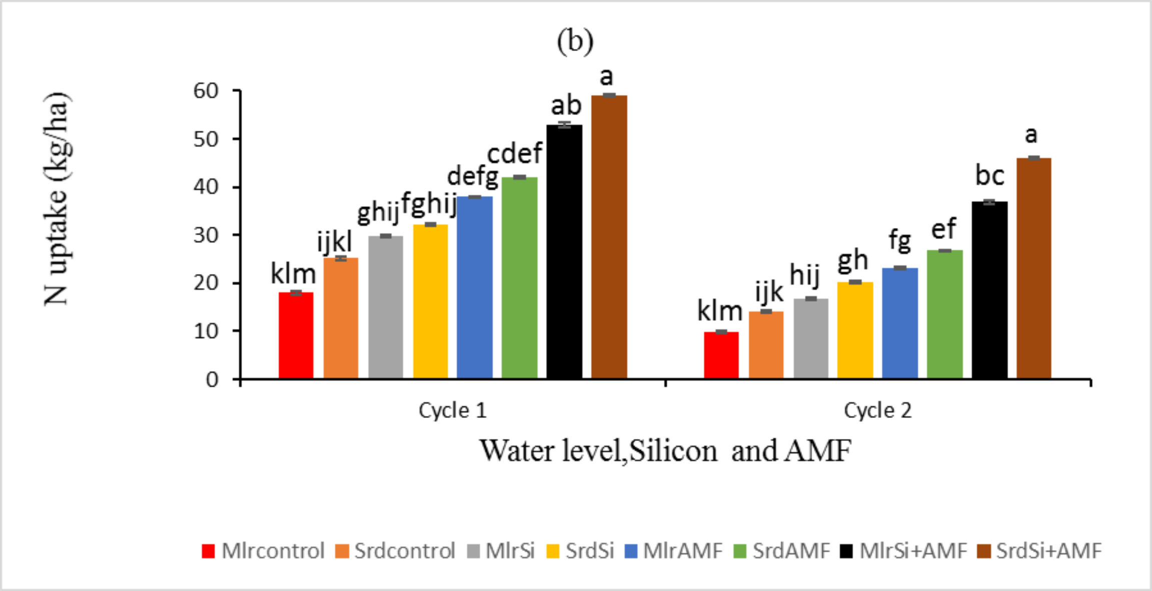
Table 4.13: Mean nitrogen uptake by plant as affected by sorghum varieties, water levels, Silicon and AMF inoculation experimental cycle 1 and 2

	N uptake (kg ha^{-1})	
Cycles	**C1**	**C2**
Variety		
Mlr	31.5^{b}	18.6^{b}
Srd	34.7^{a}	23.1^{a}
P-value	<0.001	<0.001
Water regimes (%)		
20Wr	28.9^{c}	17.9^{c}
60Wr	33.2^{b}	19.5^{b}
40Wr	37.2^{a}	25.0^{a}
P-value	<0.001	<0.001
Silicon		
Control	26.6^{b}	15.9^{b}
Si	39.7^{a}	25.7^{a}
P-value	<0.001	<0.001
Inoculation		
control	23.5^{b}	13.1^{b}
AMF	42.7^{a}	28.6^{a}
P-value	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= Experiment cycle.

The results also showed decrease in N accumulation with increasing water level (60% water field capacity). This is because of the nutrient dilution in the total dry matter which associated with the dilution factor (Faloye *et al.*, 2019; Gweyi-Onyango *et al.*, 2021). On the other hand, AMF inoculation stimulated N uptake in the two sorghum varieties irrespective of the water availability as shown in the study results (Table 13), such that low soil moisture reduced N uptake both in mycorrhizal and nonmycorrhizal plants. Furtheremore, the study showed that sorghum plants with high percentage colonization recorded considerably higher N uptake as equated to plants with less colonized roots both in water-stressed and well-watered conditions. This could be endorsed to a greater absorption of N provided by extensive fungal hyphae network as well as the improved root growth.


(a)
N uptake (kg/ha)
60
50
40
30
20
10
0
m
klm
jklm
ijkl
ghfijk
fghij
bcde
bcd
m
kl
jkl
ijk
hij
ghi
de
de
Cycle 1
Cycle 2
Water level,Silicon and AMF
Mlrcontrol
Srdcontrol
MlrSi
SrdSi
MlrAMF
SrdAMF
MlrSi+AMF
SrdSi+AMF


(b)
N uptake (kg/ha)
60
50
40
30
20
10
0
klm
ijkl
ghij
fghij
defg
cdef
ab
a
klm
ijk
hij
gh
fg
ef
bc
a
Cycle 1
Cycle 2
Water level,Silicon and AMF
Mlrcontrol
Srdcontrol
MlrSi
SrdSi
MlrAMF
SrdAMF
MlrSi+AMF
SrdSi+AMF

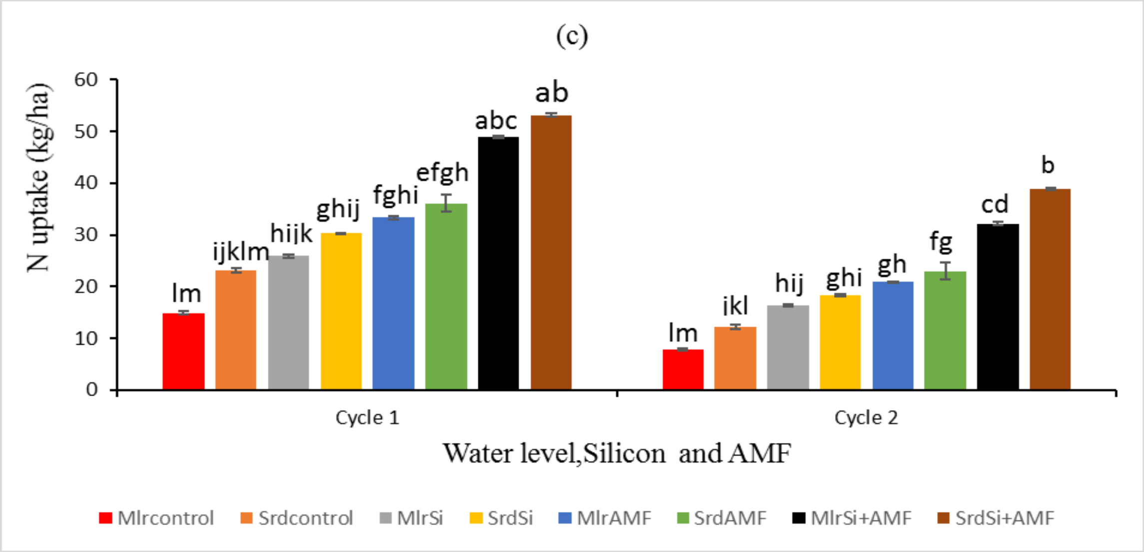


Figure 4.13a, b and c: Interactive effects between varieties, water levels, Silicon and AMF inoculant on sorghum nitrogen uptake cycle 1and 2

Srd= Seredo variety; Mlr= Machakos local red variety Si= With Silicon; AMF= With AMF inoculant; Wr =Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

The research byHodge and Fitter (2010) and Chelangat et al (2021a) also revealed that mycorrhiza can proliferate extra radical mycelia in the soil and obtain nitrogen from organic matter. Begum *et al.* (2019) and Turrini *et al.* (2018) studies have enlightened that AMF has the capability of absorbing and transferring N to the nearby host plants by use of extensive underground extraradical hyphae from the surrounding mycorrhizal sphere. Also, AM are known to have the ability to take N from dead and decomposed materials thus play a pivotal role in the N cycle (Hodge and Fitter, 2010). Moreover studies by Ahanger *et al.* (2014) informed that most of the total N uptake of AMF plants can be transferred by the AMF to their host. Studies by Begum *et al.* (2019) and Corrêa *et al.* (2015) also shows the improvement of N nutrition by AMF inoculation.

In this study,silicon amendments increased N uptake by the sorghum plant buttresing the observation by Neu *et al.* (2017) and Alsaeedi *et al.* (2019) who stated that treating wheat plants with silicon amendments boosted nitrogen use efficiency of the plant at all levels, AMF can also increase nitrogen and phosphorus uptake in drought conditions (Mbusango *et al.*, 2019). Synergistic effects of AMF with Si may be explained by Si-induced stimulation of root growth, which promoted the AMF colonization, and consequently increasing the beneficial effects of inoculated plants than non-inoculated plants. Similar results were obtained by Garg *et al.* (2020) who observed that Si and AM treatments improve the endogenous nutrients profile (K and N), growth characteristics and yield attributes under salinity stress.

4.3.3 Potassium uptake

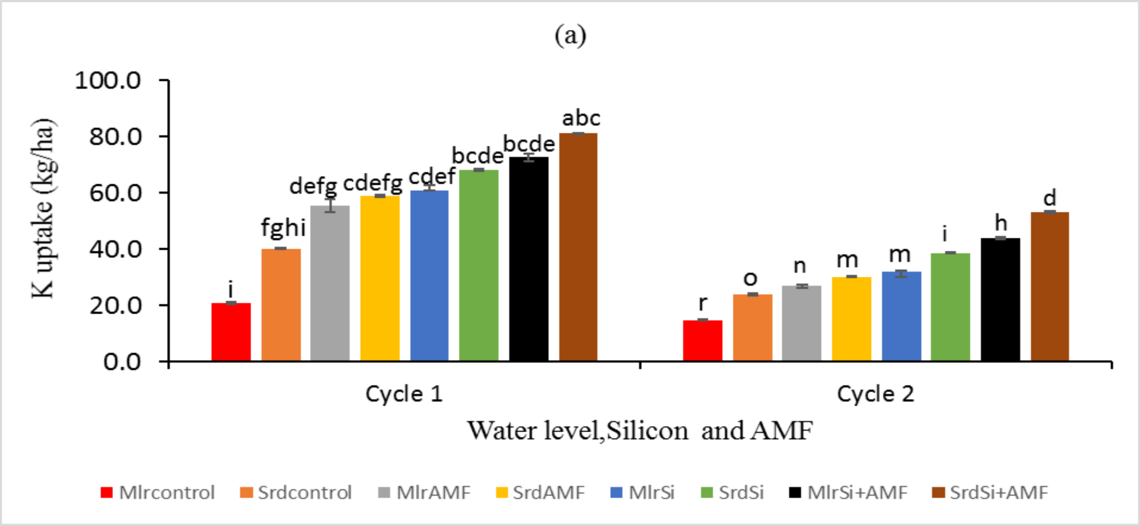
Results of the study indicate that there was variability in uptake the potassium by sorghum varieties grown in different water levels, Silicon and AMF inoculation. Significant differences ($p < 0.001$) were seen in the above-ground K accumulation between the varieties. Seredo variety had higher (69.7 kg ha^{-1} and 39.5 kg ha^{-1}) accumulation of K than Machakos local red variety which had (57.5 kg ha^{-1} and 35.4 kg ha^{-1}) in both cycles respectively (Table 4.14). The above ground, potassium uptake was also significantly ($p < 0.001$) influenced by the water levels with maximum K accumulation being noted under the 40% field capacity recording 69.79 kg ha^{-1} in cycle one while the lowest (57.26 kg ha^{-1}) was recorded under 20% water field capacity in cycle two. The results further revealed that application of silicon and AMF inoculation to sorghum significantly ($p < 0.001$) increased K uptake (Table 4.14).

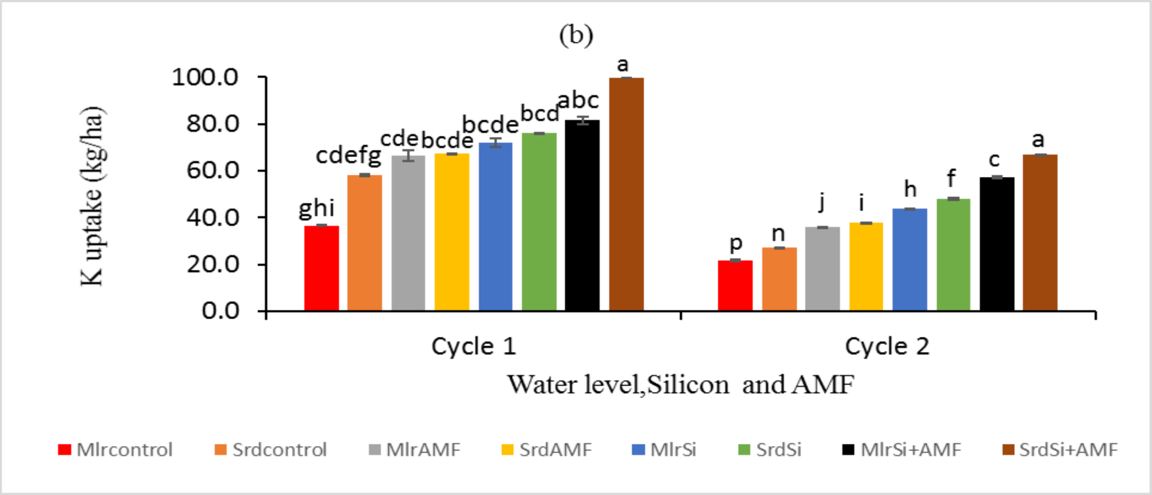
Table 4.14: Mean potassium uptake by plant as affected by sorghum varieties, water levels, Silicon and AMF inoculation experimental cycle 1 and 2

	K uptake (kg ha^{-1})	
Cycles	**C1**	**C2**
	Variety	
Mlr	57.5^{b}	35.4^{b}
Srd	69.7^{a}	39.5^{a}
P-value	<0.001	<0.001
	Water regimes (%)	
20Wr	57.26^{c}	33.2^{c}
60Wr	63.77^{b}	37.7^{b}
40Wr	69.79^{a}	41.6^{a}
P-value	<0.001	<0.001
	Silicon	
control	51.3^{b}	26.6^{b}
Si	75.8^{a}	48.4^{a}
P-value	<0.001	<0.001
	Inoculation	
control	53.4^{b}	31.3^{b}
AMF	73.7^{a}	43.6^{a}
P-value	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= Experiment cycle.

Significant interactions ($p<0.001$) between varieties, water levels, Silicon and AMF inoculation on the above-ground accumulation of K were noted with Seredo variety interacting with silicon and AMF under 40% water field capacity leading to the greatest (99.9 kg ha^{-1} and 66.9 kg ha^{-1}) of K uptake in cycle one and two respectively (Figure 4.14b).





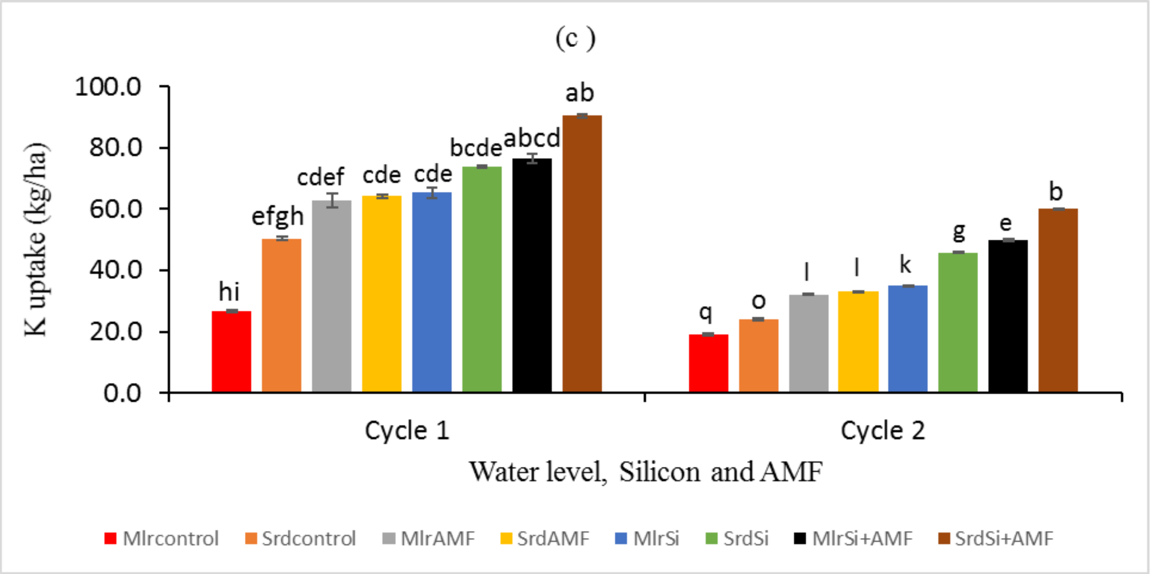


Figure 4.14a,b and c: Interactive effects between varieties, water levels, Silicon and AMF inoculant on sorghum potassium uptake cycle 1and 2

Srd= Seredo variety; Mlr= Machakos local red variety Si= With Silicon; AMF= With AMF inoculant; Wr =Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

Low K uptake in the above ground sorghum plants may be attributed to less soil moisture. (Hosseinzadeh and Ahmadpour (2018) underscored that low moisture reduces K solubility hence decreasing its absorption by plant roots. Additionally, Shabala and Pottosin (2014) reported that drought caused a reduction in the mobility of the K^+ in the soil and within the transporters in the root membrane. Although drought is known to increase the radial and axial hydraulic resistance of roots, which in turn reduces root hydraulic conductance thus affecting water transport leading to low nutrients absorption. Similarly Ibrahim *et al.* (2016), Elrys, Merwad (2017) and Markovich *et al.* (2017) results were in agreement with the results of this study.

Uptake and accumulation of K in the sorghum plant tissue increased with application of silicon as shown from this study results, agreeing with the findings of Kaya *et al*. (2006) and Dong *et al.* (2018) who report that application of silicon during previous water stress increased the K concentration in maize, and Alsaeedi *et al.* (2018) who revealed that silicon addition increased K uptake in cucumber, sugarcane and barley. Furthermore, Sudhakar *et al.* (2006) demonstrated that silicon enhances uptake of K. The results from this research reveal that silicon addition is more efficient in improving K uptake compared to inoculation of AMF. This could be attributed to the capacity of silicon to increase the activity of H+- ATPase which in turn accelerates cellular uptake of K by activating K+ channels and carriers across the plasma membrane (Liang *et al.*, 2006).

The AMF inoculated plants generally had higher above-ground biomass K compared to non-mycorrhizal plants. This could be attributed to enhanced K transporter activity within mycorrhizal plant's roots (Guether *et al.*, 2009; Berruti *et al.*, 2016). The enhanced accumulation of K might also be due to increased availability, transportation, absorption and translocation by AMF extraradical hyphae. Lehmann and Rillig (2015); Berruti *et al.* (2016) report also showed the importance of mycorrhiza symbiosis in absorption of various nutrients in crops. Results from a study by Asrar *et al*. (2012) stated that AMF association improved the contents of elements in the soil such as N, P, K, Ca and Mg in a crop of *Antirrhinum majus*. Application of both AMF and Si revealed increased uptake of K. Garg *et al.* (2020) designated that Si and AM treatments improve the nutrients profile (K and N), growth characteristics and yield attributes under salinity stress.

4.3.4 Calcium uptake

The findings of this study showed that calcium uptake by sorghum plant varied significantly ($p < 0.001$) between varieties, water levels, silicon and AMF innoculation (Table 4.15). Seredo variety recorded the maximum at (3296.0 kg ha^{-1} and 2652.0 kg ha^{-1}) Ca accumulations in the above-ground biomass in the two cycles compared to Machakos local red that recorded the lowest Ca uptake of (3131.0 kg ha^{-1} and 1925.0 kg ha^{-1}) in both cycles respectively. Drought stress had significant effects ($p < 0.001$) on Ca uptake since Calcium accumulation reduced as the water stress increased and was lowest in plants grown under 20% water field capacity.

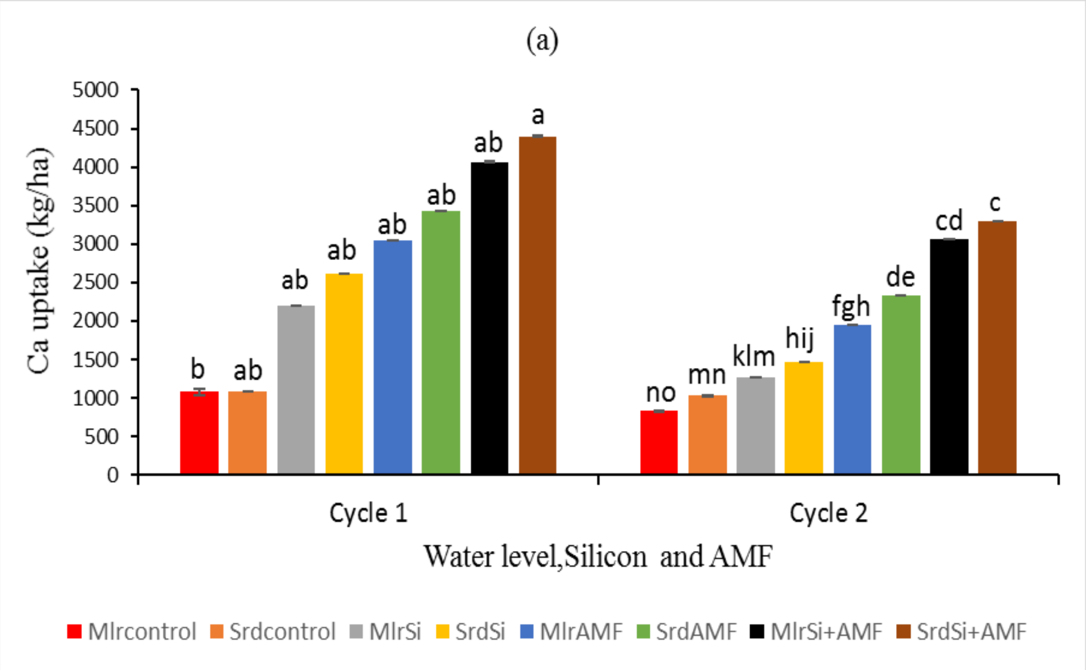
Significant differences ($p < 0.001$) were observed between plants obtained from silicon amended and non-amended soils. The greatest calcium accumulation (3589.0 kg ha^{-1}) was observed in sorghum grown with silicon in cycle one, while the lowest was observed under plants grown without Silicon amendment in cycle two. Results also revealed that AMF inoculation had significant ($p < 0.001$) impact on the Ca uptake by the sorghum plants (Table 4.15). AMF inoculated plants recorded greatest Ca uptake of 4049.0 kg ha^{-1} and 3114.0 kg ha^{-1} higher than the non-inoculated plants 2379.0 kg ha^{-1} and 1462.0 kg ha^{-1} in the two cycles respectively.

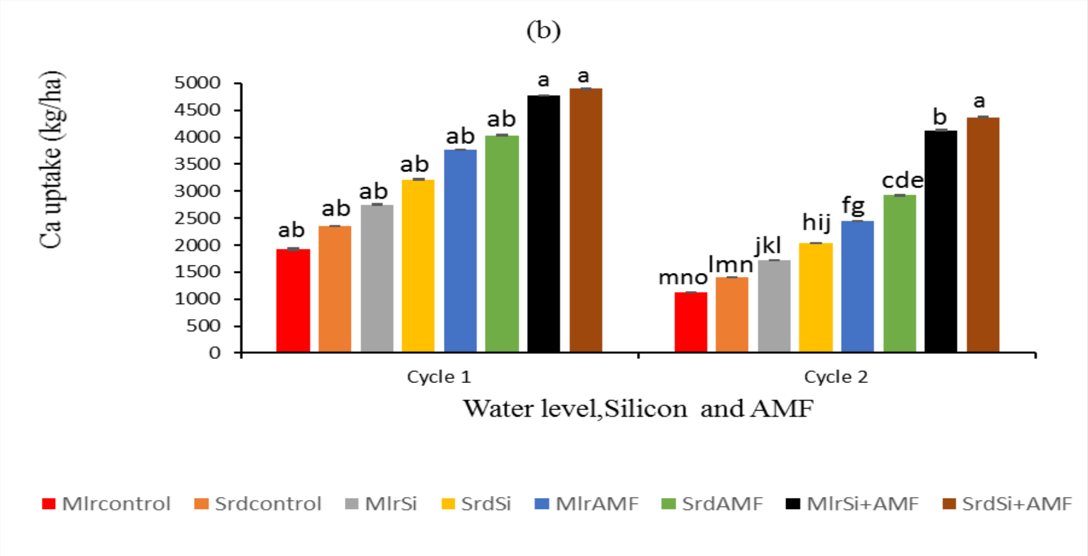
Table 4.15: Mean calcium uptake by plant as affected by sorghum varieties, water levels, Silicon and AMF inoculation experimental cycle 1 and 2

Ca uptake (kg ha^{-1})		
Cycles	**C1**	**C2**
Variety		
Mlr	3131.0^{b}	1925.0^{b}
Srd	3296.0^{a}	2652.0^{a}
P-value	<0.001	<0.001
Water regimes (%)		
20Wr	3006.0^{c}	2068.0^{c}
60Wr	3079.0^{b}	2253.0^{b}
40Wr	3466.0^{a}	2544.0^{a}
P-value	<0.001	<0.001
Silicon		
control	2839.0^{b}	1859.0^{b}
Si	3589.0^{a}	2718.0^{a}
P-value	<0.001	<0.001
Inoculation		
control	2379.0^{b}	1462.0^{b}
AMF	4049.0^{a}	3114.0^{a}
P-value	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= Experiment cycle.

The study results showed significant interactive dissimilarities ($p < 0.001$) between the varieties, water levels, Silicon and AMF inoculation on the plant Ca uptake (Figure 4.15a, b and c). The maximum Ca uptake at 4898.0 kg ha^{-1}was recorded in Seredo variety treated with Silicon and AMF inoculant and grown at 40% water field capacity in cycle one. This trend held in cycle two as shown in Figure 4.15b.





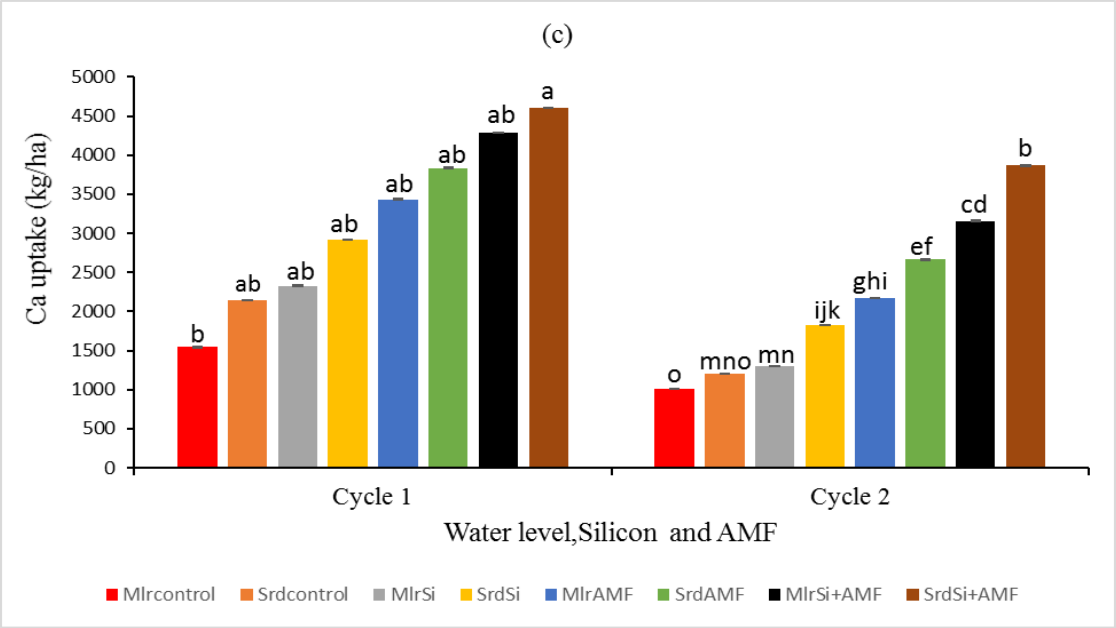


Figure 4.15a, b and c: Interactive effects between varieties, water levels, Silicon and AMF inoculant on sorghum calcium uptake cycle 1and 2

Srd= Seredo variety; Mlr= Machakos local red variety Si= With Silicon; AMF= With AMF inoculant; Wr =Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

The significant differences in the uptake of calcium by two sorghum varieties confirm presence of inherent genotypic differences affecting accumulation of the nutrient element. This is supported by Tadayyon *et al.* (2018) who indicated that calcium concentration in tomatoes varied with the cultivar. The results further indicate that decrease in soil moisture reduced the accumulation of Ca in above-ground biomass of the sorghum. Calcium ions are vital secondary messengers in the plants that are known to stimulate physiological functions in the cells of plants in response to water stress, and regulates the growth of the polar cells that help the plant in adaptation to stress

(Tadayyon *et al.,* 2018). The reduction in Ca uptake observed is consistent with the results by Celiktopuz *et al.* (2020) and Sardans *et al.* (2008) where low water in the soil led to decreased N, P, K, Ca and Mg concentration in strawberry. Plant' nutrients are transported from soil to the roots via diffusion thus low soil moisture reduces the absorption and uptake of nutrients (Mulyungi *et al*., 2019; Celiktopuz *et al.*. 2020). Moreover, the results from the study disagree with the findings of C Abdul Jaleel et al. (2007) where Ca concentration increased under water stress conditions.

Sorghum plants subjected to silicon had greater Ca uptake compared to the control on finding that concurs with Elrys and Merwad (2017), and Merwad, (2018) who reported that silicon amended plants had more Ca uptake than non-amended. The discoveries on AMF inoculation in this study are reinforced by earlier work by Begum *et al.* (2019) who indicate that AMF provides nutritional support to plants by developing symbiosis with the roots to obtain nutrients such as nitrogen, phosphorus ,potassium and calcium from the soil that are essential to plants development. Furthermore, AMF inoculation led to increased N, P and Ca in tomato crops (Begum *et al.,* 2019). Combined Si amendment and AMF inoculation enhanced Ca uptake in this study, and aspect which could be attributed to the fact that most the prominent synergistic effects of such a combination are higher root colonization and greater mycorrhizal effectiveness triggered by silicon (Hajiboland *et al.,* 2018).

4.3.5 Magnesium uptake

There were significant ($p < 0.001$) effects of varieties, water levels, Silicon and AMF inoculation on magnesium plant uptake both cycles as illustrated in Table 4.16.

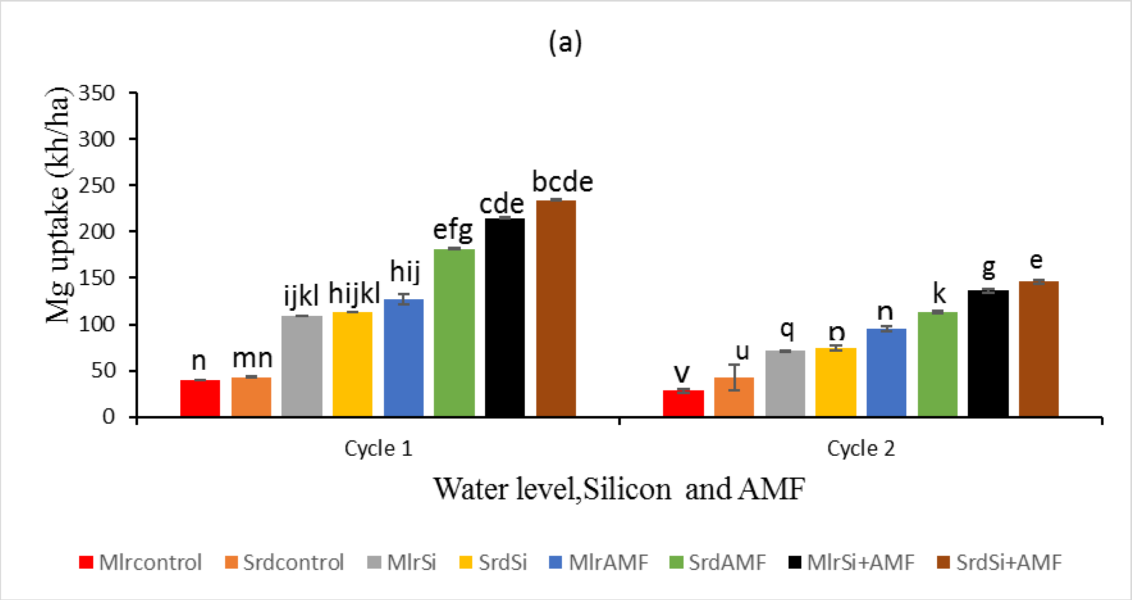
Maximum Mg uptake of 172.1 kg ha^{-1} was observed in Seredo sorghum in cycle one while the lowest uptake of 95.6 kg ha^{-1} was recorded in Machakos local red variety cycle two. Drought stress significantly affected Mg accumulation in the above-ground biomass (Table 4.16).

Table 4.16: Mean magnesium uptake by plant as affected by sorghum varieties, water levels, Silicon and AMF inoculation experimental cycle 1 and 2

	Mg uptake (kg ha^{-1})	
Cycles	**C1**	**C2**
	Variety	
Mlr	148.5^{b}	95.6^{b}
Srd	172.1^{a}	114.2^{a}
P-value	<0.001	<0.001
	Water regimes (%)	
20Wr	131.3^{c}	92.9^{c}
60Wr	165.4^{b}	102.0^{b}
40Wr	184.2^{a}	119.8^{a}
P-value	<0.001	<0.001
	Silicon	
control	123.6^{b}	86.3^{b}
Si	197.0^{a}	123.5^{a}
P-value	<0.001	<0.001
	Inoculation	
control	99.9^{b}	70.2^{b}
AMF	220.7^{a}	139.6^{a}
P-value	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr= Machakos local red sorghum variety; C= Experiment cycle.

Silicon amendment and AMF inoculation led to high uptake of Mg in the two growing cycles (Table 4.16). Based on the results of the study, there was a positive interaction between the varieties, water levels, Silicon and AMF inoculant on sorghum Mg uptake (Figure 4.16a, b and c) in the two cycles. The highest uptake of Mg (318.0 kg ha^{-1}, 206.1 kg ha^{-1}) was recorded in Seredo variety subjected to Silicon and AMF under 40% water field capacity in both cycles respectively.



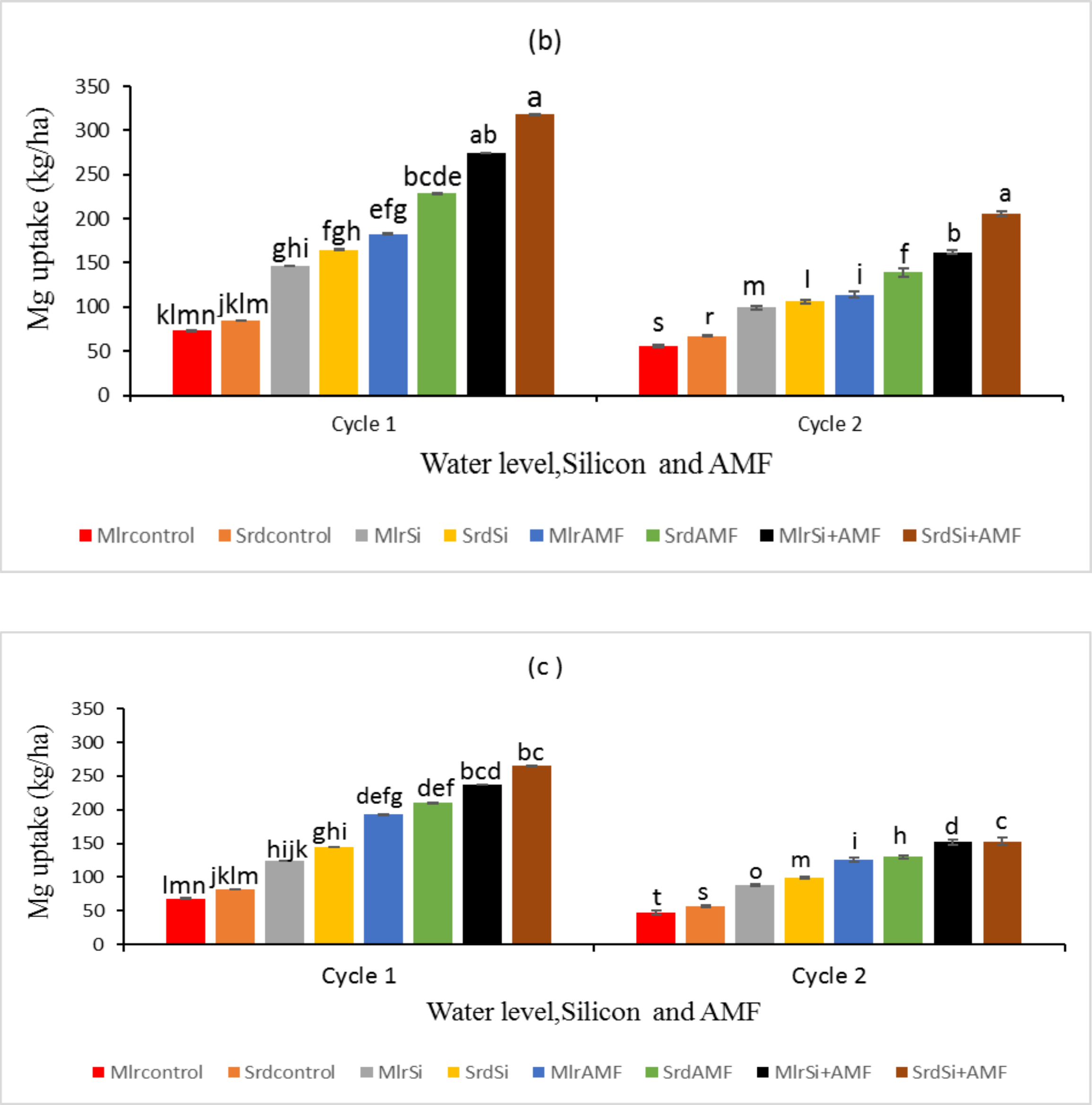


Figure 4.16a, b and c: Interactive effects between varieties, water levels, Silicon and AMF inoculant on sorghum magnesium uptake cycle 1and 2

Srd= Seredo variety; Mlr= Machakos local red variety Si= With Silicon; AMF= With AMF inoculant; Wr =Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

The sorghum plants displayed varietal differences in Mg absorption where Seredo recorded higher values than Machakos local red. A rise in water stress decreased Mg accumulation in the sorghum above-ground biomass a finding supported by Tadayyon *et al.* (2018) who reported that under drought stress Mg concentration in tomato plants tended to decrease. Additionally, Celiktopuz *et al*. (2020) underlined that the severity of drought stress reduced Mg concentration of plants while Moradtalab *et al.* (2019) indicated that low soil moisture negatively affects the nutritional status of the plants causing deficiencies in Zn, Mn, Cu and Fe.

Regarding the role of silicon, more Mg uptake was recorded with silicon addition to the plants. This observation is attributed to the finding that silicon affects the accessibility, absorption and translocation of nutrients from shoots to roots of plants (Greger *et al.*, 2018). Alsaeedi *et al.* (2018) and Neu *et al.* (2017) report indicate that silicon nutrition increased the uptake and translocation of Mg in plants. Similarly, mentioned that silicon improves absorption of nutrients by crops.

The application of the AMF inoculant led to an improved Mg uptake by both sorghum varieties where plants with higher root colonization by AMF were more efficient in the uptake of the Mg. Moradtalab *et al.* (2019) similary, found that highly colonized plants are more efficient in uptake and translocation of macro and micronutrients to the shoots of plants than less colonized. The findings are also in agreement with a study by Abdel-Salam *et al.* (2018) who show that inoculation of AMF led to an improved micronutrient status of plants and confirm that mycorrhizal plants absorb more N, P, Ca and Mg than nonmycorrhizal plants with the benefits of AMF being primarly attributed to increased uptake of nutrients such as N and P. Further synergistic effect of AMF and Si amendment was recorded where Seredo variety subjected to AMF and Si recorded higher Mg values in both cycles.

4.4 Arbuscular mycorrhiza fungi diversity

4.4.1 Arbuscular mycorrhiza fungi in experimental farm soil and trap culture

In this study, a total of 4 AMF genera (*Gigaspora*, *Scutellospora*, *Acuolospora and Glomus* spp) representing the family *Gigasporaceae*, *Acaulosporacea* and *Glomeraceae* were detected from both trap culture and initial farm soil as shown in (Plate 4.2).

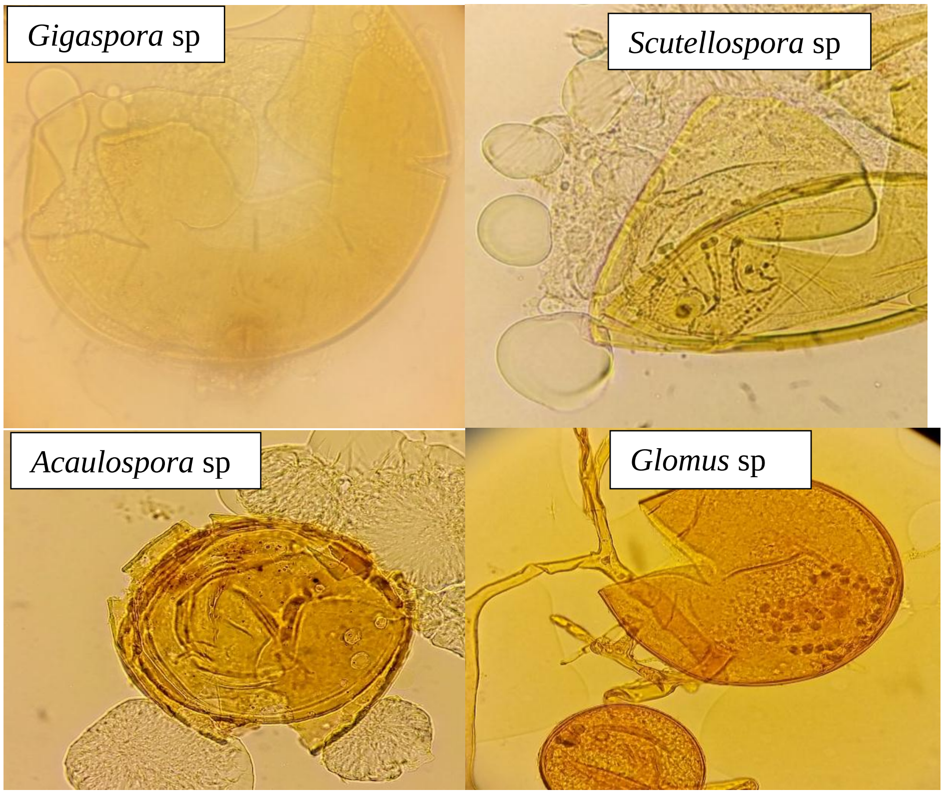


Plate 4.2: Arbuscular mycorrhiza spores from different genera

There were significant variations ($p < 0.001$) in the AMF spore diversity between the trap culture and farm soil (Table 4.17).

Table 4.17: Arbuscular mycorrhiza fungi community composition in farm soil and trap culture

AMF genera	***Glomus***	***Gigaspora***	***Scutellospora***	***Acaulospora***	
Treatments					**Spore density**
Experimental Soil	7.75^{c}	7.25^{b}	0.00^{b}	0.00^{b}	15.00^{c}
Machakos local red	11.50^{bc}	7.50^{b}	4.50^{b}	0.00^{b}	23.50^{bc}
Seredo	17.50^{ab}	15.25^{a}	0.00^{b}	0.00^{b}	32.75^{b}
Leek	23.00^{a}	7.00^{b}	15.75^{a}	11.75^{a}	57.50^{a}
P-value	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter are not significantly different at alpha=0.05.

The trap culture had the highest spore density 57.50 (leek), 32.75 (Seredo) and 23.50 (Machakos) compared to initial farm soil that detected a total of 15 spores. *Scutellospora sp* and *Acaulospora sp* were not present in the initial soil although they were detected in the trap cultures. Leek plants trapped more *Glomus* (23), *Scutellospora* (15.75) and *Acaulospora* (11.75) than sorghum varieties even though Seredo variety trapped most *Gigaspora* (15.25). The AMF fungi belonging to *Glomeraceae* family had a greater number of spores than other identified families where trap culture detected the highest number of spores 23.00 (Leek), 17.50 (Seredo) and 11.50 (Machakos) than the original soil (7.75) as revealed in Table 4.17.

The study demonstrated variation in plants used as AMF trap plants with leek trapping more AMF spores than the sorghum species. This suggested that there is selectivity between host plants and AM fungi. Similar results were reported by others (Liu and Wang;2003; Sakha *et al*., 2019) when they compared the appropriate host plants to use for trap culture of AMF. Besides Mohammad *et al*. (2003) and Picone, (2000) revealed that species diversity of AMF is determined by the natural ecosystems of plant species. Although they were not tested in this experiment Selvakumar *et al.* (2016) compared maize plant and Sudan grass as trap plants and found that maize was the most appropriate as a host crop for AMF reproductive structures dissemination and trapping than Sudan grass and that it can be used successfully to sustain the AMF culture for an extensive period. Furthermore, the study showed that leek and Machakos local red varieties trapped AMF species that were not detected in the initial farm soil. Such findings have been reported before by Schalamuk and Cabello (2010) who said that trap cultures are vital for unveiling fungal species that cannot be isolated during preliminary extraction of spores from field soils. The traps in the present study recorded more spores than initial soil agreeing with Schalamuk and Cabello (2010) who extracted more than ten AMF species in coleus and sorghum trap cultures that were not earlier existing in field soil from apple orchards.

4.4.2 Percentage abundance of AMF genus isolated from trap culture and original experimental farm soil

The findings of the study indicated that AMF genus *Glomus* and *Gigaspora* were the most prevalent in the farm soil with *Glomus* being slightly higher while *Acaulospora* was the least abundant (Figure 4.17). Leek crop was superior in the trapping of the spores where it was able to trap all genus (4) isolated in the experimental soil followed by sorghum variety Machakos local red with (3) whereas sorghum variety Seredo trapped only (2) genus.

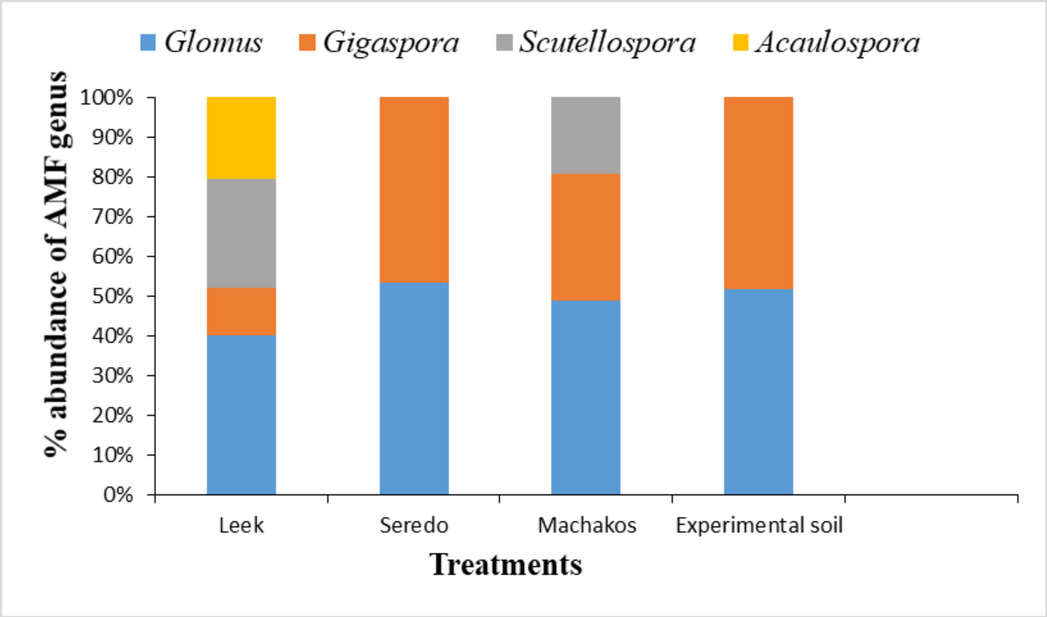


Figure 4.17: Percentage abundance of AMF genus per treatment

Prevalence of *Glomus* from the study shows that the genus was most widespread and abundant in the experiment site compared to other genera. Gai *et al.* (2006) also reported that *Glomus* is abundant in most of the agricultural soils of China and other countries worldwide. This genus may be considered as a generalist for most of the managed arable soils. Oehl *et al.* (2003) recorded *Glomus* also as generalist AMF which is consistent with the study findings. Similarly studies by Turrini *et al.* (2016) and Hontoria *et al.* (2019) specified that genera Glomus are genrally habitants of cultivated grounds. This is attributed to their better adaptation to tilled soils and also their high production of spores and mutual benefits by means of plant roots that allow faster reestablishment through myclia (Hontoria *et al.,* 2019). Also, this Genus is known to have greater survival under extremely oligotrophic conditions (de Araujo *et al.,* 2018). Furthermore, genus *Gigaspora* had more spore than *Acaulospora* and *Scutellospora*, these differential sporulation rates of the species could be due to the effects of the trap hosts. Jansa *et al*. (2002) found that *Gigaspora gigantea* produced larger amounts of spores. Although studies by Hart and Reader (2002) and Piotrowski *et al*. (2004) had revealed that *Gigasporaceae* family members produce fewer spores than those of the *Acaulosporaceae* family and are able to establish extensive hyphae in the soils.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The findings of the study showed that:

i. Silicon and AMF amendments enhanced AMF colonization intensity in sorghum plant under water stress. Water regime 40% was the optimum moisture for AMF sorghum root colonization.

ii. Silicon application and AMF inoculation improved growth and yield of sorghum, such that with 60% water regime give the maximum growth while 40% water regime recorded the highest Yield.

iii. Combined application of silicon and AMF increased N, P, K, Ca and Mg uptake by sorghum grown under water stress.

iv. The experimental soil had four AMF genus (*Gigaspora*, *Scutellospora*, *Acuolospora* and *Glomus* spp) belonging to AMF family (*Gigasporaceae*, *Acaulosporacea* and *Glomeraceae*) with *Glomus* and *Gigaspora* being more abundant. Futhermore, the study concluded that the soil native AMF diversity was very low, which could limit their association with plant.

5.2 Recommendations

The results from the study recommends:

i. Use of Si amendments and AMF inoculum as an alternative method of sorghum production to help in improved sorghum root percentage colonization.

ii. Combined application of AMF and silicon for improved sorghum growth and yield in low soil moisture. Consequently 60% water regime was the recommended for enhanced sorghum growth while 40% water regime was recommended for improved sorghum yields.

iii. Use of AMF and Silicon to increase nutrient uptake in sorghum crops grown under water stress. Accordingly 40% water regime was recommended for improved nutrient uptake by sorghum.

iv. The determination of native arbuscular mycorrhizal levels in the natural soil before inoculation and the use of more trap crops in establishing trap cultures.

5.3 Further studies

The study suggests further studies to be carried on:

i. Use of molecular techniques in AMF identification up to the species level. This is important because use of morphological identification of AMF spores is not sufficient to classify the fungal species in the ecosystem.

ii. To carry out the proper farming systems and soil fertility management practices that conserve can conserve the native AMF species. This is essential to shun eradication of these vital soil fertility improving organisms that support crop production.

iii. Determination of the right dosage of AMF inoculant and Silicon amendments for sorghum production.

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APPENDICES

APPENDIX 1: Interactive effects between Water levels, silicon and AMF inoculant on n number of tillers of sorghum in both experiment cycles.

			W 6		**Wk 9**		**Wk12**		**Wk 15**	
Variety	**Wr (%)**	**Amendments**	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**
Srd	60	Si+AMF	2.33ab	1.00ab	5.00a	2.66a	5.00a	4.66a	5.00a	4.66a
	60	AMF	2.00ab	0.66ab	4.00a	2.33a	4.00a	3.66a	4.00a	3.66a
	60	Si	1.66ab	0.33ab	4.00a	2.00a	4.00a	3.33a	4.00a	3.33a
	60	control	0.66ab	0.00b	2.66a	0.66a	2.66a	1.66a	2.66a	1.66a
	40	Si+AMF	2.00ab	0.66ab	4.00a	2.00a	4.00a	3.33a	4.00a	3.33a
	40	AMF	1.66ab	0.33ab	3.66a	1.66a	3.66a	3.00a	3.66a	3.00a
	40	Si	1.66ab	0.33ab	3.66a	1.66a	3.66a	3.00a	3.66a	3.00a
	40	control	0.33b	0.00b	2.66a	0.33a	2.66a	1.66a	2.66a	1.66a
	20	Si+AMF	1.33ab	0.33ab	3.33a	1.33a	3.33a	2.66a	3.33a	2.66a
	20	AMF	1.00ab	0.00b	2.66a	1.00a	2.66a	2.00a	2.66a	2.00a
	20	Si	1.00ab	0.00b	2.66a	0.66a	2.66a	2.00a	2.66a	2.00a
	20	control	0.33b	0.00b	2.33a	0.33a	2.33a	1.33a	2.33a	1.33a
Mlr	60	Si+AMF	2.66a	1.66a	6.00a	4.33a	6.00a	6.00a	6.00a	6.00a
	60	AMF	2.66a	1.33ab	6.00a	3.66a	6.00a	5.66a	6.00a	5.66a

	60	Si	2.66a	1.33ab	5.66a	3.33a	5.66a	5.00a	5.66a	5.00a
	60	control	1.33ab	0.00b	3.00a	1.33a	3.00a	2.66a	3.00a	2.66a
	40	Si+AMF	2.33ab	1.33ab	5.33a	3.33a	5.33a	4.66a	5.33a	4.66a
	40	AMF	2.33ab	1.00ab	4.66a	2.33a	4.66a	4.33a	4.66a	4.33a
	40	Si	2.00ab	0.66ab	4.66a	2.33a	4.66a	4.00a	4.66a	4.00a
	40	control	1.33ab	0.00b	3.00a	1.33a	3.00a	2.33a	3.00a	2.33a
	20	Si+AMF	2.00ab	0.66ab	4.33a	2.33a	4.33a	3.66a	4.33a	3.66a
	20	AMF	1.66ab	0.33ab	3.66a	1.33a	3.66a	3.00a	3.66a	3.00a
	20	Si	1.33ab	0.33ab	3.33a	1.33a	3.33a	2.66a	3.33a	2.66a
	20	control	1.00ab	0.00b	2.66a	1.00a	2.66a	2.33a	2.66a	2.33a
P-value	**V*Wr*A**		0.54	0.55	0.63	1.00	0.74	2.00	0.54	0.51

Means with the same letter are not significantly different at alpha=0.05. Si= With Silicon; AMF= With AMF inoculant; Wr=Water regime (20%, 40% and 60% field capacity); Srd= Seredo sorhugm variety; Mlr = Machakos local red sorghum variety; C= Experiment cycle.