INFLUENCE OF MICROBIAL INOCULANTS ON WATER USE EFFICIENCY AND YIELD IN A WATERMELON IN RAIN-FED CROPPING

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A RESEARCH DISSERTATION SUBMITTED TO DIRECTORATE OF RESEARCH AND GRADUATE TRAINING IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN SOIL SCIENCE OF KYAMBOGO UNIVERSITY

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DECLARATION

I Mpisa Isaac, hereby declare that this Dissertation is my original work and has never been submitted to any University for award of a degree, except where due reference has been indicated to such published work.

Signed……………………………………………………………………………………………..

Date………………………………………………………………………………………………

APPROVAL

This Dissertation entitled "Influence of microbial inoculants on water use efficiency and yield in a watermelon in rain fed cropping" has been submitted with our approval as University supervisors and confirms that the work done by the candidate under our supervision.

Signature……………………………….. Date……………………….

Dr. Robert Mulebeke

Signature……………………………….. Date……………………….

Mr. Julius Opio

DEDICATION

To the intellectual giants and my family who offered their shoulders to comfort me so that I could see this far.

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This achievement was built on the success of my academic supervisors: Dr. Mulebeke Robert and Mr. Opio Julius, academic advisors: Dr. Tinzaara William and laboratory technician Mr. Onyait Charles, Kyambogo University, I interfaced with during this academic journey. I do appreciate the exhibited profound intellect, devotion, and patience offered when guiding me through the research programme.

Further I do acknowledge the Opera Mini web-site, contributions from my family and patience rendered to me, and teamwork support from colleagues in the Department of Agriculture, Nkoma secondary school

Finally, lam conscious of the priceless time I denied my family especially my wife during the academic study.

May the lord God who has blessed me with this wisdom bless all of you.

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ABBREVIATIONS AND ACRONYMS

A	Total harvested area of watermelon
AMF	Arbuscular mycorrhizal fungi
B	Bacteria
D	Distance travelled by air bubbles in the capillary tube of the Potometer
Er	Rate of evaporation
ET	Evapotranspiration
G	Grammes
LA	Leaf area of watermelon plants
LAI	Leaf area index of watermelon plants
MM/DAY	Millimeters per day of water used by watermelon plants
PGPB	Plant growth promoting bacteria
PGPR	Plant growth promoting rhizobacteria
PGPB+AMF	Plant growth promoting bacteria plus Arbuscular mycorrhizal fungi

ABSTRACT

Smallholder rain fed systems in Uganda are often characterized by low productivity of watermelon crop caused by soil moisture deficits, leading to reduced water use efficiency and lower yields, which threaten food security and farmer's livelihood. The use of microbial inoculants like Plant Growth Promoting Rhizobacteria and *Arbuscular Mycorrhizal* Fungi could serve as a tool to improve crop tolerance to water stress. This study was set to determine the influence of microbial inoculants on Water Use Efficiency (WUE) and yield in a watermelon in rain-fed cropping. The study was laid out in a Randomized Complete Block Design (RCBD), with four factorial treatments; PGPR, AMF, PGPR+AMF and a Control, where no amendments were added. The experiment was conducted for two consecutive seasons (Aug-Dec/2022 and Marc-Jul/2023). Application of PGPR significantly ($P<0.001$) increased WUE compared to control. Also AMF significantly increased WUE. However, watermelon crops treated with combined (AMF& PGPR), recorded the highest mean WUE compared with plots treated with rhizobacteria and mycorrhizal fungi only. There are significant differences in the interactions between the season, soil moisture, WUE and PGPR treatments on yield of watermelon crop under rain fed conditions. However, watermelon crop plots treated with PGPR only, demonstrated the highest significant increase on watermelon mean yield compared to control, and plots treated with AMF only and combined (AMF+PGPR). For water use efficiency farmers are recommended to use a combined application of (AMF+PGPR.). Because their application produced the highest mean water use efficiency compared with watermelon plots treated with AMF and PGPR only. For yield, farmers are recommended to use PGPR inoculants at 10kgs per hectare. Because its treatment produced the highest mean yield of watermelon (fruit weight (tons/ha) compared with watermelon plots treated with AMF only and combined (AMF+PGPR). Further research should focus on investigating dosage rates of AMF which is most effective in rain fed watermelon conditions in Uganda.

CHAPTER ONE: INTRODUCTION

1.1 Background

Rain-fed Watermelon production is susceptible to soil moisture deficits, which negatively impacts water use efficiency and yield, that threaten food security and smallholder farmer's livelihoods. (Erdem et al., 2003, Harrod, 2023).

Use of microbial inoculants can help farmers adapt to the impacts of climate change, can improve soil health, offer a more sustainable approach to watermelon production by reducing reliance on synthetic inputs and help farmers get more watermelon yields from less water, making farming more resilient to soil moisture deficits and more profitable". Several microbial inoculants have been reported to improve water use efficiency and yield under soil moisture deficit conditions (Kumar and Verma, 2018). These microorganisms inhabit the rhizosphere and make an optimal use of their biological processes to support soil fertility, plant growth, water use efficiency and yield in soil moisture deficit environment (Khan et al., 2018).

Plant Growth Promoting Rhizobacteria, improves the physical. Chemical and biological soil properties (Estesami, 2023, Duran, Yavuz. 2023), that promotes rapid root growth and branching of the shoot enhancing nutrient, water use uptake and yield (Jinal & Amaresan et al., 2020). This physiological health's facilitate nutrient uptake, water absorption and yield (Kumar & Verma, 2018, Joshi et al., 2020).

While *Arbuscular Mycorrhizal* Fungi, forms natural root symbioses that provide essential nutrients, hence improving water use efficiency and yield (Huang, 2021, Diagne, 2020, Mohammed, 2023, Barros et al., 2018, Begum, 2019). Emerging evidence indicates that the combined application of AMF+PGPR could be more beneficial than individual strains to improve soil moisture deficit tolerance in plants (Berg & Kavadia et al., 2020).

Watermelon cropping system; Watermelon (Citrullus lanatus) is a flowering plant of a cucurbitaceae family, species: C lanatus, genus: citrullus, and kingdom: plantae (Nadeem, 2022, Tegen. 2024). Watermelon farming plays vital roles in the lives of small holder farmers. Economically, to some famers this serves as a major income source. Also the crop has improved health benefits such as lowering blood pressure and cholesterol levels as well as preventing inflammations (Kerry, 2023, Tegen. 2024). Watermelon is sensitive to soil moisture, humidity, and temperatures. Much as watermelon is a high value commercial crop, it's mainly grown under rain fed conditions. Most farmers in Uganda are known to grow the crop in-between rain seasons, when moisture is moderate and temperatures are high but, often loose due to fluctuation in the seasonal climate parameters. While chemical fertilizers have traditionally been used, they create environmental risks, creating a critical need for sustainable alternatives like microbial inoculants that can enhance watermelon resilience to water stress in rain-fed farming (Bacchus and Muir, 2020).

1.2 Statement of the problem

Rain-fed watermelon production is severely impacted by Soil moisture deficits, leading to reduced water use efficiency and lower crop yields, which threaten food security and farmer's livelihood in Uganda. (Erdem et al., 2003, Harrod, 2023)

Microbial inoculants like Plant Growth Promoting Rhizobacteria and *Arbuscular Mycorrhizal* Fungi have the potential to enhance soil health and water uptake, potentially leading to improved Water Use Efficiency and Yield in rain fed watermelon cultivation (Kumar & Verma, 2018, Joshi et al., 2020, Khan et al., 2018, Shanwei, Shi, Chen, Gao & Wang, 2022)

While chemical fertilizers have traditionally been used, they create environmental risks, creating a critical need for sustainable alternatives like microbial inoculants that can enhance watermelon resilience to water stress in rain-fed farming (Bacchus and Muir, 2020). The study addressed this gap by evaluating the effectiveness of *Arbuscular Mycorrrhizal* Fungi and Plant Growth Promoting Rhizobacteria in improving water use efficiency and increasing watermelon yield in a rain-fed system in Uganda.

1.3 Research objectives

1.3.1 General objective

The general objective of the study was to assess the influence of microbial inoculants on water use efficiency and yield in a watermelon crop.

1.3.2 Specific objectives

The specific objectives of the study were:

i. To determine the effect of plant growth promoting Rhizobacteria on water use efficiency in a watermelon crop.
ii. To examine the effect of *Arbuscular Mycorrhizal* fungi on water use efficiency in a watermelon crop.
iii. To measure the effect of *Arbuscular Mycorrrhizal* Fungi and Plant Growth Promoting Rhizobacteria on yield of watermelon crop.

1.4 Research hypotheses

i. 'Water use efficiency in watermelon crops was significantly different between treatments with and without Plant growth promoting Rhizobacteria application".
ii. '*Arbuscular Mycorrhizal* fungi application significantly increased water use efficiency of watermelon crops".
iii. '*Arbuscular Mycorrhizal* Fungi and Plant Growth Promoting Rhizobacteria significantly increased yield of watermelon crops".

1.5 Significance of the study

The study was carried out to determine the influence of microbial inoculants on water use efficiency and yield in a watermelon crop. Utilization of microbial inoculants would offer significant benefits for Ugandan farmers by enhancing watermelon crop yields, improving soil health, and reducing reliance on chemicals, ultimately contributing to food security and sustainable agriculture. These living microorganisms, when applied to soil or plants, can promote watermelon plant growth, fix nitrogen, and improve nutrient availability, leading to healthier crops and more resilient farming systems. This knowledge empowers farmers to adopt eco-friendly practices, improve their livelihoods, and make informed decisions about watermelon farming practices, fostering a more sustainable and resilient agricultural system

1.6 The scope of the study

The study focused on assessing the influence of microbial inoculants on WUE and yield in a watermelon in rain fed cropping. Watermelon (Sugar baby variety), was coated with PGPR 10kgs/ha or 5litres/ha (agritech.tnall.ac.in), and for AMF inoculum 30kgs/ha were placed directly to the seeds at planting (Shanwei, Shi, Chem, & Gao, 2022). A randomized complete block design, with 4 factorial arrangement treatments (PGPR, AMF, PGPR+AMF and control), in which each replicated 4times at spacing of 2m between blocks to avoid bias between the treatments during data collection. The major objective was to measure the influence of AMF and PGPR on water-related parameters (evaporation rate, transpiration rate, and WUE), and watermelon plant growth parameters (leaf area index and yield in fruit weight (tons/ha). Analyzing soil properties (soil moisture content (%) using gravimetric method by (Aqua-Crop model, 2023)., and the interactions between the season and microbial treatments on WUE and yield under rain fed watermelon conditions. The study was conducted for 2seasons (Aughust-Dec 2022, and March-July 2023) at the farm of Kyambogo University”

CHAPTER TWO: LITERATURE REVIEW

2.1 Watermelon crop

Watermelon (*Citrullus lanatus*) is a globally important cucurbit crop, frequently cultivated under rain fed conditions. While watermelon generally thrives in warm, dry climates, its success in rain fed systems is highly dependent on rainfall patterns. Watermelon's adaptability to various tropical and subtropical regions of Africa, coupled with low water requirements, makes it a potential commercial crop, especially in the face of climate change.

However, challenges like soil moisture deficits and inconsistent rainfall, results in low watermelon productivity. Addressing the challenges through focused research, can unlock the crop's potential contributing to food security and economic benefits (Tegen. 2024).

2.2 Plant growth promoting bacteria on water use efficiency in a watermelon crop

Water use efficiency (WUE) is a concept introduced 100 years ago (Briggs & Shantz. 1913) showing a relationship between plant productivity and water use. They introduced WUE as a measure of the amount of biomass/yield per unit of water used by plant. Watermelon crops subjected to Soil moisture deficits show significant varying responses in WUE under rain-fed agricultural farming systems.

Microbial inoculants like Plant Growth Promoting Rhizobacteria (PGPR) have the potential to enhance soil health and water uptake, potentially leading to improved WUE and yield in rain fed watermelon cultivation (Kumar & Verma, 2018, Joshi et al., 2020).

Studies have shown that PGPR colonize the watermelon plant roots (Tiepo et al., 2018, Ngoma & Babalola, 2012, Sandhya & Grover, 2009, Kohler& Hernandez, 2008, Mayak & Glick, 2004 Naveed, Farooqi & Rehman, 2014, Akhtar et al., 2022, Mohanty, Singh, Chakraborty, and Mishra et al., 2021). Can improve the watermelon root architecture under water stress conditions, demonstrating their potential to enhance root growth, WUE, and nutrient uptake (Ganesh. 2024 & Xuan. 2024, Cybulska & Drobek, 2019, Yavuz, 2023/2022 & 2025). This helps improve the physical, chemical, and biological characteristics of soils by promoting nutrient uptake and water flow (Estesami, 2023, Duran, Yavuz. 2023).

However, some studies showed that rhizobia have indirect positive effects on watermelon plant growth and potentially improve WUE through various mechanisms which include; osmotic adjustment, antioxidant enzyme enhancement and hormonal regulation (Haiying, Hassan, Feng, Liu 2022, Yavuz, 2023/2022 & 2025). Transforming organic matter into usable nutrients that enhance water uptake (Ahemad, 2012, Ahmad, Fiaz, Hafeez, Wang. 2021). Regulated by transpiration pull and stomata conductance, which facilitate water use efficiency of watermelon plants under water deficit stress (Yavuz, Seymen. 2024, Vejan & Abdullah, 2016).

Some research indicated that PGPR can decrease stomata density while increasing guard cell length, potentially leading to more efficient stomata regulation. This can be achieved by performing many ecosystem services including improved recycling of soil nutrients and water (Pathania, 2020, Faten, 2023). Which accelerate plant growth and improve the efficiency of water use (Nurgul & Metin, 2017).

Plant growth promoting bacteria like Azospirillum brasilensesp increase water content and water potential a key physiological parameter in watermelon (Role & Roldan, 2014, Vigani et al., 2019, Arzanesh & Khavazi, 2011 Chen et al., 2017 Gusain & Sharma, 2015 Shukla et al., 2012 Standiger et al., 2016). positively influenced by vegetative parameters and biochemical traits (such as solute concentrations within watermelon plant cells) of inoculated plants which improve water and nutrient uptake (Asthir & Kaur, 2017 Hussain & Zahir, 2014 Barbour et al., 2012 Chu & Shao, 2009 Asaf & Khan, 2017). Promoting root system which improves root development plant's ability to uptake water (Vigani et al., 2019 Everlon et al., 2020 Vitale, 2023) by slowing down evaporation from soil in watermelon garden (Harsh et al., 2018).

In summary, while the benefits of Plant Growth Promoting Rhizobacteria are evident, the exact mechanisms by which they improve water use efficiency under rain fed conditions can be complex and vary depending on the specific Rhizobia strains, watermelon plant species and environmental conditions. Further research is needed to fully elucidate interactions between Rhizobia, soil moisture levels, micro/macro-nutrients and watermelon plants particularly under the variable conditions of rain fed Agriculture (Pereira eta l., 2019, Maria, Diaz, Isela, Cota & Luis, 2024, Omirou, Loannides, & Ehaliotis, 2013, Miceli & Vetrano, 2023).

2.3 Arbuscular mycorrhizal fungi on water use efficiency in a watermelon crop

Rain fed agriculture, where watermelon crops rely solely on rain fall, is particularly susceptible to water stress.

Arbuscular Mycorrhizal Fungi can be a valuable tool in rain fed agriculture, helping watermelon plants with drought conditions and improving their overall productivity (Hyjazie & Sargent, 2024, Barber & Soper Gorden, 2015, Kaya, David Higgs, Halil Kimak, 2003, Gong et al., 2013, Huang, 2021).

Studies have shown that *Arbuscular mycorrhizal* fungi form a symbiotic relationship with watermelon plant roots (Huang, 2021 Diagne, 2020, Mohammed, 2023, Barros et al., 2018). This symbiotic relationships between watermelon and the fungi, is achieved by AMF that colonize watermelon roots forming arbuscules and hyphae structures (Howard& Mishra, 2018). These arbuscules are specialized structures within root cells that facilitate the transfer of nutrients and water from the soil to the watermelon plants. While the network hyphae are the fungal filaments that extend the watermelon root systems reach into the soil, increasing the surface area for nutrient and water uptake (Diagne et al., 2020 Garg & Cheema, 2021, Wahab. 2023, Murad Muhammad, 2023, Chandni Khizar, 2023). The increased water uptake facilitated by the hyphae can help mitigate the effects of water stress on the watermelon crop (Kinhal, 2023, Howard & Mishra, 218, Backer, 2018, Bosell & Davidson, 2012, Gacia et al., 2000, Tlalka et al., 2003, Nair et al., 2013, Abdulhadi & Alwan, 2020, Gideon Ufoegbune, Fadipe, Bello, 2014,George, 2023, Hashem, 2018 Begum, 2019, Haiying&Nawaz, 2022, Ouledali et al. 2018).

In the context of Backer (2018), stated that further research is needed to pinpoint specific cellular and physiological mechanisms that contribute to the observed improvements in WUE. Understanding these mechanisms could lead to more targeted applications of AMF in rain fed watermelon production, optimizing water management strategies and improving watermelon crop resilience in water limited environments.

According to Pozo et al. (2015), stated that *Arbuscular mycorrhizal* fungi cause watermelon plants to produce stomata closure and raise their Abscisic Acid (ABA) levels, which reduces water loss by lowering evaporation rates from the soil (Xie et al., 2018, Bahadur et al., 2019, Mohanta et al., 2017, Egamberdieva et al., 2018).

Promoting water uptake and transpiration in the host watermelon plants (Backer, 2018, Quiroga et al., 2019, Ortas et al., 2021), that enhance WUE (Quiroga et al., 2019, Huang et al., 2020), Bahadur et al. (2019), Hamedani et al. (2022), and Santander et al. (2017).

Arbuscular mycorrhizal fungi increase the stability and water-holding capacity of soil under moisture deficit (Gupta, 2020), that improve watermelon plant root growth which facilitate water uptake (Hashem et al., 2018). By producing glomalin secretions which facilitate nutrients and water uptake leading to increase in water use efficiency (Gong et al., 2012). Maintain water supply to watermelon plants from dry soils (Abdallah, 2023, Birhane et al., 2012). That enhance water status of host watermelon plants (Askari et al., 2019, Hijri, 2016). By preserving the osmotic equilibrium of the host watermelon plants (Ruiz, 2003, Porcel et al., 2006, Malfanova et al. 2011, Oruru & Njeru, 2016).

According to Auge et al. (2008), AMF association increases root hydraulic conductivity, which enhances water intake and sustains a higher plant water status. Their ability to enhance nutrient uptake, improve stress tolerance, and promote soil health makes them a valuable tool for sustainable watermelon production.

In summary, while the benefits of *Arbuscular Mycorrhizal* Fungi are evident, there is lack of information on optimal application rates recommended for watermelon crops under rain fed conditions. Further research should focus on investigating the above under the variable conditions of rain fed Agriculture (Pereira et al., 2019, Maria, Diaz, Isela, Cota & Luis, 2024, Omirou, Loannides, & Ehaliotis, 2013, Miceli & Vetrano, 2023).

2.4 Arbuscular mycorrhizal fungi and Plant growth promoting bacteria on yield of watermelon crop

Crop yield is a measurement of the amount of agricultural production harvested per unit area of land in tons per hectare. Recommended Yield of watermelon under optimum condition is (50-80ton/ha or 25-30ton/acre) (Scott, 2020, Begum, 2019). However, soil moisture deficits affect farmers' ability to achieve desired yields of watermelon.

Arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria has been shown to significantly enhance crop yields including watermelon, particularly under rain fed conditions

(Shanwei, Shi, Chen, Gao, & Wang, 2022). These beneficial microorganisms improve plant growth, nutrient uptake and stress tolerance contributing to more sustainable watermelon farming (Shanwei, Shi, Chen, Gao, & Wang, 2022).

Studies have shown that microbial inoculations form symbiotic relationships with watermelon plant roots, enhancing nutrient availability and promoting plant health.(Qiao, et al., 2024, Asma et al., 2023, Carfagna &Palumbo, 2020, Romano, 2020, Wang, Sun, Harman, 2019, Howard & Mishra, 2018, Fiorilli et al., 2018, Li et al., 2016, Jacoby et al., 2017, Abdul, 2023, Buczkowska &Salata, 2020, Masoero& Volpato, 2020, Baguaraj &Sridhar, 2022, Babalola & Igiehon, 2021). Some researchers have also shown that AMF, in particular, can enhance a watermelon plant's ability to absorb water and nutrients leading to improved WUE, especially under drought conditions (Mulyadi, 2023, Bernaola & Stout, 2020, Fiorilli et al., 2018, Celebi et al.(2010), Ruiz et al.(2010), Oziem Cakmakci, Talip Cakanakci, Enre Demirer Durak, Suat Sensory, 2017).

This can be achieved through forming extensive network of hyphae that extend into the soil improving access to phosphorus and water. Promoting increased growth and yield of watermelon plants (Mulyadi, 2023, Bernaola & Stout, 2020, Rezaie et al., 2020, Sharma et al., 2019, Fiorilli et al., 2018, Espidkar et al., 2017, Celebi et al.(2010), Ruiz et al.(2010), Abdelliah, Rahou, Abderrahim, Wahbi, 2021, Wu, Shi, Chen, Gao, Wang, 2022, Hijri et al., 2016, Sabia et al., 2015, Lu et al., 2015, Flores et al., 2010, Proietti et al., 2008).

Through improving physiological and photosynthetic parameters under water deficit conditions (Priyanka, Jeddi, Sami, & Kamel, 2021). The study by Celebi et al.(2010), Thirkell et al.(2017), Ruiz et al.(2010), Fiorilli et al.(2018), (Mulyadi, 2023) demonstrated the potential of AMF as an environmentally friendly agronomic measure approach to enhance watermelon productivity, reducing the need for fertilizer, and improving stress tolerance, promoting sustainable agriculture (Bernaola & Stout, 2020).

While PGPR can directly promote watermelon plant growth, help watermelon plants cope with drought stress by improving water uptake efficiency, increasing the plant's ability to tolerate water shortages (Cabral et al., 2015, Chatterjee et al., 2017, Chen, 2022).

This can be achieved through various mechanisms, including nitrogen fixation, Phosphorus solubilization photo hormone production, improved root development, enhanced water and nutrient transport and increased production of osmolytes (George, 2023, Xu et al., 2021, Mohanty, Singh, Chakraborty, and Mishra et al., 2021, Jaiswal, 2021, Gabre, 2020, Bechtaovi, 2019, Akhtar et al., 2022, Rojas et al., 2012, Abbas et al., 2020, Alori et al., 2017, Kizilkaya, 2008). These combined effects can lead to increased biomass production, improved WUE and enhanced resistance to soil moisture deficit (Wu, 2022, Sun shahrajabian, 2023, Abdul, 2023).

Improved watermelon root systems allow plants to better access water and nutrients especially in rain fed conditions where water availability can be limited (Bechtaovi, 2019, Wusirika, 2019, Kumar Pranaw et al., 2021, Ferrusquia, 2022).

Rain fed agriculture relies on rainfall for water supply. In these systems, nutrient cycling can be slower due to factors like; limited water availability, potential for nutrient loss, and reduced decomposition rate (Gabre, 2020).

Some research highlights that by improving nutrient availability, root growth, water use efficiency, and enhancing stress tolerance, PGPR can contribute to more sustainable and resilience productive rain fed watermelon cropping systems (Alori et al., 2017, Khaled and Muneera, 2021, Pathania et al., 2020 Bechtaovi, 2019, Wusirika, 2019, Kumar Pranaw et al., 2021, Ferrusquia, 2022 ,Pandey &Shukla, 2016, Qu et al., 2020, Efthimiadou et al. 2020, Cybulska & Drobek, 2019, Cipriano et al., 2021, Asghari et al., 2020, Romero et al., 2017, Aslantas et al., 2007). Different PGPR species have different capabilities. Research could focus on identifying and utilizing the most effective PGPR for specific rain fed cropping systems. Pathania et al. (2020) stated that PGPR facilitate watermelon plant growth and yields, by exploiting the interactions between the plant and rhizosphere.

Some studies have demonstrated that PGPR can produce Aminocyclopropane-1-Carboxylate (ACC) deaminase, an enzyme that reduces ethylene levels, a stress hormone that can inhibit plant growth (Duran Yavuz, 2023, Bechtaovi, 2019, Lee et al., 2017, Wusirika, 2019, Kumar Pranaw et al., 2021, Ferrusquia, 2022, Cybulska & Drobek, 2019).

Combing PGPR with AMF inoculants could further enhance nutrient availability and watermelon productivity. This is particularly important in rain fed agriculture where water availability is limited and nutrient cycling may be slower. The finding of this research could be valuable for farmers in regions where water is scarce and where watermelon is a potential cash crop. By using these techniques, could potentially increase watermelon yields and improve their livelihoods (2016 Akhtar et al., 2022, Mohanty, Singh, Chakraborty, and Mishra et al., 2021, Qu et al., 2020, Cybulska & Drobek, 2019, Rojas et al., 2012**).**

In summary, PGPR offer a promising approach to enhance watermelon growth and yield in rain fed agriculture by improving nutrient availability, promoting root development, enhancing stress tolerance and ultimately boosting high productivity **(**Bechtaovi, 2019, Wusirika, 2019, Kumar Pranaw et al., 2021, Ferrusquia, 2022, Pandey &Shukla,

2.5 Interactions between Soil moisture, WUE, LAI, Season and microbial inoculants on yield under rain fed watermelon cropping:

Interactions between the soil moisture, microbial inoculants, and yield. Soil moisture, is a key field soil characterization, influences the effectiveness of microbial inoculants and both factors significantly impact watermelon plant's access to water, which is essential for nutrient uptake, photosynthesis that promote growth and yield.

Soil moisture levels affect the survival and activity of microbial inoculants in the rhizosphere. Dry conditions can limit their growth and colonization of watermelon plant roots, while excessively wet conditions can reduce oxygen availability, impacting their activity (Lau and Lennon 2011, Kour, 2020, Kumar, 2020, Nordy, 2020, Yavuz, 2020, Abou, 2024, Badr, 2024, Cheng et al., 2023, Li et al., 2022&2023), and this study highlights the impact of soil moisture on microbial community structure and plant acclimation to drought stress.

Seasonal interaction and yield, the studies by (Ufoegbune, Fadipe, Belloo, Eruola & Makinde et al. (2014), Osinem (2023) highlight how rainfall patterns can influence watermelon growth and development. For instance, wet seasons might promote moderate increase in transpiration rate coupled with microbial inoculation can improve vegetative growth, water use efficiency and yield while dry seasons could affect fruit development and yield due to increased evaporation rates (Smith et al., 2022, Jones & Brown, 2021, Kour, Khan & Snghi, 2022, Zandalinas et al., 2016, Murata et al., 2007, Berta, Morais, & Nuria, 2019).

Contributions of Water use efficiency on yield of watermelon crop, studies have shown the use of microbial inoculation improves WUE that indirectly contributes to higher yields. This can be achieved through increased photosynthesis resulting in more biomass production and ultimately higher yields (Abdullahi et al., 2024, Hu & Markes, 2023, Keya et al., 2003)

Contribution of leaf area index (LAI), and microbial inoculants on yield, studies showed that LAI and microbial inoculants can significantly impact watermelon yield under rain fed conditions. Increased LAI often linked to improved plant growth and canopy; enhance light interception and photosynthetic capacity, contributing to higher yields (Xivier et al., 2023, Smith and Read, 2008)

CHAPTER THREE: MATERIALS AND METHODS

3.1 Study site

The study was conducted at the, Kyambogo University Farm in the crop production fields located on Banda Heights Latitude 0 35' 40.90" N, Longitude 32 63' 28.60' E. The area is characterized by a tropical climate with an average temperature 25 ^{o}c and average annual rainfall 1264.3-1180mm, mainly distributed from the month of March to July and August to December (World meteorological organization, BBC Weather). Soil type, Nitisols characterized by clay loam textured and sensitive to compaction due to factors like machinery use and overgrazing.

3.2 Experimental design

Randomized Complete Block Design with seasons as blocks, with 4 Factorial Treatments (Plant Growth Promoting Rhizobacteria, Arbuscular Mycorrhizal Fungi, Plant Growth Promoting Rhizobacteria +Arbuscular Mycorrhizal Fungi and Control) and four (4) replicates giving a total of sixteen (16) experimental units, Size of experimental unit, 4x4m, because it is an appropriate size for adequate treatment replication and allows for reliable measurements of the variable being studied (George, Johnie, Jenkins & Charles, 2008), spaced at 2m between blocks to minimize the risk of experimental error due to environmental variations. The spacing between blocks helps clearly define the boundaries of each treatment, making it easier to manage and observe the effects of treatments within each block without interference from neighboring blocks. It was conducted under rain fed system for 2 cropping seasons (Aug-Dec/2022 and Marc-July/2023).

3.3 Experimental field establishment and management

The field measured (20x20m) was ploughed at a depth (30cm), to improve soil conditions for optimal growth and yield of watermelon crops, Secondary tillage was done by a hand hoe to ensure for proper watermelon root penetration and easily access water and nutrients. Plant population was 5600 per hectare at spacing of (1x1.3 m). For PGPB inoculation was done by introducing Rhizobacteria strain as specific type of bacteria at the rates of 10kgs or 5litres per hectare (agritech.tnall.ac.in). This involved coating the watermelon seeds with 2-3ml per litre of water, which was allowed to dry in a shaded area overnight before planting at a temperature range of 21-29oc (Akifa, 2023, Oregon state university, 2010) away from direct sunlight, before planting. This prevents the rhizobacteria from being damaged by the sun and high temperatures. For Fungi inoculation was done by applying AMF strain as specific fungi at the rates of 30kgs/ha, applied directly at time of planting watermelon seeds. (Shanwi, Shi, Chen & Gao, 2022).

3.4 Data collection

3.4.1. Determining water use Efficiency:

3.4.1.1 Determining amount of rainfall received during the watermelon crop growing seasons

Rainfall received per day was recorded using a rain gauge installed at the site

3.4.1.2 Determining evaporation rate in a watermelon crop field

Evaporation rate was recorded using Micro-lysimeter cylinder 125mm diameter, 300mm height filled with the same soil as the field following the procedures by Rhitchie (1972, and, FAO-56, Penman Monteith. This was achieved by measuring the fraction of soil surface wetted in the micro-lysimeter cylinder to estimate soil evaporation (Ke). And also taking it into consideration the frequency and intensity of rainfall and its contribution to soil moisture recharge and watermelon crop growth.

Er = KeETo ……………………………………………………… Eq.1

Where; Er is the evaporation rate,

Ke is the soil evaporation, and

ETo is the reference evapotranspiration of watermelon crop.

3.4.1.3 Determining Transpiration Rate of watermelon crop:

The transpiration rate was determined using the dual coefficient approach following the procedures by Ritchie 1972, FAO-56, and Penman Monteith equation. Transpiration rate of watermelon crop was measured at different stages of watermelon crop growth, including initial (at 14days), development growth stage (at 30days), mid-season/flowering growth stage (at 49-57days) and late-season/fruit set (at 60-70days).

Tr=(KcbETo) ………………………………………………………. Eq. 2

Where; Tr is the transpiration rate,

Kcb is the basal crop coefficient, and

ETo is the reference evapotranspiration.

3.4.1.4 Determining water use efficiency of watermelon crop:

Water Use Efficiency (WUE) was determined using the procedures described by FAO Aqua-Crop model 2022. The model separates evapotranspiration into crop transpiration and soil evaporation with transpiration playing a key role in biomass and ultimately yield. WUE is calculated as the ratio of yield (Y) to the total water transpired by the crop.

WUE (ton/ha/mm)=Yield/Total water input…………………………Eq.3

3.4.1.5 Determining soil moisture storage in a watermelon crop field

Soil moisture content was determined using Gravimetric method by (FAO model, 2023). This method provides a reliable way to assess the amount of water held within the soil, which is crucial for understanding water available for watermelon plants under rain fed conditions.

$$\text{Soil moisture (\%)} = \frac{(\text{wet soil weight} - \text{dry soil weight}) \times 100}{\text{Dry soil weight}}\% \quad \text{……….Eq.4}$$

3.4.2 Determining yield of watermelon crop

Yield was determined using the procedures and formula by (Casley and Kumar, 1988). Yield was assessed as fruit weight in tons per hectare.

EY (ton/ha) =A (kg) XN/ (HA) 10,000 ………….Eq. 5

Where A is the Average fruit weight per watermelon plant (kg),

N is the number of harvested watermelon plants, HA is the total harvested area (tons/ha)

3.4.2.1 Determining leaf area index of watermelon crop

Leaf Area Index was determined following the procedure by Aqua-Crop model. Leaf Area Index is not directly inputted but is simulated based on the canopy cover (CC). The model uses the formula to calculate canopy cover over time, which is then related to LAI. The formula for canopy cover (CCt) over time (t)

CCt=CCo*e^(tCGC) …………………………………………….. Eq. 6

Where: CCo is the initial canopy cover,

CCx is the maximum canopy cover, and

CGC is the canopy growth coefficient.

The model relates canopy cover to LAI using a conversion factor that varies depending on the crop and its growth stage.

3.5 Data analysis

Two-way Analysis of Variance (ANOVA) was used to test for significant differences ($P<0.05$) between the seasons, PGPR treatment, AMF treatment and if there are any interactions between these factors on water use efficiency and yield in a watermelon crop. Genstat, version 14.1 (Nelder, 2008) was used to analyze data. To check normality, Shapiro-Wilk test (under T-test) was used, indicating a significant $P=0.001$ concluding that the data deviates significantly from a normal distribution. Levene's test (1960) & Bartlett's test was used to check for homogeneity of variances (i.e. if the P-value is equal to 05, then its normal data). LSD was used to separate the means between the treatments, season variations and the interactions between the seasons, PGPR treatment, and AMF treatment under rain fed watermelon conditions.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Effects of plant growth promoting rhizobacteria on water use efficiency in a watermelon crop

Plant Growth Promoting Rhizobacteria (PGPR) significantly ($P < 0.001$) increased water use efficiency in a watermelon crop. Watermelon crop plots treated with plant growth promoting rhizobacteria produced higher increase in mean water use efficiency (14.04 ± 0.15^{a} 1ton/ha/mm (2022) and (13.02 ± 0.18^{ab}ton/ha/mm (2023) compared with control plots (1.78 ± 0.11^{b}ton/ha/mm (2022) and (0.86 ± 0.10^{b} ton/ha/mm (2023) respectively (Table 4.1). However, watermelon plots treated with a combined (AMF + PGPR) produced the highest increase in mean water use efficiency compared with those treated with rhizobacteria alone and control (Table 4. 1). Signaling a synergistic interaction between PGPR and AMF. The statistical analysis also indicated significant differences in the water use parameters such as evaporation rate ($P < 0.001$), and transpiration rate ($P < 0.001$). However, the evaporation rates increased with a decrease in WUE in watermelon plots under control whereas there was a significant decrease in evaporation rates with increase in WUE under watermelon plots treated with rhizobacteria (Table 4.1). High evaporation rates driven by factors like temperature, wind and solar radiation lead to increased water loss from the soil surface, directly reducing the amount of water available for transpiration by watermelon plant uptake under control plots. This water loss reduces WUE as the watermelon plants under control fail to utilize all the water potentially available compared with those which are treated with rhizobacteria. Therefore, by managing evaporation rates with strategies like application of PGPR can reduce evaporation rates, improving soil water retention; enhance watermelon plant root architecture and plant growth, especially under water stress conditions. The study is in agreements with findings by (Rolli et al., 2015, Berg et al., 2013, Kroener et al., 218, Yavuz, 2025 & Vikram, 2022) showed that increase in WUE by watermelon plants could also be facilitated by rhizobacteria's ability to increase water availability to watermelon plants by slowing down evaporation rates, and by increasing time available for plants to make adjustments to water deficits. Plant growth promoting rhizobacteria can achieve this by modifying soil structure, promoting Biofilm such as biological systems the bacteria organize themselves into a coordinated functional community), and influencing soil water retention capacity. The study is in line with the findings by (Zheng, Zeng, Jacobson, David & Yan, 2018) showed that application of PGPR to rain fed watermelon crops can reduce evaporation rates, improving soil water retention, and enhance plant growth , especially under water stressed conditions.

Relationship between transpiration rate and PGPR on WUE; transpiration rates increased with increase in water use efficiency (Table 4.1). This could have been the rhizobacteria's ability enhance water use efficiency in rain fed watermelon cropping by improving transpiration and reducing the negative impacts of water stress. This is achieved through various mechanisms including; enhanced root architecture development, improved nutrient uptake and increased antioxidant production, all of which contribute to better watermelon plant performance under water-limited conditions. The study is in line with the findings by (Haiying, Hassan, Feng & Lin, 2022, Pereira et al., 2019, Maria, Diaz, Isela, Cota & Luis, 2024, Omirou, Loannides & Ehaliots, 2013, Miceli & Vetrano, 2023 Ganesh. 2024 & Xuan. 2024, Cybulska & Drobek, 2019, Tiepo et al., 2018, Ngoma & Babalola, 2012, Sandhya & Grover, 2009, Kohler& Hernandez,2008 ,Mayak & Glick, 2004 Naveed, 2018, Farooqi & Rehman, 2020, Akhtar et al., 2022, Mohanty, Singh, Chakraborty, and Mishra et al., 2021, Yavuz, Seymen. 2024, Vejan & Abdullah, 2016, Ahemad, 2012, Ahmad, Fiaz, Hafeez, Wang. 2022) showed that rhizobacteria colonize the watermelon roots can improve the plant root architecture, increase nutrient uptake contributing to WUE regulated by transpiration pull and stomatal conductance under soil moisture deficits conditions.

However, there was a synergistic interaction between PGPR and AMF meaning that the combined effect is greater than the sum of their individual effects (B+F ($14.79{\pm}0.18^{a}$ (ton/ha/mm) compared to B (14.04 ± 0.15^{a} ton/ha/mm (2022), and B+F (14.46 ± 0.18^{a} ton/ha/mm) compared to B (13.02 ± 0.14^{ab} ton/ha.mm (2023). The results liars with the study by Cabral et al. (2014), Fasus et al. (2021), showed that despite the challenges, it is essential to consider both individual and combined effects of PGPR and AMF to understand the mechanism behind WUE improvement. This knowledge can help farmers in developing more effective microbial consortia for sustainable watermelon farming under rain fed conditions.

The results also showed the significant interactions between the soil moisture storage, PGPR treatment and WUE under watermelon rain fed conditions (Table 4.1). Plant growth promoting rhizobacteria significantly ($P < 0.001$) increased soil moisture storage compared to control. Studies have shown that soil moisture storage is a crucial soil factor influencing WUE. The effectiveness of PGPR in improving WUE is often dependent on soil moisture levels. Therefore, understanding the specific interactions between PGPR, soil moisture content and watermelon growth is important for optimizing water management strategies in rain fed watermelon cultivation. By carefully selecting appropriate PGPR strains and understanding the dynamics of soil moisture in the field, farmers can potentially improve WUE in rain fed watermelon production (Maha & Emma, 2023, Yavuz & Seymen, 2023).

Interactions between the season and water use parameters of watermelon crop; There are significant seasonal variations interactions between the, soil moisture storage (P-Value <0.043), evaporation rate (P-Value =<0.05), transpiration rates ($P < 0.04$) and PGPR treatment on water use efficiency (P-Value < 0.002) (Table 4.1). Rain fed watermelon cultivation relies entirely on rain fall for water supply, making it more vulnerable to seasonal variations. Understanding the interaction between the seasonal rain fall patterns and PGPR treatment is crucial for optimizing WUE in rain fed watermelon production. The results are in agreements with the researchers showed that to improve WUE in rain fed watermelon cultivation, the use of PGPR and their interactions with seasonal variations play a vital role. Plant growth promoting rhizobacteria can enhance watermelon plant growth and resilience to water stress, by increasing nutrient uptake, promoting root development, particularly under water-limited conditions, while seasonal changes in rainfall and temperature can impact their effectiveness. (Ufoegbune, Fadipe, Belloo, Eruola, Makinde et al., 2014, Marasco et al., 2013, Wang et al., 2014, Benidire et al., 2021, Zhang et al., 2020).

Table 4.1: Effects of plant growth promoting *rhizo*bacteria on water use efficiency in a watermelon crop

Seasons	Treatments	Mean S M (%)	Mean Er (Mm/day	Mean Tr (Mm/day)	Mean WUE (Ton/ha/mm)
1(2022)	B	31.33 ± 0.44[a]	2.5 ± 0.05[b]	7.51 ± 0.48[a]	14.04 ± 0.15[a]
	B+F	31.93 ± 0.45[a]	3.20 ± 0.06[ab]	6.28 ± 0.44[ab]	14.79 ± 0.18[a]
	C	17.73 ± 0.13[b]	4.45 ± 0.07[a]	1.02 ± 0.28[b]	1.78 ± 0.11[b]
2(2023)	B	32.74 ± .53[a]	2.45 ± 0.02[b]	7.06 ± 0.48[a]	13.02 ± 0.14[ab]
	B+F	32.77 ± 0.54[a]	3.05 ± 0.05[ab]	6.4 ± 0.46[ab]	14.46 ± 0.18[a]
	C	19.62 ± 0.14[b]	4.10 ± 0.07[a]	0.75 ± 0.18[b]	0.86 ± 0.10[b]
Treatment (LSD 5%)		1.629	0.2119	0.4361	0.544
Treatment (P-value)		0.001	0.001	0.001	0.001
Seasonal treatment LSD (5%)		1.33	0.2997	0.3084	0.444
Season. Treatment (P-value)		0.043	0.05	0.04	0.002

(Where by SM is the soil moisture content (%), Er is the evaporation rate (mm/day), Tr is the transpiration rate (mm/day), and WUE is the water use efficiency of watermelon crop (ton/ha/mm), means with same letters are not significant at 5% confidence level.

4.2 Effects of *Arbuscular mycorrhizal* fungi (AMF) on water use efficiency in a watermelon crop

Arbuscular mycorrhizal fungi significantly (P < 0.001) increased water use efficiency in a watermelon crop. The statistical analysis showed that watermelon plots treated with *Arbuscular mycorrhizal* fungi recorded higher increase in mean water use efficiency (12.35 ± 0.1606[a] ton/ha/mm (2022) and (11.26 ± 0.1706[ab] ton/ha/mm (2023) compared with control (1.78 ± 0.106[b] ton/ha/mm (2022) and (0.86 ± 0.0706[b] ton/ha/mm (2023). However, the integration of AMF and PGPR recorded the highest mean water use efficiency compared with watermelon plots treated with AMF only (Table 4.2).

The increase in mean water use efficiency demonstrated that where AMF applied make significant contribution to water use efficiency in the watermelon production than control. This could be due to the ability of AMF establishing symbiotic associations with the host watermelon plants (Huang, 2021 Diagne, 2020, Mohammed, 2023, Barros et al., 2018). This is achieved by AMF colonize watermelon roots forming arbuscules and network hyphae that extend the root systems reach, increasing the surface area (Howard & Mishra, 2018, Diagne et al., 2020, Garg & Cheema, 2021, Wahab. 2023, Muhammad, 2023, Khizar, 2023). Enhance root hydraulic conductance under abiotic stress through regulating water flow channels (Bitterlic et al., 2018), exhibit less negative leaf water potential rates and maintain moderate transpiration rate than watermelon plants under control plots that enhance WUE (Backer, 2018, Quiroga et al., 2019, Ortas et al., 2021, Hayat et al., 2019).

There are significant differences in the interactions between the seasons, Soil moisture, Evaporation rate, Transpiration rate and AMF treatment on water use efficiency (Table 4.2). Watermelon crops have varying water needs throughout their growth stages. They require more water during flowering and fruit development. Understanding how seasonal variations affect soil moisture, evaporation rates and transpiration rates is crucial for maximizing WUE in rain fed watermelon cultivation. Seasonal variations in rainfall directly impact soil moisture availability for rain fed watermelon crops. Adequate rainfall promotes optimum soil moisture storage whereas dry spells lead to soil moisture depletion caused by increased evaporation rates (Ufoegbune, Fadipe, & Belloo et al., 2014, Smith et al., 2022, Jones & Brown, 2021). Some studies have shown that extreme weather can induce physiological stress affecting transpiration and photosynthesis by watermelon crops (Murata et al., 2007). Indicating that the interaction between transpiration and microbial inoculation under rain fed watermelon conditions is not about maximizing water loss but about optimizing the watermelon plant's ability to use the available water effectively (Kour, Khan, Singhi, 2022).

Table 4.2: Effect of *Arbuscular mycorrhizal* fungi on water use efficiency

Season	Treatments	Mean S M (%)	Mean Er (Mm/day)	Mean Tr (Mm/day	Mean WUE (ton/ha/mm)
1(2022)	F	30.00 ± 0.62[a]	3.00 ± 0.06[a]	5.20 ± 0.42[a]	12.35 ± 0.16[a]
	B+F	31.03 ± 0.65[a]	3.20 ± 0.07[a]	6.28 ± 0.48[ab]	14.79 ± 0.17[ab]
	C	17.73 ± 0.60[b]	4.45 ± 0.08[b]	1.02 ± 0.40[b]	1.78 ± 0.10[b]
2(2023)	F	32.51 ± 0.64[a]	2.97 ± 0.05[a]	5.18 ± 0.42[a]	11.26 ± 0.15[a]
	B+F	32.77 ± 0.65[a]	3.05 ± 0.06[a]	6.4 ± 0.48[b]	14.46 ± 0.17[ab]
	C	19.62 ± 0.62[b]	4.10 ± 0.07[b]	0.75 ± 0.38[c]	0.86 ± 0.07[b]
L S D ((5%) level		1.97	0.2119	0.4361	0.514
P-value		0.001	0.001	0.001	0.001
Seasonal treatment L S D (5%)		1.608	0.2997	0.3084	0.499
P-value		0.035	0.05	0.04	0.001

Where by SM is the soil moisture content (%), Er is the evaporation rate (mm/day), Tr is the transpiration rate (mm/day), and WUE is the water use efficiency of watermelon crop (ton/ha/mm). and means with same letters are not significant at 5% confidence level

4.3 The effect of AMF and PGPR on yield (ton/ha) of a watermelon crop

Arbuscular mycorrhizal fungi (AMF) and Plant growth promoting rhizobacteria (PGPR) significantly (P = 0.001) increased the yield of watermelon crop (Table 4.3). Both AMF and PGPR recorded significant increase in mean yield (R (21.0 ± 0.42[a] ton/ha), F (16.70 ± 0.38b ton/ha) (2022) and R, 20.72 ± 0.42[a] ton/ha, F, 15.58 ± 0.36[b] (2023) compared with control (5.30 ± 0.32[c] ton/ha (2022) and 1.92 ± 0.22[c] (2023). However, the statistical analysis showed that watermelon plots treated with PGPR recorded significantly highest increase in mean yield, followed by a combined (AMF + PGPR) & AMF compared with control (Table 4.3).

The significant highest increase in mean yield recorded in watermelon treated with PGPR demonstrated significant contribution to watermelon production than control. This could be due to the ability of plant growth promoting rhizobacteria significantly enhance watermelon yield under rain fed conditions by improving plant growth, nutrient uptake, and stress tolerance (Cabral et al., 2015, Chatterjee et al., 2017, Xianni Chen, 2022). This can be achieved through various mechanisms, including nitrogen fixation, phosphorus solubilization, photo hormone production, improved root development, enhanced water, nutrient transport, and increased production of osmolytes (George, 2023, Xu et al., 2021, Mohanty, Singh, Chakraborty, and Mishra et al., 2021).. These combined effects can lead to increased biomass production, improved WUE, enhanced resistance to soil moisture deficit promoting higher yields (Wu, 2022, Sun shahrajabian, 2023, Abdul, 2023).

Whereas, significant increase in both microbial inoculants in mean yield compared to control, might have been due to microbial inoculant's ability form symbiotic relationships with watermelon plant roots, enhancing nutrient availability and promoting WUE.(Qiao, et al., 2024, Asma et al., 2023, Carfagna &Palumbo, 2020, Romano, 2020, Wang, Sun, Harman, 2019, Howard & Mishra, 2018, Fiorilli et al., 2018, Li et al., 2016, Jacoby et al., 2017, Abdul, 2023, Buczkowska &Salata, 2020, Masoero& Volpato, 2020, Baguaraj &Sridhar, 2022, Babalola & Igiehon, 2021). By improving WUE, microbes help watermelon plants thrive even under water stressed conditions leading to more consistent and increased yields. This can be achieved through increased photosynthesis resulting in more biomass production and ultimately increased yields

A combination of bacteria and fungi recorded a synergistic interaction in the mean yield (B+F, 18.00 ± 0.407^{ab} ton/ha (2022) and 19.54 ± 0.41^{ab} ton/ha (2023) compared with watermelon plants inoculated with sole F (16.70 ± 0.38^{b}ton/ha (2022) and 15.58 ± 0.36^{b} ton/ha (2023), (Table 4.3) and control (5.30 ± 0.32^{c} ton/ha (2022) and 1.92 ± 0.22^{c} ton/ha (2023), but it did not affect watermelon crops treated with rhizobacteria only (Figure 4.3). Meaning that their combined effect is greater than the sum of their individual effects in particular with AMF. The results are in agreement with the study by Cabral et al. (2015), Fasus et al. (2021), showed that while analyzing individual microbial data is important, understanding the synergistic interactions between the PGPR and AMF is crucial for a comprehensive interpretation of the results, especially in the context of a rain fed watermelon cropping systems.

The statistical results also showed the significant differences in the interactions between season ($P < 0.005$) and microbial treatment ($P < 0.001$) increase in the yield (Table 4.3}. In rain fed watermelon cultivation, seasonal and microbial inoculation interactions significantly impact yield. Microbial inoculants like *mycorrhizal* fungi and Rhizobacteria can enhance water and nutrient uptake, especially under water stress conditions, while also improving soil health. Understanding seasonal variations in rainfall and temperature, and their effects on microbial activity and watermelon growth, is essential for optimizing planting times, and management practices to maximize yield. The results liars with the studies by UfoegbuneFadipe, Belloo, Eruola & Makind et al. (2014) highlight how rainfall patterns can influence watermelon growth and development. For instance, wet seasons might promote moderate increase in transpiration rate coupled with microbial inoculation can improve vegetative growth, water use efficiency and yield while dry seasons could affect fruit development and yield due to increased evaporation rates (Smith et al., 2022, Jones & Brown, 2021, Kour, Khan & Snghi, 2022, Zandalinas et al., 2016, Murata et al., 2007, Berta, Morais, & Nuria, 2019).

There are also significant interaction differences between the soil moisture ($P < 0.001$), & microbial inoculants, on yield of watermelon crop. Soil moisture, is a key field soil characterization, that influence the effectiveness of microbial inoculants and both factors significantly impact watermelon plant's access to water, which is essential for nutrient uptake, photosynthesis that promote growth and yield. Soil moisture levels affect the survival and activity of microbial inoculants in the rhizosphere. Dry conditions can limit their growth and colonization of watermelon plant roots, while excessively wet conditions can reduce oxygen availability, impacting their activity. The results are in line with the studies by (Lau and Lennon 2011, Kour, 2020, Kumar, 2020, Nordy, 2020, Yavuz, 2020 & 2023), showed that soil moisture content is a critical field soil characterization for understanding water use efficiency and the effectiveness of microbial inoculants under rain fed watermelon cropping. Understanding how soil moisture interacts with microbial inoculation and how it affects WUE can help farmers optimize watermelon production, particularly in water-limited environments.

Interactions between the seasonal variations, leaf area index and yield, though there are significant differences ($P < 0.002$) between microbial treatments and the LAI on yield of watermelon crops, the statistical analysis did not indicate any significant interactions between the seasonal treatment and LAI but recorded significant interactions between the seasons (in particular rainfall) and microbial treatments on yield (Table 4.3). This might have mediated by other environmental factors. The results are in line with the study by (Mabhaudhi and Modi. 2013) showed that while seasonal variations can influence watermelon growth and yield, LAI might not be a primary driver of fluctuations in rain fed systems, particularly when considering water availability and other environmental factors. There is limited statistical data about no interactions between the seasons and LAI. Need for further research to fully understand the complex interplay between seasons, LAI and water availability in rain fed watermelon production systems. Watermelon plants treated with microbial inoculants (AMF and PGPR) recorded significant increase in the mean LAI compared with control. The increase in the mean LAI signified positive relationship contribution to watermelon yield under rain fed conditions. Leaf area index and microbial inoculants can significantly impact watermelon yield under rain fed conditions. This result is in agreement with studies by Xivier et al. (2023), and (Smith & Read, 2008) showed that increased LAI, often linked to improved plant growth and canopy development, enhances light interception and photosynthetic capacity contributing to higher yields.

Contributions of Water use efficiency on yield of watermelon crop, WUE significantly increased with increase in yields under watermelon plots treated with microbial inoculants signaling significant relationship between the WUE and yields under rain fed watermelon cultivation. The study is in line with studies by (Abdullahi et al., 2024, Hu & Markes, 2023, Keya et al., 2003) have shown that application of AMF and PGPR improved WUE, which indirectly contributed to higher yields of watermelon crop under water-limited conditions. This can be achieved through increased photosynthesis resulting in more biomass production and ultimately higher yields.

Table 4.3 Effects of *Arbuscular mycorrhizal* fungi and plant growth promoting rhizo bacteria on yield of watermelon crop

Season	Treatment	Mean L A I	Mean Yield (ton/ha)
1(2022)	B	1.52 ± 0.27[a]	21.00 ± 0.42[a]
	B+F	1.30 ± 0.23[ab]	18.00 ± 0.40[ab]
	C	0.15 ± 0.20[c]	5.30 ± 0.32[c]
	F	1.02±0.21[b]	16.70 ± 0.38[b]
2(2023)	B	2.19 ± 0.29[a]	20.72 ± 0.42[a]
	B+F	1.49 ± 0.27[ab]	19.45 ± 0.41[ab]
	C	0.08 ± 0.12[c]	1.92 ± 0.22[c]
	F	1.35 ± 0.19[b]	15.58 ± 0.36[b]
Treatment L S D (5%)		0.802	1.257
Treatment (P-value)		0.002	0.001
Seasonal treatment L S D (5%)		1.134	1.777
Season. Treatment P-value		0.808	0.005

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The application of Plant growth promoting rhizobacteria significantly ($P < 0.001$) increased water use efficiency. The statistical analysis showed that watermelon plots treated with plant growth promoting rhizobacteria recorded higher mean water use efficiency compared with control. Also AMF significantly increased water use efficiency. However, watermelon crops treated with combined (AMF& PGPR), recorded the highest mean water use efficiency compared with plots treated with rhizobacteria and mycorrhizal fungi only. Signaling the potential of synergistic interactions on water use efficiency under rain fed watermelon cultivation.

There are significant differences in the interactions between the season, soil moisture, *Arbuscular Mycorrhizal* Fungi and Plant Growth Promoting Rhizobacteria treatments on yield of watermelon crop under rain fed conditions. However, watermelon crop plots treated with PGPR only, demonstrated the highest significant increase on watermelon mean yield compared to control, and plots treated with AMF only and combined (AMF+PGPR). Suggesting that PGPR has the potential to offer benefits like improved soil moisture, soil health, nutrient availability, water use efficiency, and reduced reliance on chemical fertilizer, ultimately boosting high yields and contributing to more sustainable and profitable agriculture for farmers under water-limited environments in Uganda.

5.2 Recommendations of the study

- For water use efficiency farmers are recommended to use a combined application of (AMF+PGPR.). Because their application produced the highest mean water use efficiency compared with watermelon plots treated with AMF and PGPR only.
- For yield, farmers are recommended to use PGPR inoculants 10kgs or 5litres per hectare (agritech.tnall.ac.in). Because its treatment produced the highest mean yield as fruit weight (tons/ha) of watermelon compared with watermelon plots treated with AMF only and combined (AMF+PGPR).
- Further research should focus on investigation on the application rates of AMF in rain fed watermelon cultivation. This is because the application of AMF produced less than recommended Yield of watermelon under optimum condition (50-80ton/ha).

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APPENDICES

	
Plate 3: Soil sampling for moisture testing	*Plate 4:Recording of data on soil moisture*

Plate 5: Rain gauge in the experimental lay out to collect data on amount of rainfall

	
Plate 6: Harvested Water Melon	*Plate 7: Weighing harvested Water melon*

Operational definition of terms

Biological soil amendments are soil amendments used in agriculture to support plant growth and development, specifically by adding organic and inorganic nutrients to the soil, and improving soil tilth, organic matter, and water holding capacity.

Plant growth-promoting bacteria (PGPB), are bacteria that promote plant growth, water uptake and yield through a wide variety of mechanisms.

Plant growth promoting fungi (PGPFs), are the heterogeneous group of non-pathogenic fungi that can be obtained in rhizosphere at the root surfaces or inside the root.

Crop biomass can be defined as the product of cumulative radiation incident on the crop.

Water use is the water that a crop needs to cater for evapotranspiration.

Leaf area index (LAI), is defined as the one-sided green leaf area per unit ground surface area. LAI quantifies the amount of leaf materials in a canopy.

Yield, a measurement of the quantity (ton/ha) of crop produced per unit of land.

Smallholder farmers are small-scale farmers, pastoralists, forest keepers, fishers, who manage areas varying from less than one hectare to ten hectares. About 90% of the world's 570 million farms are smallholder farmers, most found in the rural areas of the developing world, and are owned and operated by family.