UNIVERSITY OF CAPE COAST

EVALUATION OF A SELF-REGULATING LOW ENERGY CLAY-BASED IRRIGATION (SLECI) SYSTEM USING BELL PEPPER (*Capsicum annuum*) AS A TEST CROP

GILBERT OSEI

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BY

GILBERT OSEI

Thesis submitted to the Department of Agricultural Engineering of the School of Agriculture, College of Agriculture and Natural Sciences, University of Cape Coast, in partial fulfilment of the requirements for the award of Doctor of Philosophy degree in Irrigation Technology & Management

FEBRUARY, 2025

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree at this university or elsewhere.

Candidate's signature: ……………………… Date: ……………………….

Mr. Gilbert Osei

Supervisor's Declaration

We hereby declare that the preparation and presentation of the dissertation were supervised in accordance with the guidelines on supervision of dissertation laid down by the University of Cape Coast.

Principal supervisor's Signature: ……………………. Date: …………………

Prof. Livingstone K Sam-Amoah

Co-supervisor's Signature: …………………………… Date: …………………

Prof. Joshua Danso Owusu-Sekyere

ABSTRACT

The study evaluated the SLECI system's effectiveness, using bell pepper (*Capsicum annuum*) as a test crop. Five specific objectives were set to accomplish the aim of the study. Objective one aimed at assessing how irrigation water quality and soil properties influence the performance indicators of (SLECI) system. This objective was accomplished by undertaking a laboratory experiment, with soil type (clay, sand, and loam) and source of irrigation water (river, well, and tap water) as treatments. Performance parameters of the SLECI system, such as seepage rate, hydraulic conductivity, and drainage porosity, were recorded. Pearson correlation tests conducted at a 5% probability level indicated that eight (8) correlations (Zinc, Copper, Calcium, Magnesium, Sodium, Iron, Potassium, and SAR) were statistically significant to the performance of the SLECI system. In contrast, soil properties (bulk density, porosity (%), particle density, infiltration rate, soil salinity, and soil sodicity) were significant to the performance of the SLECI system. Objective two aimed to assess the response of bell peppers to different irrigation systems (watering, drip irrigation, and SLECI system) and fertilizer application methods (basal application and fertigation), under greenhouse conditions. Analysis of variance ($p < 0.05$) revealed that bell peppers grown under the SLECI system had significantly higher growth, yield, productivity, and quality parameters. Fertigation resulted in significantly superior growth, yield, productivity, and quality parameters. The interaction of the SLECI system and fertigation outperformed all the remaining interactions of the irrigation system and fertilizer application method for data collection. Objective three aimed at investigating the effects of SLECI system burying depth (5 cm, 10cm, and 15 cm) and fertilizer recommended application dosage (100% RAD, 80% RAD, and 60 RAD) on bell peppers under open field conditions. Analysis of variance ($p < 0.05$) showed significantly higher growth, yield, productivity, and parameters from a burying depth of 10cm. Among fertilizer application dosage treatments, 80% of RAD produced bell pepper plants exhibited significantly higher growth, yield, and productivity parameters. The best-performing treatment interaction was the SLECI system burying depth of 10cm and 80% RAD. Objective four aimed to assess bell peppers' response to saline irrigation water (0.54 dS/m (control), 2.0 dS/m, 4.0 dS/m, 6.0 dS/m, and 8.0 dS/m) using the SLECI system. Compared to the control (0.55 dS/m) increasing water salinity levels to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m, and 8.0 dS/m resulted in decreased growth, yield, and productivity parameters of bell pepper. Objective five aimed at simulating moisture and salinity levels using MATLAB. A coefficient determination of 0.99413, 0.98613, and 0.96689 was observed between experimental and simulated results indicating the robustness of MATLAB in simulating water and soil dynamics in the soil. Overall, the research highlights the potential of the SLECI system to enhance agricultural land and water productivity.

Keywords: Irrigation, SLECI, Depth, Fertilizer, Salinity

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DEDICATION

I dedicate this work to my family

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LIST OF ABBREVIATIONS

ANOVA	Analyses of variance
CWP	Crop Water Productivity
CWU	Cumulative Water Use
ET	Evapotranspiration
FUE	Fertilizer Use Efficiency
IEA	International Energy Agency
ITAS	Institute for Technology Assessment and Systems Analysis
IWS	Intelligent Water Solutions
MoFA	Ministry of Food and Agriculture
NaCl	Sodium chloride
NPK	Nitrogen Phosphorus Potassium
OECD	Organisation for Economic Co-Operation and Development
SAR	Sodium Absorption Ratio
SDI	Subsurface Drip Irrigation
SLECI	Self-regulating Low Energy Clay-based Irrigation
SRID	Statistics Research, and Information Directorate
SSI	Small-Scale Irrigation
WUE	Water Use Efficiency

CHAPTER ONE

INTRODUCTION

Background to the Study

The rapid increase in population growth remains a major obstacle to achieving the United Nations Sustainable Development Goals (SDGs), particularly in eradicating poverty and hunger. Projections indicate that the population in the least developed countries, as defined by the United Nations (UN), is expected to surpass 1 billion in 2020 and reach 1.76 billion by 2050 (United Nations Population Fund, 2019). By 2030, SDG 2 (zero hunger) seeks to put an end to all sorts of malnutrition and hunger by ensuring that every individual has adequate food access throughout the entire year, through water management (SDG 6, clean water and sanitation). Sustainable food security can be achieved by supporting small-scale farmers by ensuring equal access to land, water, and technology (Da Silva, Ronoh, Maranga, Odhiambo, & Kiyegga 2020). Acknowledging the wide range of uses and users of water is essential for the SDGs' successful implementation (Renault et al., 2013). Food security as defined by Alemu and Bosena (2017) is the existence of safe, nutritious, sufficient, and socially acceptable food for all people at all times to live healthy, active, and productive lives. According to Alkire et al. (2015), there are over 800 million chronically undernourished people on the earth who lack adequate access to food. This problem is further heightened by high dependency on natural rainfall in addition to climate-change-induced drought periods. This validates the notion that only rain-fed agriculture will guarantee sustainable access to food requirements.

Artificial water application to crops through irrigation has been a crucial part of agriculture. In many parts of the world, the ability to provide and distribute water in suitable irrigation systems has always been a requirement for enhancing agriculture and ensuring food security for a growing population (Ejeta, 2019). Irrigation is not only essential for achieving food security (SDG 2, Zero Hunger), but it also plays a crucial role in preventing impoverished individuals from sinking deeper into temporary or permanent poverty (SDG 1, No Poverty) by generating additional economic benefits through food, livestock feed, and other crops. Through irrigation, smallholder farmers can adopt more diverse cropping methods and transition from low-value subsistence farming to high-value market-oriented production. This leads to increased food production, making it more accessible and affordable for all (Hussain & Hanjra 2004; Lynch et al., 2019). Findings from Awulachew et al. (2008), Gebregziabher & Namara (2008), Mangisoni (2008), Omilola (2009), Demeke et al. (2011), Maxwell et al. (2013), Norton et al. (2014), Wineman (2016), Kassie and Alemu (2021) There is sufficient research evidence supporting the positive impact of irrigation on global food security, by the year 2030, it is expected that the total land area equipped for irrigation, especially in developing regions, will witness a 20% increase.

Accordingly, 20% of the total amount of land having irrigation potential but not yet in use will be covered by irrigation (Darko et al., 2016). Water resources have been and will continue to be crucial commodities for human existence and economic progress; they are crucial for human sustenance, agriculture, and industrial development (Tripathi et al., 2017). Only 2.5% of the water covering the surface of the world is fresh, yet 70% of it is used for irrigation. The agriculture sector loses the most water, with developing regions' water withdrawal rates reaching 50% by 2050 (Bhople et al., 2014a). Due to increased demand for non-agricultural purposes and the need to produce more crops on current farmlands to support a growing global population, the scarcity of water in agriculture is becoming a prominent concern. Hence, it is vital to optimize the utilization of irrigation water to the highest degree possible (Darko et al., 2016). Ghana has six agroecological zones namely the Deciduous-forest zone, Forest/Savannah Transitional Zone, Sudan Savannah, Coastal Savannah, Guinea Savannah, and the Rainforest Zone. Variations in climatic conditions do exist among the various agroecological zones of Ghana (Asravor et al., 2019). To irrigate their crops, farmers mostly depend on groundwater and surface water. However, issues of water shortage persist (Tagar et al., 2016). As a result, for successful crop production, innovative irrigation systems and techniques are required. Although modern irrigation techniques like sub-surface drip irrigation and sprinklers can save nearly half the water used for irrigation, adoption of such technologies is hampered by technical, economic, and sociocultural issues (Bhayo et al., 2018). Modern irrigation techniques, such as subsurface drip systems, sprinkler irrigation systems, and drip irrigation systems, have the potential to reduce water usage in agriculture by approximately 50%. However, the widespread adoption of these methods is hindered by various technical, economic, and societal challenges. Issues such as limited access to financing, farmers' reluctance to take risks, a lack of technical knowledge, high upfront investment and operational costs, and problems in the supply chain have impeded the implementation of innovative agricultural technologies in developing nations (Bizimana, James & Richardson 2019). Even in cases where these modern irrigation technologies have been implemented on a pilot basis, attempts to spread their use to a wider reach have frequently failed (Burney & Naylor, 2012). Low productivity caused by limited or no access to proper agricultural technologies frequently causes ongoing food insecurity in developing countries. Small-Scale Irrigation (SSI) technologies have the potential to increase crop output and serve as a viable option for adapting to climate change (Balana et al., 2020). The development and adoption of low-cost, water-saving technologies for sustainable agricultural production, continue to face significant challenges, especially in semiarid and arid regions (Siyal et al., 2009). Through direct evaporation, runoff, and deep drainage, a substantial portion of rainfall is lost, indicating crop water stress since the amount of soil water available throughout the growing season is insufficient to make up for the crop's need for water. Consequently, one of the climatic risks that frequently cause significant shortages of food in the region is drought stress (Araya et al., 2015). Even when irrigation is applied, a significant amount of water may still evaporate, particularly in extremely hot and dry conditions (Elavarasan et al., 2014).

Researchers in regions with low rainfall and dry climates have consistently shown the effectiveness of clay-based irrigation as a cost-effective, efficient, and water-saving method of irrigation (Tesfaye et al., 2012). Clay based irrigation systems' permeable walls allow water to slowly seep into the effective root zone of crops in the soil (Ansari et al., 2015). Water-saving and effective characteristics of the clay-based irrigation system can be attributed to the clay-based irrigation systems' great autoregulative capacities, which result from close interactions with the soil, climate, and plants in its environment. The rate at which water seeps through is determined by the pressure inside the clay based and the saturated hydraulic conductivity, both of which contribute to a slow rate of evaporation. Conversely, when the rate of evaporation is large, the negative pressure exerted on the outer surface of the clay based becomes substantial (Abu-Zreig et al. 2006). Clay based irrigation is utilized for small-scale irrigation in regions where water is either costly or scarce. Additionally, it is employed in areas where the water is saline and cannot be used in conventional surface irrigation methods like basin or furrow irrigation. This method is particularly suitable for fields with uneven terrain that are challenging to level. Furthermore, clay-based irrigation is implemented in remote areas where vegetables are both expensive and hard to come by (Borse et al., 2017). Clay based irrigation has been shown to provide a better environment for root growth than drip irrigation in these difficult soils. Clay based irrigation is also likely to be of importance in gravel or very coarse sand where it is difficult to hold water in the plant root zone.

Several annual and perennial plants, including maize, watermelons, tomatoes, and numerous other crops, have been successfully irrigated through a clay-based irrigation system (Bainbridge et al., 2006a). While conventional irrigation methods may not be effective, clay-based irrigation provides a solution for cultivating crops in saline soil with pH levels as high as 10.5 or using saline water. Remarkable tomato yields of 27 tons per hectare were achieved using saline irrigation water with an electrical conductivity (EC) of 10.2 mmhos/cm, compared to only 15-25 tons when utilizing fresh water with an EC of 0.4. In comparison to drip irrigation, clay-based irrigation system proved to be effective in relocating or reducing salt in the crop's root zone (Bainbridge et al., 2006). The use of clay-based irrigation has demonstrated high water efficiency and uniform application, making it particularly effective in managing irrigation water across various cropping systems (Ashrafi et al., 2002). It involves connecting or joining clay pipes end to end to form elongated tubes of the desired length. These clay tubes are then buried at the desired depth in the soil, and a single-point source consistently provides water to them (Bhople et al., 2014). By capitalizing on the pressure head gradient along the walls of the clay-based irrigation system, water permeates directly into the effective root zone of the irrigated crops. This method proves advantageous for land restoration, particularly in arid environments. Embracing clay-based irrigation as an effective water management strategy that offers a solution to the impending water crisis and has the potential to expand the total irrigated land area in Ghana (Tripathi et al., 2017).

Adopting clay-based irrigation can be economical because it creates rural employment, the maintenance cost is low and can be utilized in place of pressurized water systems, which are sometimes challenging to install and operate at remote sites as well as being expensive. Clay based irrigation is more affordable and dependable than several high-tech drip irrigation systems, which typically require level fields and are more susceptible to damage by animals or being clogged by insects. The clay-based irrigation system can be built entirely from locally accessible materials and expertise (Mondal et al., 1987). Considering the initial investment cost for the clay-based irrigation system, the system per hectare generates a sizable net profit. The potential gains would be significantly higher in regions with expensive water costs (due to labour or pumping expenses) and limited water resources (Bainbridge & Virginia, 1990). An additional benefit derived from clay-based irrigation is weed control. The crop-weed competition for water will be curtailed to its bare minimum in terms of weed quantity, intensity, and biomass. Research indicates, that weeding accounts for up to 30% of labour costs, which could be used more effectively. The precise distribution of water reduces weed development, labour costs associated with weeding and weed competition with crops for water and nutrients. The implementation of clay-based irrigation decreases the dry mass of weeds to 62 kg/ha from 465 kg/ha when employing basin irrigation (Bainbridge et al., 2006).

The self-regulating low energy clay-based irrigation (SLECI) system consists of short-length clay pipes of varying length, width, and thickness and may be linked or set end to end to create longer tubes of a required length. The clay pipes are continuously supplied with water from a source while being buried in the ground. Water moves from the water tank into the porous clay pipe, from which the water seeps into the root zone in the soil where water gradient pressure exists. A wetting front is created along the whole length of the lateral as a result of the water seeping out of the porous pipe wall.

Problem statement

The increasing need for food is putting a significant strain on water, soil, and land resources worldwide. Rapid urbanization has led to the depletion of these resources and the encroachment on productive farmland. Moreover, approximately 33% of the Earth's soil is experiencing varying degrees of deterioration. The global water stress indicator, SDG 6.4.2, shows regional variations, with an increase from 17% in 2017 to 18% in 2018. Water resources per capita per annum are decreasing rapidly as the world's population rises, from 6994.9 m^3 in 2012 to 5630.2 m^3 in 2018. 72% of all groundwater and surface withdrawals worldwide are used for agriculture, mostly for irrigation. Out of the total 342 million hectares of irrigated land worldwide, approximately 38% is considered to be in good condition, whereas the remaining 62% has suffered from damage or degradation ([Food and Agriculture Organization], FAO 2021). Agriculture has a significant role to play to ensure a positive influence on the climate and developmental goals as well as reducing pressure on essential food production resources such as water and land. Sustainable agriculture systems may directly enhance the condition of the land, the soil, and water resources as well as cause benefits for the environment. To achieve these goals, it is crucial to have precise data and implement a substantial change in the way these assets are managed (FAO, 2021). In light of the declining precipitation and more frequent periods of drought during Ghana's rainy season, the Ministry of Food and Agriculture of Ghana is promoting the use of irrigation as a crucial approach to cope with climate variability (MOFA, 2014).

Rainfall-dependent farming generates 60 % of global food production on 80 % of the world's cultivated land, whereas farming under irrigation produces an additional 40 % of the remaining 20 % of the world's land (FAO, 2021). This indicates that a shift or focus on expanding cultivable land under irrigation will result in more food production per unit area of land. To ensure the preservation of the environment, it is crucial to uphold the necessary levels of agricultural output. By prioritizing and expediting the safeguarding of land and water resources, we can concentrate on advancements in management and technology. The implementation of innovative techniques and tools can aid in the cultivation of neglected soils, mitigation of drought, and resolution of water limitations (Balana, Bizimana, Richardson, Lefore, Adimassu, & Herbst 2019). Mueller et al. (2012) and Nagaraja, Prousta, Todeschinia, Rullic, & D'Odorico (2021), emphasized that irrigation is indispensable for bridging the productivity disparity between the current and maximum attainable yields in numerous regions across the globe. Africa has the potential to irrigate 42.5 million hectares, based on available water and land resources (FAO Aqua stat, 2005; Lebdi, 2016), however, about 6 % of the total land is equipped with irrigation systems (Scheumann, Houdret & Brüntrup 2017). In the case of Ghana, 226,909 hectares of the 15,722,500 hectares of agricultural land make it 1.4 % of agricultural lands under irrigation. High irrigation investment costs, lack of credit, low profitability in the field, low prices for food at international markets, distant markets, unfavourable topography and soils, labour, etc (Lebdi, 2016).

There has been a severe lack of success in the adoption of irrigation systems to increase food production in Sub-Saharan as well as Western Africa (Wani et al, 2009). Water-efficient irrigation systems, such as drip, sub-surface, and sprinkler irrigation, come with significant upfront installation and maintenance expenses, additionally, skilled labour is also required before these irrigation systems can successfully be operated and maintained. Even though a greater proportion of global drylands are currently being cultivated by small-holder farmers, small-scale, inexpensive irrigation systems have been generally disregarded in favour of expensive, sophisticated, and large-scale irrigation systems. Conventional irrigation systems that could be very helpful to smallholder farmers have not received enough attention or study (Bainbridge, 1987a). In light of these factors, it is crucial to design and make available irrigation systems, which can easily and affordably reduce soil evaporation (Batchelor et al. 1996: Bainbridge, 2001). The clay-based irrigation system is highly efficient since the rate at which water seeps out of the clay tube or clay based is influenced by the rate at which the plant uses water (Bainbridge & Virginia, 1990b). This makes clay-based irrigation superior to drip irrigation and traditional surface irrigation systems.

According to Bainbridge et al. (2006), the yield of melon cultivated under clay-based irrigation was 25 tons/hectare with seasonal crop water use of 2cm per hectare compared to melon yields of 33 tons/ha cultivated under flood irrigation with seasonal water use of 26 cm per hectare. Although a yield reduction of 32% was recorded, there were 92.3 % savings in irrigation water. Cultivating cucumber under clay-based irrigation with seasonal crop water use of 1.9 cm per hectare produced yields that were comparable to cucumber yield grown under manual (hand) irrigation with seasonal crop water use of 7.3 cm per hectare. Water use efficiency of 17 kg/cm was recorded in beans cultivated with clay-based irrigation compared to 10 kg/cm for beans grown under traditional basin irrigation, 12 kg/cm for beans grown under subsurface drip, and 13 kg/cm for beans grown under drip irrigation system (Bainbridge et al., 2006). Siyal et al. (2009) reported 80 % water savings when clay-based irrigation was compared to surface irrigation methods. Additionally, a 5-16 % increase in the yield of vegetables (turnip, okra, and eggplants) was observed when the productivity of crops cultivated using clay-based irrigation was compared to that of crops grown using surface irrigation techniques.

Clay-based irrigation systems are not only more effective than drip irrigation systems but they can also be used in the absence of pressurized, filtered water supply. In terms of water supply, a clay-based irrigation system may require 3 to 4 days or weekly supply of water, whereas even a small interruption of a drip irrigation system's water supply owing to a pump or filter failure can cause major issues and expensive crop loss (Bainbridge et al., 2006).

Additionally, a clay-based irrigation system is not sensitive to clogging and can be manufactured or assembled with locally available materials and skills compared to drip systems (Bainbridge, 1987). Clay based irrigation should be considered in areas where there is a limited supply of water or where soil or irrigation water characteristics make traditional irrigation systems unworkable (Bainbridge, 1987). Clay based irrigation can serve as a feasible alternative to sprinkler or drip irrigation in regions with limited water supply. This method is especially suitable for farmers who rely on their small plots of land to make a living (Tripathi et al., 2017). According to Sen et al. (2007), the efficiency of irrigation is influenced by plant species, soil type, soil fertility, soil structure, and weed competition. There are limited scientific studies on clay-based irrigation relating to these factors that influence the efficiency of irrigation. The clay-based irrigation system still needs to be sufficiently understood for design requirements to change. Due to inadequate information and a lack of suitable standard designs for various crops, the clay pot technique has also not been widely adopted even with its enormous benefits. Siyal, Van Genuchten and Skaggs (2009) assert that improved operational guidelines and technical standards must be created to improve clay-based irrigation method performance and adoption.

There is a gap in technical knowledge in the application and subsequent adoption of SLECI system by smallholder farmers for the irrigation of high-value crops like vegetables in dryland regions. Despite the apparent advantages of SLECI system, factors that have the potential to influence the system's performance have not been satisfactorily described. This research seeks to evaluate the SLECI system using bell pepper (*Capsicum annuum*) as a test crop.

Research Objectives

General Objectives

The overall aim of the research is to evaluate the SLECI system using bell pepper (*Capsicum annuum*) as a test crop.

Specific Objectives

Specific objectives of the study included;

1. Evaluating the performance of the SLECI system as influenced by source of irrigation water and different soil types.
2. Assessing the effect of different irrigation systems and fertilizer applications on bell peppers.
3. Evaluating bell pepper's growth, yield and productivity response to varying SLECI system burying depth and fertigation levels.
4. Assessing the effect of irrigation water salinity levels on bell peppers grown under the SLECI system.
5. Simulating water and salt dynamics under the SLECI system.

Research questions

1. Will the source of irrigation water and different soil types have any impact on the performance of the SLECI system?
2. What will be the effect of different irrigation systems and fertilizer applications on bell peppers?

3. What will be bell pepper's growth, yield and productivity response to varying SLECI system burying depth and fertigation levels?
4. What will be the effect of irrigation water salinity levels on bell peppers grown under the SLECI system?
5. Will the simulated water and salt dynamics SLECI system differ from the results from the experimental field?

Research Hypotheses

The following hypotheses were formulated to guide the study:

1. Ho: Source of irrigation water and different soil types will not affect the performance of the SLECI system.

   H1: Source of irrigation water and different soil types will affect the performance of the SLECI system.
2. Ho: Bell pepper will not respond to different irrigation systems and fertilizer application.

   H1: Bell pepper will respond to different irrigation systems and fertilizer application.
3. Ho: Varying burying depth of the SLECI system and fertigation will not influence bell pepper's growth, yield and productivity.

   H1: Varying burying depth of the SLECI system and fertigation will influence bell pepper's growth, yield and productivity.
4. Ho: Bell pepper will not respond to different water salinity levels under the SLECI system.

H1: Bell pepper will respond to different water salinity levels under the SLECI system.

5. Ho: The simulated distribution of salt and water will not differ from the actual distribution of water and salt under the SLECI system.

   H1: The simulated distribution of salt and water will differ from the actual distribution of water and salt under the SLECI system.

Justification

By the end of the research, the SLECI system will be shown as an ideal system for smallholder farmers. It is a modified version of traditional clay-based irrigation methods that provides several benefits over surface and drip systems. These advantages include reducing crop stress, minimizing evaporation, preventing weed growth, and decreasing chemical leaching.

To improve land productivity, the adoption of the SLECI system, which effectively delivers nutrients and water directly to the root zones of crops. This approach has the potential to significantly enhance the productivity of agricultural areas. This method increases crop production, yield, and quality while using less water compared to other irrigation methods. The efficiency of converting water into food is crucial due to the limited availability of irrigated and rainfed agriculture. Implementing the pitcher irrigation system can significantly reduce evaporation and improve water conservation and usage efficiency in regions with water scarcity. The SLECI system regulates water release based on soil moisture deficit and tension, allowing the direct seepage of water into the plant root zone from the pitcher's wall.

The water supply in Sub-Saharan Africa, including Ghana, is crucial for increasing crop productivity. However, the presence of weeds can lead to increased water demand by crops due to higher evapotranspiration. Soils with abundant weed growth have higher evapotranspiration compared to weed-free soils. Implementing the SLECI system can reduce surface water evaporation and control weed growth. This system ensures that water reaches the root zone of crops, depriving weeds of water and impacting their growth. Weeds, which contend with crops for scarce resources such as water and space, lead to reduced water productivity and impede agricultural production.

Salinity affects crop production by hindering nutrient uptake, reducing water absorption, stunting growth, and inhibiting plant reproduction. SLECI system allows crops to be grown in highly saline or alkaline soils, as well as utilizing salty water that is unsuitable for traditional irrigation methods like sprinklers or drip systems. By accumulating salt at the soil's surface or within the pitcher walls, this system ensures that the water in the plant root zone has lower salt content compared to the water inside the clay tube. Therefore, the SLECI system is particularly advantageous for food production in regions dominated by saline water or with limited access to non-saline water sources.

Irrigation water sources can contain plant pathogens. Hong & Moorman (2007) found numerous species of Phytophthora and Pythium in irrigation water worldwide. These pathogens cause issues like damping off, foliar blights, and fruit rots. SLECI system is recommended for plants susceptible to diseases and damage from wet leaves or overwatering. Using the SLECI system eliminates wet soil surfaces, reducing weed growth. Weeds can harbour disease-causing organisms, so this method reduces the need for pesticide spraying and creates a more natural growing environment.

The amount of fertilizer needed for crops can be reduced by 25-40% if the SLECI system is used. This allows for uninterrupted fertigation, which is important as a large portion of crop production expenses go towards replenishing soil nutrients. Fertigation is more effective due to the higher density of roots in a concentrated root zone. It increases crop yields, performance, and efficiency. Additionally, the lower water application rate of the SLECI system prevents the leaching out of nutrients from the effective root zone of crops.

The SLECI system is beneficial for smallholder farmers who face challenges in cultivating crops due to uneven topography and odd-shaped lands. It is adaptable to various field shapes, soil types, land sizes, and even difficult terrains like slopes and undulations. By adopting the SLECI system, farmers can expand their production to areas that cannot accommodate conventional irrigation systems, thereby increasing their irrigable acreage.

The adoption of SLECI system by Ghana Irrigation Development Authority can help increase the total cultivable land under irrigation in Ghana due high adaptability of various terrains, the potential to reduce production cost (irrigation service charge) as well as the utilization of poor irrigation water quality.

Structure of thesis

Chapter One, the introduction gives a background statement, the problem statement and sets the general and specific objectives, as well as research questions and hypotheses. It also describes the justification for undertaking the study. Chapter Two encompasses a review of relevant literature that supports this research. Chapters Three to Seven are structured as journal articles that deal with the five specific objectives set out in Chapter One. Each of these chapters will have its Introduction, Materials and Methods, Results and Discussion as well as a conclusion. Chapter Eight presents' conclusions and recommendations. In this chapter, research questions that were set out in chapter one is revisited, while contributions from research findings as well as recommendations for future research are also included.

CHAPTER TWO

LITERATURE REVIEW

Irrigation and its importance

Irrigation is undertaken to support the growth of crops, in dry regions and during periods of insufficient precipitation (Snyder & Melo-Abreu, 2005; Aydogdu et al., 2015). Dryland agricultural production is limited by a water deficit induced by low and variable patterns of precipitation and high evaporative demand. In these circumstances, irrigated agriculture offers an option. It lessens or eliminates the water deficit that limits plant growth, enabling the cultivation of crops in regions where the environment is too dry for such purposes. It also boosts agricultural yields in regions where available soil water for plant growth is a factor that limits yield for portions or the entirety of the growing season. (Reinders, Stoep & Backeberg 2013).

Water, food production and food security

Irrigated agriculture produces a substantial amount of food on an economic and food production scale (Foley et al., 2011; Caron et al., 2018; Baumgartner et al., 2019). Throughout the world, irrigation is probably the most important use of water, as it accounts for 60% of the world's freshwater extraction (UN-Water, 2015). Irrigation plays a vital role in agriculture, especially for crops that rely heavily on water supply (Adhikary & Pal, 2020). In recent times, advancements in cost-effective drilling and pumping techniques have brought about a transformative change in agriculture. These innovations have granted farmers affordable and dependable means of accessing water for their crops. The significant role of irrigation in addressing global food requirements is evident, as approximately 40% of the world's food production currently originates from just 20% of the irrigated land (Abdel-Mawly, 2004; Kadiresan & Khanal, 2018). Water is vital for crops grown purposefully for agricultural purposes, such that the provision of supplementary water in addition to rainfall is often carried out to intensify crop production (Yang, Reichert, Abbaspour & Zehnder, 2003; Alexandratos & Bruinsma 2012). The rise in incomes and economic progress is also anticipated to shift the growth of food demand towards dairy-based products, fish and meat (OECD/FAO. 2016). The impact of this trend on water resources will be significant, as the production of meat and dairy requires more water compared to cereals. It is projected that around 90% of the necessary increase in global food production by 2050 will occur in developing countries. These countries' share of global food production is expected to rise from 67% in 2007 to 74% in 2050 (Alexandratos & Bruinsma 2012). A significant portion of the ongoing food insecurity in 2050, similar to the present time, will be prevalent among impoverished households in nations with lower incomes. Additionally, it will be observed in regions where natural resources have been depleted or degraded, rendering them incapable of sustaining viable livelihood activities for small-scale farmers. The primary factor contributing to food insecurity is persistent poverty, which hinders households from acquiring an adequate amount of food, especially during times of scarcity or elevated prices (FAO, 2017). Given the importance of smallholder farmers, the sector must be transformed with a focus on irrigation inclusivity, as irrigation is essential to agriculture (Garrity et al., 2010; Tscharntke et al., 2012; Dethier & Effenberger, 2012; Herrero et al., 2014; Adeniyi & Dinbabo, 2020).

Irrigation in Africa

Regions characterized by unpredicted and insufficient precipitation for agricultural growth and during dry seasons require irrigation, which is essential to maintaining food supply. Additionally, it has become increasingly important in areas where rainfall patterns are unpredictable. The use of irrigation leads to higher crop yields, typically ranging from 30-60% more than rainfed crops. This is due to the support it provides for the cultivation of high-yielding seeds and the application of additional inputs like fertilizers (Rosegrant, Ringler & Zhu 2009). A little over one-third of the world's harvested land, 40% of the total global food output is today produced through irrigated agriculture, demonstrating the critical role that irrigation plays in ensuring food security. Future food production will depend even more heavily on irrigation (Rosegrant et al., 2009; Ringler 2017). Roughly 70% of all water withdrawals worldwide, including groundwater withdrawals, come from irrigation, which also provides more than 80% of the water used for consumptive purposes after water withdrawals (FAO, 2016; Ringler, 2017; WWAP 2019). Large-scale irrigation schemes are typically built by the government and receive ongoing support. They primarily aim to cultivate staple crops like rice or cash crops for exportation. On the other hand, small-scale irrigation involves smallholder farmers who rely on various sources and technologies to irrigate their land. This is done either to supplement rainfall during the rainy season or to irrigate their crops during the dry season, with a particular focus on high-value crops such as vegetables. A further type of irrigation system is the community-managed irrigation scheme, in which a greater number of farmers co-manage the system, usually with institutions for administration they have established on their own (IEA, 2019). Aside from its being vital to crop production and food security, irrigation helps to mitigate the high reliance on food imports in Africa (Mekonnen et al., 2019). According to Xie et al. (2018), increased investment in irrigation can significantly decrease food import dependency, ranging from 54% to 17-40%, depending on factors such as the cost of irrigation technology. Additionally, irrigation offers potential advantages such as the cultivation of a wider range of valuable and nutrient-rich crops, the ability to intensify livestock systems through irrigated fodder, and higher income generation (Domènech, 2015; Passarelli et al., 2018).

Irrigation Adoption and Expansion in Africa

Approximately 630 million hectares of land in Africa, which accounts for 60% of the global arable land, is deemed suitable for farming. This land directly sustains the livelihoods of more than 70% of the population on the continent through both subsistence and commercial agriculture (Biteye, 2016; Phiri et al., 2020). According to You et al. (2011), the potential expansion of irrigated land in Africa over the next 50 years is estimated to be 24 million hectares, which represents a 177% increase over the 13 million hectares of equipped irrigated land now in place. Most of this region, measuring 21 million hectares, would be located in Sub-Saharan Africa. The economic potential for growth relies heavily on the expense of irrigation, which encompasses the costs of the utilized technology, additional workforce, increased use of agrochemicals, and improved seed quality. The costs of irrigation technology for small-scale systems owned by individual farmers can vary from a few hundred to several thousand US dollars per hectare. Consequently, small-scale irrigation is most feasible for cash crops or high-value food crops that yield revenues surpassing US$2,000 per hectare. There is limited scope for expanding small-scale irrigation by farmers to irrigate staple crops (Ringler, Mekonnen, & Xie & Uhunamure 2020). Public, large-scale systems can incur a cost of $3,200 to $8,800 per hectare or more if the construction of roads, dams, electricity, and agro-processing infrastructure is included. The justification for such systems typically lies in the reduction of food import reliance on essential crops or the generation of foreign exchange through cash crops. Furthermore, these systems often offer supplementary benefits such as domestic water supply and employment opportunities in related agro-processing activities (Rosegrant, Ringler, & De Jong 2009).

Adoption of Irrigation technology

Small-scale irrigation (SSI), is the adoption of a small-scale irrigation system that utilizes technology that can be easily managed, operated, and maintained by individual farmers (Carter & Howsam 1994; Namara, 2010). These technologies are vital in increasing crop productivity with the additional benefit of being a viable climate change adaptability practice (Balanaa, Bizimana, Richardson, Leforec, Adimassu & Herbst 2020). Yengoh, Armah and Svensson,

(2009) emphasized that numerous governments and various development organizations have made efforts to enhance agricultural productivity and profitability through the introduction of agricultural technologies, however, the outcomes have been limited. Factors such as limited access to credit, lack of technical expertise, farmers' risk aversion, and high costs of investment and operations, among other factors hinder agricultural technology adoption in developing nations (Doss, 2006, Burney & Naylor 2012, De Fraiture & Giordano, 2014, Giordano & de Fraiture 2014, Namara, Hope, De Fraiture & Owusu, 2014, Bizimana, James, & Richardson 2019). Yengoh, Armah and Svensson (2009), reported that throughout numerous instances, the implementation of these technologies in trial communities has proven unsuccessful when attempting to reach a wider population.

Notwithstanding, the lack of extension provision and adequate technical assistance to farmers SSI continues to expand in Ghana (Namara, 2010; Giordano, de Fraiture, Weight & van der Bliek, 2012; Namara, Hope, De Fraiture & Owusu 2014), compared to extensive public irrigation schemes, this SSI serves 20 times more land area and employs 45 times more people. Evans, Giordano & Clayton (2012) indicated that as of 2010, nearly 185,000 hectares were encompassed by SSI, supporting 500,000 small-scale farmers. The utilization of SSI has the potential to benefit around 700,000 farmer households and as well as increasing total lands under irrigation (Drechsel, Graefe, & Fink, 2007; Drechsel, Graefe, Sonou, & Cofie 2006; FAO, 2012). There is also potential for utilizing shallow groundwater through different methods of water lifting, distribution, and application technologies. This can be combined with the enhanced utilization of versatile small reservoirs (Barry et al 2010; Namara et al., 2014). According to Williams, Balana, Appoh, Kadyampakeni and Muthuwatta (2016), the rising demand for vegetables has been driven by the increasing income and evolving dietary preferences of the expanding middle-class urban consumers. As a result, the likelihood of SSI adoption is expected to grow. The successful implementation and expansion of different SSI technologies rely on factors such as biophysical conditions, economic viability within the value chains, and various other considerations.

Availability of water for irrigation

Presently, the majority of the food needs are obtained from irrigated agriculture, but due to the inappropriate organization of irrigation schemes, farmers cannot obtain desirable outputs in terms of food production. Water for agriculture is an indispensable component of food security. Global water consumption between the years 1996-2025 is estimated to increase by 16% (Rosegrant & Chai, 2001). Due to high water consumption, by industry and urban sectors, there is an increase in pressure on irrigated agriculture sector (Pareira, 2003, Afzal et al., 2016). Climate fluctuations are anticipated to diminish the amount of water accessible for farming and, consequently, for crop output. Given that food production needs to double by 2050 and that the world's population is expected to exceed 9 billion by then, improving agricultural efficiency is crucial (Ragab et al., 2015). As the Global population increases, there is heightened competition among various sectors such as energy, agriculture, fisheries, livestock, mining, and others. The consequences of this competition on livelihoods and the environment are difficult to predict (Alexandratos & Bruinsma 2012). Global freshwater reserves are anticipated to face increased pressure in numerous areas, as more than 40% of the global population is estimated to reside in river basins that will experience significant water scarcity by 2050. As the demand for water resources intensifies, it creates conflicts among various users and industries, as well as excessive strain on the environment (OECD. 2012).

Challenges facing water resources

The increase in temperature, coupled with irregular rainfall patterns has, caused a scarcity of irrigation water and has resulted in low food production. Currently, water resources are characterized by heavy degradation and near depletion. Climate change is predicted to decrease annual rainfall even further (Hitomi, 2007). The global population is projected to increase two folds within the next five decades, necessitating the need to maximize productivity in existing agricultural regions as well as less productive areas (Pimentel et al., 2004; Al-Omran, Wahb-allah, Wahb-Allah, Nadeem, & Al-Eter, 2010). The ongoing depletion of water resources globally, particularly in arid regions, has become a pressing concern. The most valuable resource and a barrier to agricultural growth is water (Al-Omran & Louki, 2011). Water scarcity occurs when there is a shortage of freshwater due to high demand, conversely, factors contributing to water scarcity can be anticipated, prevented, or reduced in their impact (FAO, 2017). Globally, there will be enough freshwater resources to fulfil the agricultural demand by 2050, provided that suitable technologies and investments are implemented. However, there will be a notable disparity in water availability both between and within countries. Industries are in competition with agriculture for water usage, leading to an increasing number of countries or regions experiencing alarming levels of water stress and pollution (FAO, 2003; Turral et al., 2011; Kumar & Padhy 2013; FAO, 2015; Kadiresan & Khanal, 2018).

Irrigation Water Quality

Water availability is a major constraint on agriculture and the main source of agronomic constraints in semi-arid areas (Boudjabi, Kribaa, & Chenchouni 2019). Crop productivity and crop product quality are negatively impacted by irrigation water quality (Etteieb et al., 2017). Since 80–90% of plants are made of water, having access to clean water is essential for productive agriculture (Taiz & Zeiger, 2010). The amount of dissolved salts in the solution determines the quality of the water (Salisbury & Ross, 1985). According to Sonneveld and Voogt (2009), the makeup of nutrient solutions is influenced by the substantial amounts of nutrients present in the irrigation water. As such, it is imperative to conduct a water quality test before use (McCauley, Jones, & Jacobsen 2005). The availability and solubility of nutrients for plants are greatly influenced by the pH level (Styer & Koranski, 1997). According to Calpas (2002), a nutrient solution's ideal pH range falls between 5.5 and 6.0 to provide plants with the best possible nutrient availability. Irrigation has the potential to affect soil permeability, according to Raju et al. (2016), water quality is evaluated by evaluating the effects of irrigation water on crops and soil properties, as noted by Guemmaz et al. (2019), Koull et al. (2013), and Wimbaningrum et al. (2016). Thus, as noted by De Troyer et al. in 2016, it is imperative to monitor water quality. Roy et al. (2015) found that appropriate soil and water management techniques, along with high-quality water, can maximize agricultural productivity. Zhang et al. (2012) pointed out that the Sodium Absorption Ratio (SAR) is important because high salinity or sodium levels can cause problems with soil sodicity, as Akinbile (2012) pointed out. According to Shaki and Adeloye (2006), an excessive concentration of sodium in water can replace calcium and magnesium ions in the soil, decreasing permeability and compressing the soil. While elevated magnesium concentrations might result in higher alkalinity, high chloride concentrations and boron concentrations can be harmful to plants. Other substances, such as heavy metals, might also be detrimental to crops. It is significant to note that high salinity inhibits the growth of plants and makes it more difficult for their roots to absorb water because it raises the osmotic pressure around the roots of the plant, which is brought on by an elevated number of water-soluble ions (Chenchouni, 2017). According to Boudjabi et al. (2019), irrigation water characterized by an electrical conductivity level of greater than 0.7 mS/cm will negatively affect water flow. Chenchouni (2017) claims that salinity can also have an impact on the flocculation and deflocculation processes, which alter the structure of the soil. The quality of the irrigation water determines how much soil salinization is influenced by soil characteristics. Miyamoto and Chacon (2006) found that clay-textured soils are more prone to salinization when watered with saline water. As noted by Belaid et al. (2010), several factors, including the salt content of the water, high evapotranspiration, plant water uptake, and the amount of water sprayed, can be responsible for the increase in soil salinity caused by irrigation. Tedeschi and Dell'Aquila (2005) explore how several parameters such as ion migration, soil permeability, salt solubility, and irrigation intensity affect salt leaching in irrigated soils. Since plants can only absorb a certain quantity of soluble salts. Nakayama and Bucks (1986) found that water drainage correlates with irrigation intensity, and together determines the vertical dispersion of these salts in the soil.

Subsurface Irrigation system

Subsurface irrigation involves water being held at a specific depth beneath the soil's surface, through which water is supplied beneath the soil surface. Water can be moved for subsurface irrigation using a variety of conduits, including plastic drip tape with emitters, pots, pitchers, perforated pipes, porous clay pipes etc. Water moves into the soil as it passes through the buried medium, hence moistening and raising the soil's moisture content (Bainbridge, 2001, Ashrafi et al., 2002). Studies by Batchelor et al. (1996), Hagazi (1998), and Bainbridge (2001) have shown that subsurface irrigation systems have a notable water consumption efficiency. A wide variety of crops are increasingly being watered using the subsurface approach (Camp, 1993; Singh et al., 2006). Using permeable clay pipes is a novel approach to conventional subsurface irrigation (Siyal & Skaggs, 2009). Kong et al. (2012) reported that subsurface irrigation reduced water use by 7% while producing a 4% greater yield of bell peppers than drip irrigation. It was discovered that under subsurface irrigation, root length densities were 2.44 times higher than under border irrigation. They concluded that subsurface irrigation promotes deep root development in the soil together with crop root growth, which increases the uptake of nitrogen, decreases nitrogen leaching, improves bell pepper yield, and increases nitrogen usage efficiency.

Clay based irrigation system

Subsurface irrigation utilizing clay pipes comprises the burial of permeable clay pipes beneath the soil surface and the provision of water to the pipes, allowing it to gradually infiltrate the soil and reach the root zone. To enhance the efficiency of subsurface irrigation using porous clay pipes, it is necessary to establish rules and design criteria for managing and installing the system. After installation, water is transported through various mediums whereas the crop is cultivated on the surface. Plant roots uptake water and, facilitated by capillary action, transport the moisture upwards to the surface of the soil, where it is accessed by the crops' roots (Ashrafi et al., 2002). Qiaosheng et al. (2007) Vasudevan et al. (2011), Abu-Zreig et al. (2012) and Vasudevan et al. 2014) reported that self-regulative ability is a distinct feature of clay-based irrigation systems concerning water discharge. Bainbridge (2001) & 2007; Vargas (2012), reported that in comparison with conventional irrigation systems, clay-based irrigation exhibits a higher water application efficiency. Studies by Masri (2002), Elavarasan et al. (2014), Ashrafi et al. (2002), Vargas et al. (2010), Jangir (2012), Martínez deAzagra and Del Río (2012) indicate that it is extensively and successfully been used in arboriculture, horticulture and reforestation. The continuous-flow feature of clay-based irrigation permits fertigation (Setiawan et al., 2006) and the use of low-quality water for irrigation (Bhatt et al., 2013). Clay based irrigation uses the soil's matric suction, which sets it apart from subsurface drip irrigation. Backpressure in the soil can occasionally impede the delivery of water in subsurface drip irrigation (Lazarovitch et al., 2006; Gil et al., 2011). The same concept governs the operation of buried porous clay pipelines (Martínez de Azagra Paredes & del Río San José, 2019). Clay based irrigation is a self-regulating system that can efficiently irrigate a variety of crop types while also having significant water-saving potential (Igbadun & Barnabas 2013; Tripathi et al., 2017). Clay based irrigation system proves beneficial in challenging circumstances characterized by high salinity, extreme aridity, limited water availability, and constrained resources. Additionally, there is a substantial decrease in weed competition among plants which alters the microclimate. Moreover, clay-based irrigation has the potential to utilize as little as 10% of the water consumed by traditional surface irrigation methods. By ensuring controlled water delivery, it mitigates issues related to waterlogging and rapid evaporation. Clay based irrigation also facilitates quick establishment and accelerated growth of plants, making it suitable for steep slopes and areas with fast drainage where conventional irrigation techniques are impractical (Tripathi et al., 2017). In regions where temperatures reach extreme levels and traditional irrigation techniques prove ineffective, the utilization of clay-based irrigation system emerges as a viable solution. This method shows particular promise for cultivating and nurturing orchards on small parcels of land in arid zones with soil that has low water retention capability (Vasudevan et al., 2014).

SLECI system

The SLECI system consists of fired, short-length clay pipes of varying length, width, and thickness and may be linked or set end to end to create longer tubes of a required length. The clay pipes are continuously supplied with water from a source while being buried in the ground. The PE-hose pipe segment is connected to a water source (water tank). Via the PE hose, water moves from the water tank into the porous clay pipe. Subsequently, water seeps into the root zone in the soil where water gradient pressure exists. A wetting front is created along the whole length of the lateral as a result of the water seeping out of the porous pipe wall (Figure 1). The clay tube is buried in the depths of the plants and near the plants. Depending on the soil tension, the distance should not exceed 30 cm in sandy soil resp. 50 cm in loamy soils. The mechanism of water transportation via clay tubes is based on evaporation from the clay tube surface into the soil. The water transport via evaporation depends on the soil tension: Dry soil has a high soil tension (150 – 200 mbar), while moist soil has a low soil tension (< 120 mbar). The clay tubes themselves have a higher suction tension than the soil (Hansmann, 2018). The hydraulic gradient and seepage rate along the SLECI system wall increases as soil water declines as a result of evapotranspiration and corresponding changes in soil water pressure head. One end of the irrigation line has to be connected to a water tank; the other end has to be closed firmly with an end cap. To check the water flow in the irrigation –

line at the beginning of the operation, the end cap has to be removed. Therefore, this end of the irrigation line should be positioned above the surface of the ground. If water flows freely, the irrigation line will work. In this case, the end cap has to be replaced immediately. For maintenance purposes, the irrigation line has to be closed by closing the valve on the water tank (Hansmann, 2018). It is important, that the irrigation line will be ventilated in the case, that the irrigation - line had sucked in a higher amount of air. This can happen when the water tank runs empty. For ventilation, open the valve of the tank filled with water and remove the end cap. When the water flow at the end of the line is constant, replace the end – cap and the system work (Hansmann, 2018).

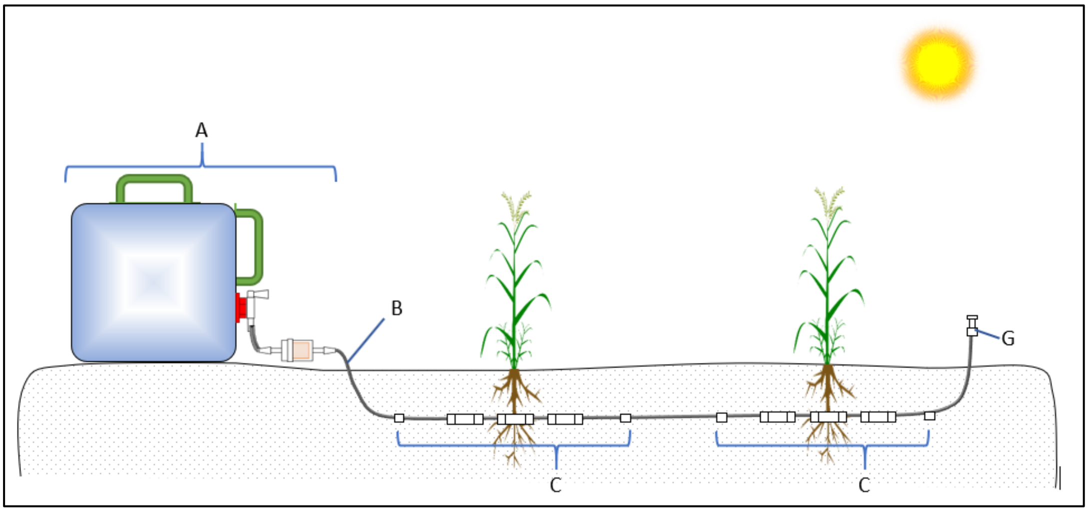

Figure 1: Schematic layout of SLECI system

Factors affecting the performance of clay-based irrigation system

Self-regulation is a vital feature of pitcher irrigation (Stein 1997, Abu-Zreig et al. 2006; van Iersel et al., 2010; van Iersel et al., 2013). The close relationship between the plant, the soil, the water tension in the soil, and the clay pipes allows for this self-regulation. When the soil is dry, coupled with high soil water tension, water is released into the soil. Water flow diminishes or stops as a result of a drop in soil water tension brought on by an increase in soil moisture content. The porosity and hydraulic conductivity of the clay pipe material are essential for pitcher irrigation to work effectively (Stein 1996, Dührkoop, 2008, Dührkoop, 2011, Abu-Zreig et al., 2006). The potential evapotranspiration of crops and the conductance of clay pipes both directly impact the rate of seepage; these factors are controlled by the moisture content of the soil matrix and the surrounding environment, which includes the soil, plants, climate, and clay pipe (Adhikary & Pal, 2020).

Empirical review of Pitcher irrigation

When compared to water with buckets and sprinkler irrigation, pitcher irrigation pots can save up to 70% of the water used, according to Daka (1991).

Mondal et al. (1992), reported that pitcher irrigation was successfully used for irrigation using saline water. A 10% reduction in the yield of cauliflower was observed at Ec at 12 ds/m and 15 ds/m compared with the yield obtained while surface irrigating with water of salinity of 0.04 dS/m. Water at 10 dS/m can be safely used in pitcher irrigation for cultivation, since tonnes of cauliflower could be harvested, parallel to harvests from surface irrigation

Stein (1998), reported an increase in dry matter of maize and water use efficiencies with pitcher irrigation.

In a study conducted by Siyal (2008), the water consumption for cultivating turnips was calculated using pitcher irrigation. A comparison was made between pitcher irrigation and flood irrigation, revealing that pitcher resulted in greater water savings. The clay pipe method achieved a turnip production of 11 tons per hectare, surpassing the yield obtained through conventional flood irrigation by approximately 20%.

Siyal et al. (2011) reported that 80% water conservation was achieved with clay pipe irrigation when compared to conventional surface watering techniques. Furthermore, compared to conventional surface watering techniques, this system produced a 5–16% higher crop production observed in turnip, aubergine and okra.

Fresh water and saline water with salinity levels of 1.2 dS/m and 10 dS/m were used in a study on bottle gourd cultivation by Siyal et al. (2015). The experiment's conclusions showed that pitcher irrigation greatly decreased water usage by around 82%–84% when compared to traditional surface watering techniques. Based on these findings, the researchers concluded that pitcher irrigation is an effective technique appropriate for dry areas with limited access to freshwater.

Bhayo et al (2018) evaluated different techniques for pitcher irrigation to determine their effectiveness in conserving water and increasing crop yield. The findings from the experiment demonstrated a significant water savings of approximately 65.56% when compared to the traditional flood irrigation method.

A study was carried out by Mahata et al. (2021) to assess pitcher irrigation's effectiveness in the production of vegetable crops. Comparing pitcher irrigation to alternative treatment methods, the results showed that pitcher irrigation boosted tomato yield parameters. The improved availability of nutrients in the soil, in particular, was credited by the researchers as the cause of the yield increase.

Babiker et al. (2021) reported that in comparison to the surface irrigation system, the maize output from the clay pipe irrigation system was 30% higher. Furthermore, water usage was decreased by 95.46% and an increase in water use efficiency of up to 2800%.

Salinity

Intensive vegetable cultivation in arid areas is especially susceptible to the detrimental impacts of salt resulting from irrigation (Yasuora, Yermiyahub & Ben-Galc, 2020). Soil salinity presents a two-fold problem for plants. Firstly, it decreases the osmotic potential of the soil water solution, making it harder for roots to absorb water. Secondly, it induces toxic reactions in plant tissues and organs as a result of the buildup of ions (Munns & Tester, 2008; Butcher et al., 2016). The classification of soil salinity is often determined through assessing the soil solution's electrical conductivity (EC). Soils are classified as salty when the electrical conductivity (EC) approaches or surpasses 4 dS/m, according to

Köster et al. (2019). Vegetable crops exhibit a relatively limited capacity to withstand high levels of salinity, often ranging from 1-2.5 dS/m.

Plant salt tolerance refers to a plant's ability to tolerate the negative effects of salt salinity, while yet maintaining normal growth and yield throughout its life cycle (Maas & Grattan, 1990; Shannon & Grieve, 1999; Parida & Das, 2005). Halophytes exhibit strong adaptation to high salinity conditions and thrive in environments with salt concentrations ranging from 20-500 mM NaCl, which is significantly greater than non-saline soils or media (Hasegawa et al., 2000; Parida & Das, 2005). In contrast, glycophytes have a lesser tolerance for salt concentrations compared to halophytes (Flowers & Flowers, 2005; Sairam et al., 2006). Regrettably, most crops, such as grains and vegetables, are glycophytes (Flowers & Flowers, 2005) and can be classified as either sensitive or moderately sensitive to salinity (Shannon & Grieve, 1999; Sairam & Tyagi, 2004; Schleiff, 2008; Munns & Tester, 2008). Osmotic stress causes a decline in soil water potential (Munns, 2002; Munns & Tester, 2008). In addition, the increase in salt concentration in saline soils, specifically NaCl, can have negative effects on other ions that are important for plant nutrition. This is because it changes the ratios of significant cations and anions, such as Na^+/K^+, Na^+/Ca^{2+}, and Cl^-/NO_3^-. When the concentration of Ca^{2+} in the soil is lower than that of Na^+, it can have a detrimental effect on the absorption of Ca^{2+} by plants (Läuchli, 1990). In a similar vein, Munns & Termaat (1986) found that an overabundance of Cl^- in the soil can impede the uptake of NO_3^-, leading to a deficit of nitrogen. Nevertheless, it is possible to control both of these elements in greenhouse circumstances by implementing irrigation with precise volumes of saline water to avoid a decrease in crop productivity. In their study, Romero-Aranda et al. (2002) found that boosting the relative humidity in a greenhouse helped to alleviate the negative impact of saline on tomato plants, preventing a decrease in output. Rising atmospheric temperature, especially in environments with low moisture content, diminishes the capacity of plants to endure high levels of salt (Shannon et al., 1994). Conversely, increasing the soil temperature to a specific threshold improves their ability to tolerate salt. Dalton et al. (1997) conducted a study to examine how different root zone temperatures (18°C and 25°C) affected the shoot biomass production of tomato plants. The study also investigated the impact of 14 degrees of salinity (range from 0 to 140 mM Cl^-) using a saline solution with a molar ratio of 2:1 $NaCl/CaCl_2$. The findings revealed that plants cultivated with a higher root zone temperature (25°C) demonstrated considerably increased biomass and yield in comparison to those cultivated at 18°C. Based on the relationship between soil temperature and root zone salinity, it is logical to consider using irrigation water with a salinity level of around 64 mM Cl^- in regions with high radiation and warm soil conditions, rather than in temperate regions with cool soil or during cloudy days (Dalton et al., 2001).

Fertigation

Fertigation represents a groundbreaking approach to irrigation, where fertilizers are administered alongside the irrigation water through a specialized system. This technique aims to enhance fertilizer utilization and enhance crop productivity (Bar-Yosef, 1999; Fanish et al., 2011). A well-designed fertigation system has the potential to optimize the absorption of water and nutrients by crops, while also minimizing the leaching of nutrients (Gardenas et al., 2005). Crop irrigation and the management of nutrients rely heavily on the quality of water, specifically its salinity (Yasuora, Yermiyahub, & Ben-Galc 2020). Fertigation has the potential to be used on both the surface and subsurface of the soil, offering an effective approach for introducing fertilizers (Segars, 2002, Solaimalai et al., 2005; Fares & Abaas, 2009: Hu et al., 2021). Under fertigation, the occurrence of excessive fertilization and irrigation remains prevalent. The excessive application of fertilizer can be detrimental to the soil and crops (Wang et al., 2015; Ullah et al., 2017; Li et al., 2018). Different methods of fertilization can have varying effects on the distribution of nutrients and water in the soil, as well as the growth of plant roots and absorption of nutrients. Research has shown that subsurface fertigation, compared to surface fertigation, leads to a greater concentration of roots at deeper levels and higher ear yield (Hernandez et al., 1991; Phene et al., 1991). However, the benefits of subsurface drip fertigation depend on soil type. In highly permeable coarse-textured soils, soil solution quickly moves downwards from the emitter, which can make it difficult to moisten the near-surface area if the emitters are buried too deeply (Cote et al., 2003). To achieve food security, there is a dilemma regarding recommending a decrease in the amount of fertilizer used. This reduction is seen as a potential risk to lower crop yields. Excessive fertilization has led to decreased efficiency in fertilizer usage, higher production costs, and an increase in nutrient loss. These issues have resulted in significant environmental problems, including the emission of greenhouse gases and contamination of groundwater with nitrates. Given the current circumstances, it is imperative to take additional measures to minimize fertilizer loss and mitigate soil degradation (Delang, 2017). A concentrated zone of roots contains a significantly higher number of roots within a given unit of soil, resulting in a more effective delivery of fertigation to the soil. The use of subsurface irrigation at a lower application rate prevents the loss of minerals from the root zone into groundwater and avoids runoff. This can lead to a reduction in fertilizer requirements by approximately 25-40%. Additionally, the system allows for uninterrupted fertigation and simultaneous multiple operations (Eckas, 2005; Umair et al., 2019). By employing subsurface irrigation, the wetted surface area is greatly reduced, resulting in minimal weed growth. This reduces the need for tilling and spraying (IWS 2022).

Fertigation & crops

Gowda et al. (2002), reported that bell pepper plants exhibited various positive attributes such as maximum height, branch count, leaf area, dry matter production, fruit yield, fruit length and girth, seed count per fruit, and dry weight of a hundred fruits. Furthermore, fertigation resulted in increased levels of quality parameters of dried peppers.

Santos et al. (2003), reported that the application of fertigation led to a 98% increase in plant height, 278% increase in leaf area, 119% increase in leaf dry matter, 67% increase in number of fruits, and 92% increase in fruit production.

Eckas (2005) stated that conserving water can lead to various advantages, such as increased crop yields, improved crop quality and reduced fertilizer usage. Subsurface drip irrigation resulted in a 26% reduction in evapotranspiration compared to flood irrigation, and a 15% reduction compared to surface drip irrigation. This reduction in evaporation losses contributed to significant gains in grain yield and biomass formation.

Kumar et al. (2008) researched how onions respond to fertigation in a semi-arid environment. The findings revealed a significant decrease in onion yield when fertigation was reduced.

Stone et al. (2010) found that corn grain yields increased with fertigation.

Gupta et al. (2010) researched bell peppers and found that fertigation led to notable enhancements in crop yield, and quality, as well as water and fertilizer utilization efficiencies.

Michalska-Klimczak and Wyszynski (2010) reported that fertigation increased beet root yield by 28.3% and sugar yield increase by 27.2%.

Olaniyi and Ojetayo (2010), found that the pepper plant height, leaf count and yield demonstrated excellent growth after being subjected to fertigation.

Ciba and Sadasakthi (2011) observed that the combination of drip fertigation, 100% water-soluble fertiliser, and biostimulants led to substantial improvements in plant height, branch count, flowers and yield.

Malik et al. (2011) discovered that fertigation was more effective in enhancing growth and yield attributes compared to other treatment combinations. Furthermore, fertigation led to increased levels of vitamin C, dry matter content, and fruit nutrient levels.

Sabli et al. (2012) noted that fertigation, in comparison with the control significantly increased bell pepper yield by 8%. The improved yield was attributed to factors such as larger leaf area, greater overall dry matter production, increased number of fruits per plant, and enhanced efficiency in fertilizer utilization.

In their research, Bhuvneshwari et al. (2013) noted that fertigation resulted in the highest plant height.

Biwalkar et al. (2015) examined the performance of sweet peppers and noted that fertigation resulted in the highest plant growth parameters.

Zang et al. (2015) reported a 24.8% improvement in yield and fruit quality attributes of tomatoes discovered when fertigation was compared to the conventional method of fertilizer application.

Xing et al. (2015) reported that tomato fruit yield was increased up to 46.9% - 61.8% respectively under fertigation.

According to Sharma's findings in 2016, the application of fertigation resulted in notable increases in plant growth and yield parameters.

Lv et al. (2019) reported that fertigation reduced the dissolved inorganic and organic nitrogen leaching by 90% and irrigation water use by 50% compared with conventional flooding.

Umair et al. (2019) reported that subsurface fertigation increased water productivity, compared to flood irrigation. The plants subjected to subsurface fertigation exhibited a roughly 10% increase in net photosynthesis, a higher intrinsic water use efficiency of 36%, and a reduced transpiration rate of 22%.

Wu et al. (2019) reported that fertigation improved maize yield and water productivity regardless of the soil type.

Rasool et al. (2020), Yan et al. (2020) and Zarski, Kusmierek-Tomaszewska & Dudek (2020) reported a yield increase in sugar beet roots, a 16.5% - 24.7% boost in tomato yield and an improvement in wheat grain yield and NPK uptake.

Chtouki et al. (2022) demonstrated that the findings indicated a notable improvement in the electron transport chain between PSII and PSI in chickpea plants that received fertigation when compared to the control treatment. Additionally, crops subjected to polyphosphate fertigation exhibited higher absorption of phosphorus, resulting in improved growth, grain yield, and overall productivity.

According to IWS (2022), fertigation resulted in a decrease of 20-30% in the use of fertilizers, resulting in a significant increase of at least 40% in crop yields overall. Notably, the quality of melon crops has also seen improvement.

Bell Pepper

Bell pepper is a perennial plant that has a relatively short lifespan and can reach heights of up to two meters. It is characterized by its hairy leaves, multiple flowers per node, and highly spicy fruit (Jovicich et al., 2007) Bell peppers flourish in regions where the daytime temperatures during the growing season range from 18 to 27°C, while the nighttime temperatures range from 15 to 18°C. When the nighttime temperatures are lower, the bell pepper plants tend to produce more branches and flowers. Conversely, higher nighttime temperatures prompt earlier flowering, especially when there is a higher intensity of light (Kamaruddin et al., 2001; Calpas, 2002; Awuku & Egyir 2018). Bell peppers are cultivated extensively in rainfed conditions, and optimal yields are achieved with a rainfall range of 600 to 1250 mm throughout the growing season, which should be evenly distributed (Hoyos & Rodriguez-Delfin, 2007).

According to Yildirim, Demirel and Bahar (2012), the growth period duration is influenced by climate and the specific variety, but on average, it takes between 120 to 150 days from the time of sowing to the final harvest. To encourage the growth of branches, the plants are sometimes pruned 10 days before transplanting. Approximately 1 to 2 months after transplantation, the flowering process begins, followed by the first harvest of green peppers about a month later (FAO 2022). When gently squeezed, the fruits are considered mature for harvesting if they feel firm and produce a distinct popping sound (Grubben & Mohamed, 2004; Hoyos & Rodriguez-Delfin, 2007).

CHAPTER THREE

EFFECT OF IRRIGATION WATER AND SOIL PROPERTIES ON THE PERFORMANCE OF SELF-REGULATING LOW-ENERGY CLAY-BASED IRRIGATION SYSTEM

Introduction

Efficient utilization and preservation of water resources hold significant global significance, particularly in times of water scarcity or unavailability. Technology for irrigation is essential since irrigation accounts for a significant portion of water usage in agriculture. Technology-based irrigation systems undoubtedly save a lot of water, but technical barriers limit their adoption (Bainbridge 2001; Siyal, van Genuchten & Skaggs 2009; Kumar & Rajitha 2019; Khamidov et al 2023). The pitcher irrigation system helps maintain consistent soil moisture levels, allowing crops to thrive in both regular and saline soils. This system is also effective in irrigating crops using saline water sources (Batchelor et al., 1996; Mondal et al., 1992; Bainbridge, 2001; Naik et al., 2008; Singh et al., 2011) and perfect for the fertigation process (Kefa, 2013; Mawardi, 2016). The movement of water into and within the soil is vital to the success of any form of irrigation system. Several factors influence the movement of water from the irrigation system into the soil and subsequent movement in the soil. The movement of water through the walls of the SLECI system is influenced by a combination of factors, including hydraulic conductivity, evaporation rate of soil water, evaporation rate, and soil water tension. According to Abu-Zreig and Atoum (2004), there is a direct relationship between seepage rate and the hydraulic conductance of pitchers with different levels of porosity. Abu-Zreig et al. (2006) demonstrated a linear correlation between evaporation rate and seepage rate. The extent of the wetting front in the soil surrounding the pitcher affects the availability of soil water for plant growth (Bhatt, Kanzariya, Motiani & Pandit 2013). Pitcher materials feature such as saturated hydraulic conductivity, wall thickness, surface area (Abu-Zreig & Atoum 2004) evapotranspiration, soil and crop (Abu-Zreig, Abe & Isoda 2006) influence water seepage from the pitcher wall into the soil. The utilization of irrigation water with a high sodium adsorption ratio (SAR) disintegrates the soil's physical composition. Sodium is adsorbed and binds to soil particles, causing the soil to become dense and compact when it dries, making it more resistant to water infiltration (Punthakey & Nimal, 2006). The sodium adsorption ratio can serve as an indicator of soil quality. The replacement of adsorbed calcium and magnesium by sodium is problematic as it leads to soil damage, resulting in compaction and reduced permeability (Nishanthiny, Thushyanthy, Barathithasan, & Saravanan 2010; Bardan, 2014; Wantasen et al 2019). Uncertainty about the effects of irrigation systems on the physical and chemical properties of soils can be a reason for the unwillingness to invest or adopt in irrigation systems (Costa, 1999; Hassan, Jafaar, & Mohamm 2019; Mohanavelu, Naganna & Al-Ansari 2021). The success and sustainability of the SLECI system depend on factors affecting water conductance from the clay tube wall which needs to be thoroughly studied. There is limited research on the effect of water quality and different soils on the performance of the SLECI system, thus the present work aimed at studying the effect of irrigation water quality parameters and soil properties on the performance of the SLECI system.

Materials and Methods

Study area

The experiment took place in the laboratory at the A. G. Carson Teaching and Research farm, School of Agriculture, University of Cape Coast, Cape Coast, which is situated at Latitude: 5°6'57.37" N and Longitude: -1°17'6.55" E.

Water sampling and collection

Water samples were collected from three different sources (river, well and tap water). Water samples were taken with a 1-litre capacity sterile polyethylene terephthalate bottle, which had been sterilized with diluted hydrochloric acid after which it was rinsed with distilled water. and both the sterile polyethene terephthalate bottle and the 20-litre storage tank were washed thoroughly with the water from the three different sites (river, well and tap) before filling was done.

Water analysis

The assessment of irrigation water quality parameters was conducted by employing the prescribed protocols for physiochemical analyses, as outlined by FAO (2003) and WHO (2006), which are universally implemented across the globe.

EC (dS/m)

Electrical conductivity probe was dipped into the water and readings were taken.

pH

pH was determined by using a pH meter.

Bicarbonate

Bicarbonate of irrigation water was determined by titration with standard sulphuric acid (H_2SO_4) using methyl orange as an indicator.

Zinc, Boron, Copper, Manganese, Iron and Molybdenum

Zinc, Boron, Copper, Manganese, Iron and Molybdenum were determined with a flame atomic absorption spectrophotometer.

Calcium, Magnesium, Sodium and Potassium

Calcium, magnesium, sodium and potassium of irrigation water were determined in 1.0M ammonium acetate extract and exchangeable acidity (hydrogen and aluminium) was determined in 1.0M KCL extract.

Chloride, Nitrate, Ammonium and Phosphate

Chloride, Nitrate, Ammonium and Phosphate of irrigation water were determined using AQUA-CHECK photometer

Sulphate

Sulphate levels of irrigation water were determined using the turbidimetric method.

SAR

The sodium adsorption ratio (SAR) was determined using Equ 1

$$SAR = \frac{Na+}{(\frac{Ca2+ +Mg2+}{2})^{\frac{1}{2}}} \qquad \text{Equ (1)}$$

Soil sampling and collection

Soil analysis

Soil samples (clay, loam and sand) were air, dried naturally at room temperature in the laboratory, and subsequently sifted through a 2 mm mesh.

Soil textural class

Soil texture was assessed through the utilization of the particle size analysis technique. This technique involves two essential steps: the dispersion of the soil and the segregation of particles into distinct size categories.

Dispersion and pre-treatment

The soil was pretreated to remove organic matter, iron oxides, calcium carbonate and magnesium carbonate since they serve as cementing agents. The soil was able to disseminate entirely after undergoing pre-treatment.

Fractionation

Fractionation is the process of segregating the soil that has been processed into distinct groups based on particle size, namely sand, silt, and clay. A predetermined amount of soil is placed into a measuring cylinder. Subsequently, distilled water was introduced to create a homogeneous mixture. Various soil particles of varying sizes settled at distinct intervals. Afterwards, the fractions are desiccated and measured, ensuring that the sand, silt, and clay collectively amount to 100%.

Using the soil texture triangle

The soil textural triangle is a tool utilized to transform the distribution of particle sizes into a recognised classification of soil texture. This classification is based on the proportions of sand, silt, and clay present, expressed as a percentage.

Infiltration rate (mm/hr)

Infiltration rate of soils

Equipment used were (Shovel, wooden mallet, stopwatch, 10 litre buckets, measuring rod graduated in mm (30 cm ruler) and double ring infiltrometer). Inner ring infiltrometer (34 cm diameter) outer ring infiltrometer (60 cm diameter)

Procedure

The double-ring infiltrometer was inserted into the soil using a wooden mallet. While hammering, the ring's side was maintained in a vertical position. The measurement rod was inserted into the soil, leaving approximately 16 cm from the ground surface. H_2O was introduced into the ring infiltrometer, while simultaneously being added to the area between the two rings at an equivalent depth. The stopwatch was started simultaneously with the beginning of the test, while also recording the water level on the measurement rod. The decrease in water level in the inner ring of the measuring rod was recorded every 60 seconds. Subsequently, water was introduced to restore the level to nearly its initial state at the commencement of the experiment. Subsequently, the water level was documented. The water level outside the ring was equivalent to that of the inside ring. The test was extended until the decrease in water level became stable.

Soil sodicity (Exchangeable Sodium Percentage, ESP)

Soil sodicity was measured using Equu 2.

$$ESP = \frac{100\ (-0.0126 + 0.01475\ x\ SAR)}{1 + (-0.0126 + 0.01475\ \text{x SAR})} \qquad \text{Equ (2)}$$

Soil salinity

The determination of salinity by use of electronic conductivity method. 5g of air-dried, sieved soil samples were placed in a centrifuged tube. Subsequently, distilled water (25 millilitres) was added into a centrifuge tube after which shaking was done for 15min and it was allowed to settle overnight. Electrical conductivity probe was dipped into the solution and readings were taken.

Soil pH

A quantity of 10 g of air-dried soil was measured and placed into a bottle with a screw cap. A volume of 25 millilitres of distilled water was then added, and the screw cap was tightened. Subsequently, the bottle containing the solution was agitated for 15 minutes on a mechanical shaker. Next, the electrode of the pH meter was placed into the suspension and the pH value was determined.

Bulk density

An undisturbed flat horizontal surface in the soil was prepared with a spade. A core sampler was gently hammered into the soil. The area around the core sampler was excavated without disturbing the soil. The core sampler was carefully removed with the soil intact. The soil was then poured into a plastic bag and sealed. All soil was carefully removed from the bag into an ovenproof container. The soil was oven-dried for 24 hours at a temperature of 105ºC. The dried weight of the soil was then determined. To determine the volume of the ring the height and radius of the core sampler were determined (Equ 3). Bulk density was determined by Equ 4.

Volume of core sampler (cm3) = 3.14 x radius^2 x ring height Equ (3)

$$\text{Bulk density}\left(\frac{\text{g}}{\text{cm3}}\right) = \frac{\text{Dry soil weight (g)}}{\text{Soil volume (cm3)}} \qquad \text{Equ (4)}$$

Particle density

A predetermined quantity of soil sample was poured into a flask, followed by the addition of distilled water. The soil-water solution was heated to eliminate any presence of air within the sample. Eventually, the solution was cooled. Subsequently, distilled water was introduced into the solution to achieve a predetermined volume. Subsequently, the solution's weight was determined. The weight of the water was thereafter deducted from the combined weight of the soil and water.

$$\text{Particle Density } = \frac{\text{Mass of dry soil (g)}}{\text{Volume of soil particles (air removed,cm3)}} \qquad \text{Equ (5)}$$

Porosity

The porosity of the soil was calculated using the Equ 6:

$$\text{Porosity} = 1 - \left(\frac{\text{Bulk density}}{\text{Particle density}}\right) \text{x } 100\% \qquad \text{Equ (6)}$$

Research design and treatment

The experiment, factorial (A^3 x B^3) was laid out in a Completely Randomized Design (CRD) with three replicates (Figure 2). Treatment A consisted of three types of soil (clay, sand and loam) while treatment B consisted of three sources of irrigation water (river, well & tap water) in a factorial combination to obtain 9 treatment combinations. 1 plastic pot represents a plot.

Figure 2: Experimental layout indicating various treatments

Experimental setup

The SLECI system consisted of a water tank (20 litres), valve, filter, clay tube, connectors, coupling, PE- tubes, and an end cap. Each of the 27 rectangular plastic pots (dimensions of 25 cm in length, 25 cm in width and a height of 30 cm) was filled with gravel to a height of 4cm after which soil was filled to the

30 cm mark. Twenty-seven (27) clay tubes of the same length (9cm) inner and outer diameters of 10 mm and 12 mm and wall thickness (2 mm). The water storage tank was mounted at a height of 50 cm, and the filter together with the valve was connected to the water storage tank. The PE – hose on which the core of the clay tube was mounted was then connected to the valve. A PE–hose length of 30cm was allowed between adjacent clay tubes. an end cap is fixed at the end of the PE tube at the end of the last plastic pot.

Data collection

Data collection was carried out on SLECI irrigation systems performance parameters such as seepage rate, hydraulic conductivity and drainage porosity.

Seepage rate

The seepage rate is the rate of movement of water through the clay tube from one point to another. The seepage rate was estimated by the formulae used Kasali et al. (2018).

$$S = \frac{L * (d1 - d2) * W}{L * P * t} \times 24 \qquad \text{Equ (7)}$$

Where,

S = seepage rate (cm^2/day)

L = length of clay tube

d1 = initial water depth

d2 = final water depth

W = average width of clay tube

P = average wetting perimeter

t = time (duration)

Saturated hydraulic conductivity

Saturated hydraulic conductivity is the ease with which the pores of a clay tube transmit water. Saturated hydraulic conductivity was estimated by using the formulae by Vasudevan et al. (2014).

$$\mathrm{Ks} = \frac{a*L}{A*t} \text{ X In } \left(\frac{ho}{ht}\right) \qquad \text{Equ (8)}$$

Ks = Saturated hydraulic conductivity

a= cross-sectional area of a water container

A = cross-sectional area of clay tube

L= wall thickness of clay tube

t = time (seconds)

ho = initial time

ht = final time

Drainage porosity

Drainage porosity is the ratio of the volume of water drained by gravity from a saturated soil sample to the total volume of the sample.

$$\text{Drainage porosity} = \frac{\text{Volume of water drained}}{\text{Total volume of the sample}} \times \mathbf{100} \qquad \text{Equ (9)}$$

Wetting perimeter

Wetting perimeter was determined using the formula

$$\text{Wetting perimeter} = 2\pi r$$

Statistical analysis

Statistical analysis (One-way ANOVA) of performance indicators of the SLECI system was performed to assess the influence of different soil types, using Genstat statistical software (Introduction to GenStat for Windows 18th Ed, VSN International, Rothamsted Experimental Station, Reading University, United Kingdom). Treatments were examined for significant mean differences using Tukey's least significant difference test at a 5% probability level. The Pearson correlation tests were employed to determine the relationships between the irrigation water quality parameters and soil attributes, as well as the performance indicators of the SLECI system.

Results and Discussion

Effect of soil type on hydraulic conductivity of SLECI system

Figure 3 shows the significant effect of soil type on hydraulic conductivity after irrigation was carried out using a SLECI system. The maximum hydraulic conductivity of 0.000186 cm/s was recorded in sandy soils whereas the minimum hydraulic conductivity of 0.0001163 cm/s was recorded in clay soils. A hydraulic conductivity of 0.0001752 was recorded in loamy soils. The movement of water in the soil is connected to its storage because the water potential is determined by the water content, which in turn is affected by the texture and structure of the soil. Pore size distribution controls hydraulic conductivity (Childs & Collis-George 1950; Vogel 2008). Low hydraulic conductivity observed in clay soils could be attributed to its highly tortuous flow path. Conversely, sandy soil recorded a higher hydraulic conductivity due to its larger pores and lower tortuosity that facilitate rapid water flow. Additionally, a strong soil structure, consisting of very fine and fine aggregates facilitates rapid drainage of soil by increasing macroporosity, whereas weak structure or coarse-sized structural units and platy structure has the potential to inhibit flow, creating a more tortuous flow path constraining water to inter-structural voids. Results from Figure 3 follow that of Mondal (1983) and Abu-Zreig et al (2004) A positive linear relation between pitcher wall porosity (governed by the proportion of sand and clay) and hydraulic conductivity. They concluded that hydraulic conductivity increased with the increase in the porosity of the clay tube. Thus, the higher the porosity of the clay tube, the greater the hydraulic conductivity.

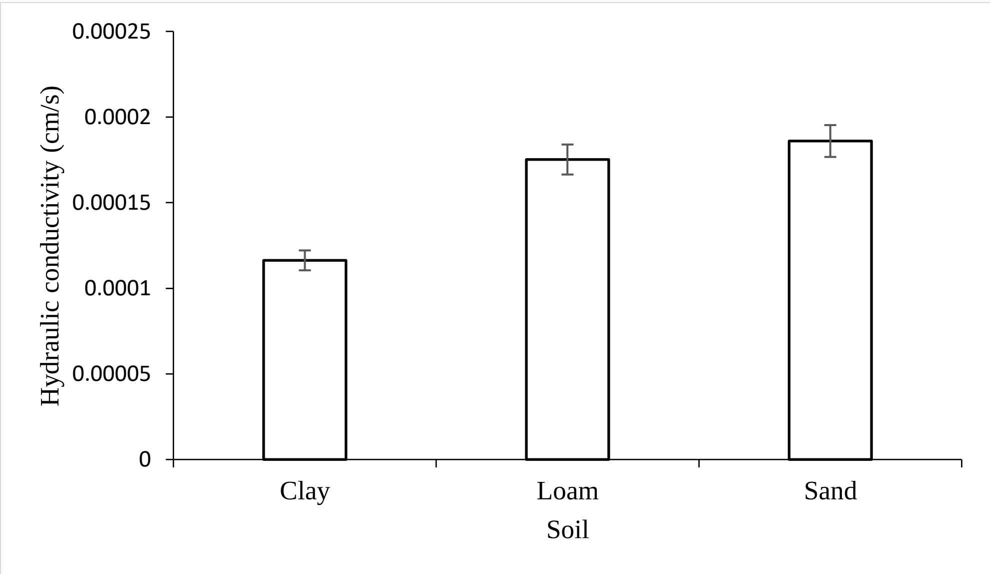

Figure 3: Hydraulic conductivity of the SLECI system as influenced by soil type.

Effect of soil type on seepage rate of SLECI system

Figure 4 illustrates the impact of various soil types on the seepage rate of the SLECI system. The seepage rate measured in sandy soil (4.853 cm2/day) and loamy soil (4.227 cm2/day) did not show any significant variations, but both were significantly greater than the seepage rate seen in clay soils (3.363 cm2/day). Evapotranspiration depletes water from the soil near the roots, resulting in the generation of negative pressure that is then transferred to the wall of the clay tube. It is important to observe that the water flow from the clay tube will rise when there is a lack of moisture, regardless of the soil's texture and structure. Moisture deficit and evapotranspiration are directly linked, meaning that when the soil's suction potential increases, the rate of seepage also increases. According to Abu-Zreig et al. (2006), the seepage rate is influenced by the pore structure on the wall of the clay tube and can be reduced by clogging whereas Vasudevan et al. (2007) reported that the seepage rate varies consistently with soil moisture and moisture deficit. Though clay tubes used across soils had the same dimensions yet the volume of water seeped from clay tubes placed in sandy soil was 12.9 % and 30.7 % more than that of clay tubes placed in loam and clay soils (Figure 4). An average volume of 4.853 cm^2/day, 4.227 cm^2/day and 3.363 cm^2/day of water seeped from clay tubes in sandy, loamy and clay soils resulting in different radii of wetted zones, indicating that porosity and hydraulic conductivity influences seepage rate.

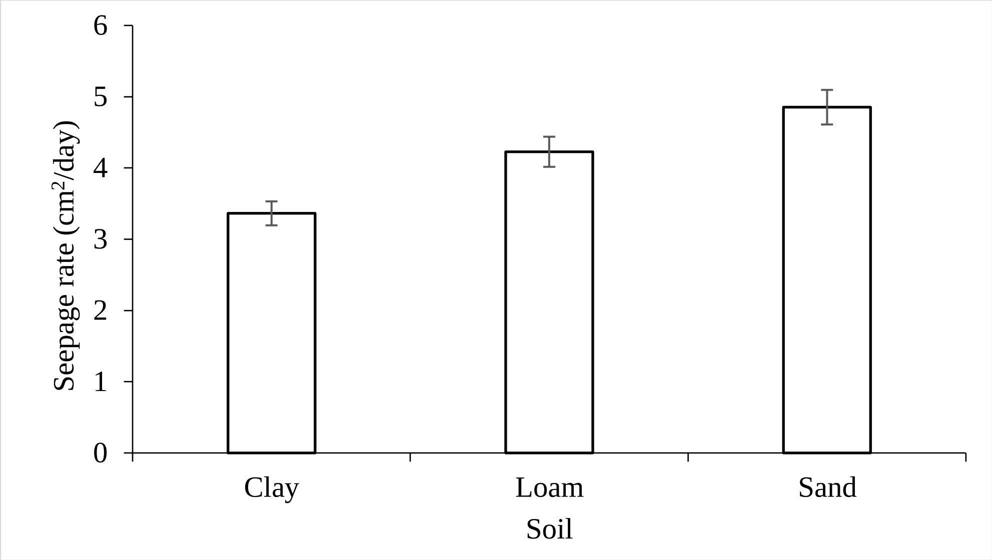

Figure 4: Seepage rate of the SLECI system.

Wetting perimeter of SLECI system.

The wetting perimeter of the SLECI system as influenced by different soil types is presented in Figure 5. After 330 minutes of operating the SLECI system, the significantly highest wetting perimeter of 75.9 cm^2 was recorded in loamy soils, whereas a wetting perimeter of 56.73 cm^2 and 55.89 cm^2 was recorded in clay and sandy soils respectively. Wetting perimeter after 330 minutes was 25% and 26.3% greater for clay tubes in loamy soils compared to clay tubes in clay and sandy soil. The degree of saturation was highest close to the clay tube but decreased gradually as farther from the clay tube. Abu-Zreig et al. (2006), Siyal et al. (2009) and George (2011) reported a positive linear relationship between soil wetting front radius and hydraulic conductivity of clay tube wall whereas Setiawan et al. (1988) and Thingujam et al. (2017) explained that the horizontal spreading of moisture is influenced by the soil properties, irrigation rate, and duration. Soil wetting front is usually defined as the soil profile with a matric potential of -763 cm -200 and for sandy loam soils and fine sand respectively

(Ashrafi, et al 2002). Variations in soil texture and structure impact both the moisture content and the movement of water during saturation. The pore size distribution of soil is determined by its texture and structure, which in turn affects the movement of water. Results from Figure 5, suggest that sandy soil exhibited a limited wetting perimeter, which can be related to the predominance of large pores in its pore size distribution, hence reducing its capacity to retain water. Clay, which is a fine textured soil, recorded a moderate wetting perimeter since its pore size distribution consists mainly of micropores. The loamy soil exhibited the greatest wetting perimeter due to its specific textural class, which leads to a diverse range of pore sizes and creates an optimal composition of meso- and micro-porosity. According to Abu-Zreig et al. (2006) and Siyal et al. (2009), there is a direct relationship between the porosity of the clay tube wall and the radius of the soil-wetting front.

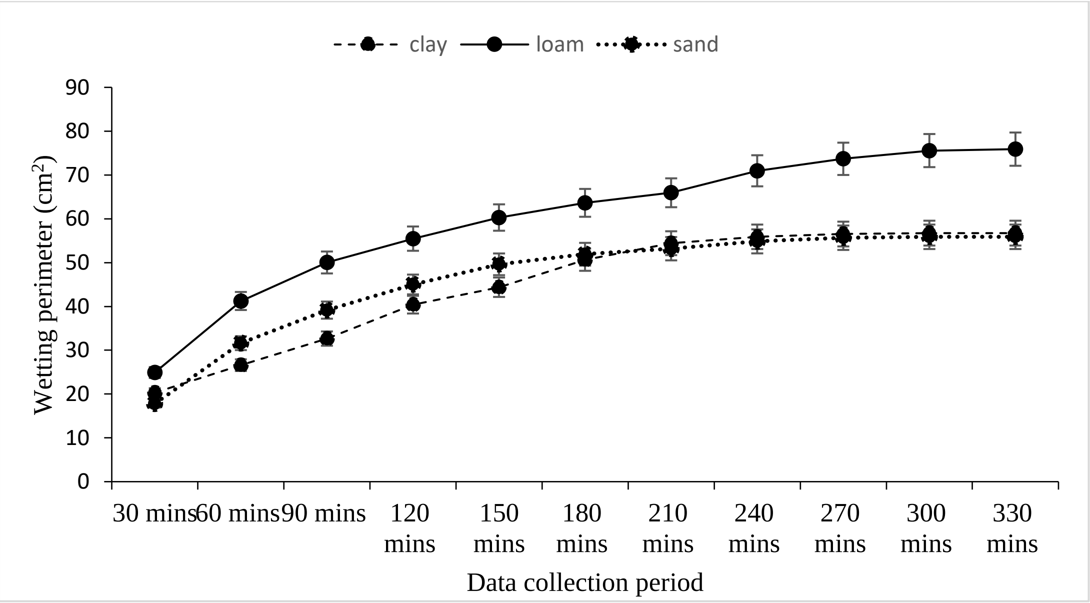

Figure 5: Wetting perimeter of the SLECI system as influenced by soil type at different periods.

Drainage porosity of the SLECI system as influenced by soil type.

Figure 6 illustrates the impact of various soil types on the drainage porosity of the SLECI system. The sandy soils had a maximum drainage porosity of 0.5433, whereas the clay soils had a minimum drainage porosity of 0.3833. The loamy soils had a reported drainage porosity of 0.4667. The results from Figure 6 corroborate the findings of Fattah et al (2017), which indicate that the drainage of water is influenced by the size of the soil pores. Specifically, larger pores exhibit a high drainage rate, followed by medium-sized pores, while smaller pores drain at a much slower pace. The findings of Liu, et al (2020) provided additional evidence that drainable porosity is a soil hydraulic characteristic that remains constant and is affected by soil texture and structure. Coarse-textured soils, such as sandy soil, have a higher drainage porosity compared to fine-textured soils, such as clay soil (Figure 6). Coarse-textured soils include a higher proportion of large-size pores, whereas fine-textured soils contain a higher proportion of small and narrow pores.

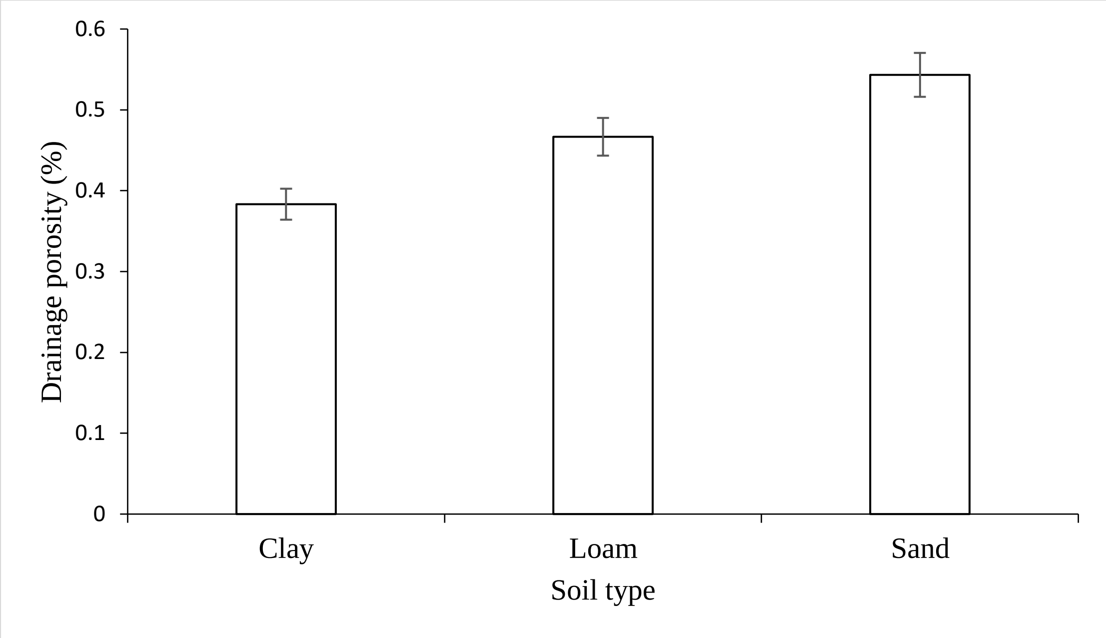

Figure 6: Drainage porosity of the SLECI system as influenced by soil type

Soil Tensiometer readings content

The soil tensiometer reading on 9-hour intervals under 3 different soil types is presented in (Figure 7). Soil tensiometer readings from each soil showed to consistently vary, with variation becoming clearer after 5 hours of operating the SLECI system. Results from Figure 7 indicate clay and sandy soils experience high moisture deficit due to low tensiometer readings as compared to higher tensiometer readings observed from loamy soils. Soil tensiometer reading serves as a threshold for irrigation scheduling can be carried out. An inverse relationship exists between tensiometer reading and soil moisture deficit, thus the lower the tensiometer reading the higher the soil moisture deficit and vice versa. Differences in soil physical properties such as porosity and bulk density can reflect differences in changes in the moisture deficit of the soil. Swarowsky et al. (2011) explained how water is stored and distributed in the soil, responding to variances in potential energy. The redistribution and loss of soil moisture are influenced by a gradient of potential energy, causing water to move from high-energy areas to low-energy areas. When the soil is saturated or close to saturation, the water potential is usually around 0 MPa. As the soil dries out, negative water potentials develop, creating suction or tension that enables the soil to retain water.

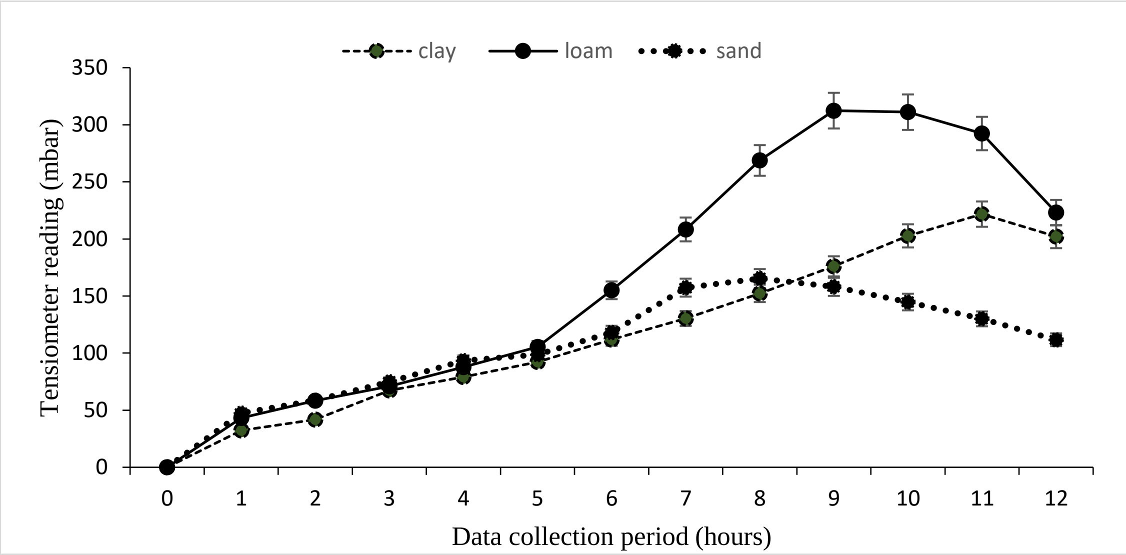

Figure 7: Soil tensiometer reading under different soils

Relationship between irrigation water quality parameters and performance of SLECI system

Out of the 19 correlation tests between irrigation water quality parameters and the performance of the SLECI system, eight (8) correlations (Zinc, Copper, Calcium, Magnesium, Sodium, Iron, Potassium and SAR) were statistically significant. Soil salinity, Bicarbonate, Manganese, Molybdenum, Chloride, Sulphate, Ammonium, Nitrate, Phosphate and Potassium correlations were not significant.

	EC (dS/m)	HCO3 (mg/L)	Zn (mg/L)	Cu (mg/L)	Mn (mg/L)	Fe (mg/L)	Mo (mg/L)	Ca++ (mg/L)	Mg++ (mg/L)	Na+ (mg/L)	Cl- (mg/L)	SO4- (mg/L)	NO (m
SR	.121	.486	-.905**	-.902**	-.106	.805**	.631	-.760*	-.705*	.867**	.503	.483	.12
Ks	-.161	.220	-.890**	-.906**	-.379	.606	.381	-.914**	-.871**	.693*	.239	.215	-.1
DP	.185	.541	-.908**	-.880**	-.049	.838**	.677*	-.709*	-.674*	.892**	.556	.538	.18

Figure 8: Pearson correlation coefficients of irrigation water quality parameters and perfor

Soil salinity: EC (dS/m) Bicarbonate: HCO_3 (mg/L) Zinc: Zn (mg/L) Copper: Cu (mg/L
Molybdenum: Mo (mg/L) Manganese: Mn (mg/L) Iron: Fe (mg/L) Calcium: Ca^{++} (mg
Phosphate: P04-P (mg/L) Sulphate: $SO4^-$ (mg/L) Boron: B (mg/L) Ammonium: NH4-

Seepage rate: SR Hydraulic conductivity: Ks Drainage porosity: DP

Figure 8: Pearson correlation coefficients of irrigation water quality parameters and performance of SLECI system

A Pearson correlation coefficient (r) between 0 and 1 indicates a positive relationship between the value of irrigation water quality parameters and the performance indicators of SLECI systems. This means that when the value of irrigation water quality parameters increases, the performance indicators of SLECI systems also increase, and vice versa. A Pearson correlation coefficient (r) between 0 and -1 implies a negative relationship between the value of irrigation water quality parameters and the performance indicators of SLECI systems. In other words, as the value of irrigation water quality parameters increases, the performance indicators of SLECI systems drop, and vice versa. Seepage rate positively correlated with Iron, (r = .805, P= .009) SAR (r = .918, P = .000) Sodium (r= .867 P = .002) and negatively correlated Zinc (r= -.905, P = .001), Copper (r = -.902, P = .001), Calcium (r = -.760, P = .017) and

Magnisium (r = -.705, P = .034). (Figure 8) Hydraulic conductivity (ks) positively correlated with SAR (r = .774, P= .014) Potassium (r = .734, P = .024) sodium (r= .693, P = .039) and negatively correlated Zinc (r= -.890, P = .001), Copper (r = -.906, P = .001), Calcium (r = -.914, P = .001) and Magnisium (r = -.871, P = .002). Drainage porosity positively correlated with Iron (r= .838, P = .005), Molybdenum (r= .677, P= .045), Sodium (r= .892, P= .001), SAR (r = .938, P= .000) and negatively correlated Zinc (r= -.908, P =.001), Copper (r= -.880, P= .002), Calcium (r = -.709, P=.033) and Magnisium (r = -.674, P= .046). (Figure 8). Motuzova et al. (2012) and Bauer et al. (2019) have explained the correlation between zinc and water flow. They have reported that zinc leads to an increase in the specific surface area of soil and the fine fractions of soil. The explanation for this phenomenon is attributed to the creation of Me-organic complexes involving cations and the partial disintegration of mineral-organic compounds, both of which significantly contribute to the production of soil structure. Results in affirm the findings of Unamuno et al. (2009) who indicated that copper is associated strongly with the soil solid phase and generally persists in the soil surface for extended periods. Elevated copper concentrations cause toxic effects on micro-organisms Oorts (2013). This was similar to later research by Rabot et al. (2018) and Fukumasu et al. (2022) who indicated that the presence of copper increases magnesium and widens soil C: N ratio. This negatively affects soil physical properties that are vital for soil physical quality, which in turn influences many critical soil properties and processes including the transport and retention of water. The significant relationship between calcium and the performance of SLECI systems could be attributed to the vital role calcium plays in improving the soil's physical condition. Calcium works as a bonding agent in the aggregation of soil particles, in which it helps to bind organic and inorganic substances (Hocking et al 2016). Calcium bonds to clay and/or silt particles, which affects particle size. Highly aggregated, stable clay soils may behave like coarse sands in terms of water infiltration and movement within the soil (Becker & Knoche 2011). The results depicted in Figure 8 corroborate the conclusions of Vyshpolsky et al (2017), who observed that the existence of Magnesium (Mg) can significantly deteriorate soil structure, resulting in reduced infiltration rates and hydraulic conductivity. Excessive quantities of magnesium, either alone or combined with salt, negatively impact the physical qualities of soil due to its presence as a divalent cation on the cation exchange complex. Subsequently, Gransee, and Führs (2013) indicated that the hydration energy and radius of magnesium are greater than calcium and this weakens the attractive forces between individual soil particles thereby causing them to slump or disperse. High magnesium levels in soils can characteristically form massive clods that impede the flow of water thus resulting in poor water distribution. The problem is compounded where magnesium concentrations are higher than calcium in irrigation water. The significant correlation between potassium and the performance of SLECI systems can be explained by the fact that potassium is a more stable cation in aqueous solutions compared to sodium and calcium. It is also the most suitable cation for controlling hydraulic transport. This relationship has been supported by studies conducted by Russo et al. (2001), Persson (2010), Sardans et al. (2015), and Sardans and Peñuelas (2021). The studies conducted by Langer et al in 2002, Lebaudy et al in 2007, Gajdanowicz et al. in 2011 and Sardans in 2015 highlight the significance of potassium as a crucial element in the flow of water and the transportation of solutes. This is accomplished by exerting control over the transmembrane potentials and osmotic pressure. The interplay between potassium and aquaporins is a notable mechanism for controlling the flow of water. Aquaporins have essential functions in plant water relations by promoting the movement of water and regulating osmotic potential and hydraulic conductivity (Maurel et al 2008; Hachez et al 2014). According to McCauley et al (2005), under anaerobic conditions, the diffusion of oxygen in saturated soil occurs at a sluggish pace, failing to meet the oxygen requirements for aerobic respiration by microbes. In the absence of oxygen, facultative microbes utilize iron as the terminal electron acceptor to generate energy. As a result, these elements undergo reduction and become soluble in the soil solution. When water mobilizes these soluble constituents, they eventually come into contact with air, where they oxidize and re-precipitate as iron. Jacobs et al. (2002), reported that the depth at which redoximorphic features occur determines the extent of saturated water conditions within the soil. The significant correlation between sodium and the performance of the SLECI system can be explained by the fact that the presence of sodium in water can adversely affect soil characteristics and decrease soil permeability. The utilization of water containing a high Sodium Adsorption Ratio (SAR) disintegrates the physical composition of the soil. When sodium is absorbed and binds to soil particles, it causes the soil to become dense and compact when it dries up. As a result, water finds it increasingly difficult to penetrate the soil. The replacement of adsorbed calcium and magnesium with sodium is detrimental and causes damage to the soil structure, making it compact and impermeable (Nagarajah et al., 1988; Appelo & Postma 2005).

Relationship between soil properties and performance of SLECI system

Out of the 7 correlation tests between soil properties and the performance of the SLECI system, six (6) correlations, bulk density, porosity (%), particle density, infiltration rate, soil salinity and soil sodicity were significant. Soil pH, correlation was not significant (Figure 9). A positive Pearson correlation coefficient (r) between 0 and 1 indicates that an increase in the value of soil property results in the increase in performance indicators of the SLECI system, and vice versa. A negative Pearson correlation coefficient (r) between 0 and -1 indicates that an increase in the value of soil property results in a decrease in performance indicators of the SLECI system, and vice versa. Seepage rate positively correlated with porosity (r= .986, P= .000) infiltration rate (r= .994, P= .000) negatively (bulk density r= -.991, P= .000) particle density (r=-.889, P= .001) soil salinity (r= -.789, P= .012) soil sodicity (r= -.878, P= .002) (). Hydraulic conductivity (ks) positively correlated with porosity (r= .960, P= .000) infiltration rate (r= .957, P= .000) negatively correlated bulk density (r= -.970, P= .000) particle density (r=-.855, P= .003) soil salinity (r= -.925, P= .000) soil sodicity (r= -.966, P= .002) (Figure 9). Drainage porosity (ks) positively correlated with porosity (r= .982, P= .000) infiltration rate (r= .990, P= .000) negatively correlated bulk density (r= -.984, P= .000) particle density (r=-.887, P= .001) soil salinity (r= -.748, P= .020) soil sodicity (r= -.852, P= .004) (Figure

9). The relationship between bulk density and particle density is crucial in determining the efficiency of the SLECI system. The reason for this is that density directly affects the physical arrangement of the soil, leading to a displacement of soil-solid components and changes in the porosity and arrangement of pores. The movement and storage attributes of soil-water and soil-gas, that occupy the pore space and are affected by pore size, are regulated by density (Drewry, 2006). Prior studies have shown that soil density has a notable impact on both soil-water retention and hydraulic conductivity. Specifically, Croney and Coleman (1954), Gupta et al. (1989), Kern (1995), Gent Jr et al. (1983), Pachepsky, Timlin, and Rawls (2001), and Chamindu et al. (2019) have all documented these impacts. Bulk density is a metric that quantifies the level of soil compaction, which in turn affects parameters such as water infiltration, available water capacity, and soil porosity. It is impacted by the composition of the soil, which includes the relative amounts of sand, silt, and clay. Varying soil compositions lead to different bulk densities. Particularly, coarse-textured sandy soils contain lesser pore spaces as opposed to fine-textured soils like loam, which have more porosity (Mukhopadhyay et al., 2019). The density of soil has the potential to manage its moisture state and aeration (Ball, 2013). Soil compaction leads to an increase in bulk density and a decrease in total pore volume, which in turn reduces the soil's ability to store water. The data unambiguously demonstrate a negative correlation between density and saturated water content, corroborating prior research findings. Compaction results in an elevation of water retention at greater matric potential and a reduction of water retention at lower matric potential (Gupta et al., 1989).

The results suggest a reduction in overall porosity and a change in the relative distribution of pore sizes during compaction, as demonstrated by alterations in the arrangement of pore sizes (Zuraidah et al., 2011). The changes in soil water content resulting from density are significantly impacted by the specific kind of soil. Hill & Sumner (1967) found that sandy soil has a greater capacity to hold water as its bulk density increases at a particular matric potential, contrasting sandy loam and clay loam. Conversely, clay soils, with their higher capacity for hygroscopic water (water that is chemically absorbed into the internal structure of clay particles), can retain more water at lower matric potentials when compacted, as compared to other soil textures (Chamindu et al., 2019). The correlation between porosity and the performance of the SLECI system is significant. The relationship between compaction and porosity can be explained by the observation that as compaction intensifies, macroporosity decreases while mesoporosity and microporosity rise. This has been previously acknowledged (Zuraidah et al., 2011). More precisely, there is a reduction in the presence of large aerated voids that efficiently drain at low matric potentials, whereas there is an augmentation in the number of capillary pores that retain water even at low matric potentials (Chamindu et al., 2019). Porosity and bulk density have an inverse relationship, meaning that as bulk density increases, porosity decreases. The porosity of soil is significantly influenced by its texture. The soil porosity of both sandy and clayey soils typically ranges about 50%. Nevertheless, sandy soils possess larger pores, known as macropores, whereas clayey soils contain smaller pores, referred to as micropores. Sands with macropores facilitate the circulation of air and water but have a limited capacity to retain water. Clay possesses exceptional water retention capabilities due to its micropores, yet it has little ability for air and water circulation, resulting in inadequate drainage. Loamy soils exhibit much greater porosity in comparison to mineral soils due to their lower bulk density (Mobilian & Craft 2022). The strong correlation between the infiltration rate and the effectiveness of the SLECI system can be attributed to the fact that the infiltration rate represents the velocity at which water penetrates the soil. Infiltration is a measure of how well water can enter and travel through the soil. Water quickly permeates through dry soil. As the moisture level in the pores rises, it leads to a reduction in the pace at which water from the soil surface can penetrate. Ultimately, a consistent level of penetration is attained. The rate of infiltration is affected by variables such as the soil's texture and structure, as well as the clay's mineral makeup (Brouwer et al., 2002). Water flows more rapidly through the wide gaps in sandy soil compared to the narrow gaps in clayey soil, particularly when the clay is compressed and lacks structure or aggregation (USDA, 2008). The correlation between infiltration rate and soil sodicity, as well as the performance of the SLECI system, can be explained by the fact that soil sodicity leads to reduced infiltration and the formation of puddles. This is supported by studies conducted by Waskom et al. (2012) and Shahid et al. (2018). Additionally, the hydraulic properties of the soil, as discussed by Rengasamy (2006), Edelstein et al. (2010), Van der Zed et al. (2014), and Klopp & Daigh (2020) contribute to Sodic soils can undergo significant structural deterioration and display unfavourable soil-water and soil-air interactions (Rengasamy et al., 2003). Even when sodicity is at its lowest level, a seal is created and the rate at which water infiltrates decrease. Soil sodicity had an impact on the rate at which seals formed. This is because sodicity causes the soil clay to disperse chemically (Levy, 2012). The soil surface's susceptibility to sodicity is attributed to the mechanical influence of water, as elucidated by Levy and Nachshon in 2022. The infiltration rate of sodic soils is closely linked to the rate at which soil particles become wet, and this relationship is strongly influenced by soil texture. In soils with coarse and medium textures, the impact of sodicity on the rate at which water infiltrates is minimally affected by the speed at which aggregates become wet. When fine-textured soils are wetted at a slower pace before being exposed to rain, the sensitivity of the infiltration rate to sodic conditions is greatly reduced (Levy & Shainberg 2005). According to Levy et al. (2014), sodic soils are prone to forming a seal and experience a drop in infiltration rate due to the significant impact of clay concentration. Soils with a clay content of 10-30% are most susceptible to seal formation and have the lowest rate of infiltration. With an increase in clay content, the stability of the soil structure improves, leading to a reduction in seal formation. In soils with clay concentrations below 10%, there is a scarcity of clay particles that can distribute and block the soil pores, leading to the creation of an inadequately formed seal. When sodic soils lose their structure, the flow of water through the compressed soil is greatly slowed, which leads to a decrease in the soil's ability to absorb water (Heydari et al., 2001; Shainberg et al., 2001).

The infiltration rate of sodic soils is influenced by both soil qualities and prevailing conditions, including the speed at which aggregates become wet and the moisture level before penetration. The correlation between infiltration and soil texture is stronger in fine-textured soils than in coarse ones (Kjaergaard et al., 2003: Levy et al., 2014). The strong correlation between soil salinity, exchangeable sodium percentage, soil porosity, and the performance of the SLECI system can be explained by the accumulation of salts from irrigation water in the soil over time. This accumulation leads to changes in soil characteristics and waterlogging problems. While salinity can enhance soil stability and aggregation, excessive concentrations can cause osmotic stress, leading to reduced water retention in the soil (Evelin et al., 2019). Salinity induces soil flocculation. The citation Sparks (2003) refers to a source or reference made by Sparks in the year 2003. The stability of the soil is greatly influenced by the level of salinity and sodicity present in the soil. This may be easily measured using the salinity-to-sodicity ratio, also known as the swelling factor (Marchuk, 2013). Soils with a high swelling factor exhibit a stable soil structure, however, a drop in the swelling factor value increases the probability of soil structural issues (Warrence et al 2002; Shahid et al 2018). The exchangeable sodium percentage (ESP) can lead to the disintegration of soil aggregates (Levy & Shainberg 2005; Singh, 2016). The presence of irrigation water with elevated SAR values can significantly impact the permeability of the soil, which is contingent upon the soil type and the degree of surface sealing (Abrol et al., 1988; UOC, 2021). SAR can significantly reduce permeability in textured clays, while it has negligible effects on sandy soils (Rollins, 2007).

	EC (dS/m)	HCO3 (mg/L)	Zn (mg/L)	Cu (mg/L)	Mn (mg/L)	Fe (mg/L)	Mo (mg/L)	Ca++ (mg/L)	Mg++ (mg/L)	Na+ (mg/L)	Cl- (mg/L)	SO4- (mg/L)	NO3-N (mg/L)	NH4-N (mg/L)	P04-P (mg/L)	K+ (mg/L)	B (mg/L)	pH	SAR			
SR	.121	.486	-.905**	-.902**	-.106	.805**	.631	-.760*	-.705*	.867**	.503	.483	.121	-.129	-.178	.515	.360	.486	.918**	SR		
Ks	-.161	.220	-.890**	-.906**	-.379	.606	.381	-.914**	-.871**	.693*	.239	.215	-.155	-.271	-.449	.734*	.086	.223	.774*	.957**	Ks	
DP	.185	.541	-.908**	-.880**	-.049	.838**	.677*	-.709*	-.674*	.892**	.556	.538	.185	-.096	-.106	.456	.401	.539	.938**	.992**	.930**	DP

Figure 8: Pearson correlation coefficients of irrigation water quality parameters and performance of SLECI system

Soil salinity: EC (dS/m) Bicarbonate: HCO_3 (mg/L) Zinc: Zn (mg/L) Copper: Cu (mg/L) Magnisium: Mg^{++} (mg/L) Chloride: Cl^- (mg/L)
Molybdenum: Mo (mg/L) Manganese: Mn (mg/L) Iron: Fe (mg/L) Calcium: Ca^{++} (mg/L) Sodium: Na^+ (mg/L) Potassium: K+ (mg/L)
Phosphate: P04-P (mg/L) Sulphate: $SO4^-$ (mg/L) Boron: B (mg/L) Ammonium: NH4-N (mg/L) Nitrate: NO3-N (mg/L)

Seepage rate: SR Hydraulic conductivity: Ks Drainage porosity: DP

Figure 8: Pearson correlation coefficients of irrigation water quality parameters and performance of SLECI system

	Bulk density (g/cm3)	Porosity (%)	Particle density (g/cm3)	Infiltration rate (mm/hr)	Soil pH	Soil Salinity	Soil sodicity			
Seepage rate	-.991**	.986**	-.889**	.994**	-.074	-.789*	-.878**	Seepage rate		
Hydraulic conductivity	-.970**	.960**	-.855**	.957**	.195	-.925**	-.966**	.957**	Hydraulic conductivity	
Drainage porosity	-.984**	.982**	-.887**	.990**	-.152	-.748*	-.852**	.992**	.930**	Drainage porosity

Figure 9: Pearson correlation coefficients of soil properties and performance of SLECI system

Conclusion

The purpose of this objective was to examine the effect of irrigation water quality and soil properties on the performance of the SLECI system. Pearson correlation tests identified significant associations between the parameters of irrigation water quality and soil characteristics. For irrigation water quality parameters seepage rate positively correlated with Iron, (r = .805, P= .009) SAR (r = .918, P = .000) Sodium (r= .867 P = .002) and negatively correlated Zinc (r= -.905, P = .001), Copper (r = -.902, P = .001), Calcium (r = -.760, P = .017) and Magnesium (r = -.705, P = .034). Hydraulic conductivity (ks) positively correlated with SAR (r = .774, P= .014) Potassium (r = .734, P = .024) sodium (r= .693, P = .039) and negatively correlated Zinc (r= -.890, P = .001), Copper (r = -.906, P = .001), Calcium (r = -.914, P = .001) and Magnesium (r = -.871, P = .002). Drainage porosity positively correlated with Iron (r= .838, P = .005), Molybdenum (r= .677, P= .045), Sodium (r= .892, P= .001), SAR (r = .938, P= .000) and negatively correlated Zinc (r= -.908, P =.001), Copper (r= -.880, P= .002), Calcium (r = -.709, P=.033) and Magnisium (r = -.674, P= .046). For soil properties seepage rate positively correlated with porosity (r= .986, P= .000) infiltration rate (r= .994, P= .000) negatively (bulk density r= -.991, P= .000) particle density (r=-.889, P= .001) soil salinity (r= -.789, P= .012) soil sodicity (r= -.878, P= .002). Hydraulic conductivity (ks) positively correlated with porosity (r= .960, P= .000) infiltration rate (r= .957, P= .000) negatively correlated bulk density (r= -.970, P= .000) particle density (r=-.855, P= .003) soil salinity (r= -.925, P= .000) soil sodicity (r= -.966, P= .002). Drainage porosity (ks) positively correlated with porosity (r= .982, P= .000) infiltration rate (r= .990, P= .000) negatively correlated bulk density (r= -.984, P= .000) particle density (r=-.887, P= .001) soil salinity (r= -.748, P= .020) soil sodicity (r= -.852, P= .004). The analysis of variance and subsequent Tukey pairwise test showed significant differences among soil types where Hydraulic conductivity in sandy soils was highest and was 37.4 % and 5.8% compared to clay and loamy soils, seepage rate was highest in sandy soils 12.9% and 30.7% better compared to loamy and clay soils, wetting perimeter was 25% and 26.3% greater for clay tube in loamy soils compared clay tube in clay and sandy soil, while drainage perimeter was 29. 4% clay 14% greater for the SLECI system in sandy soils compared to clay soil.

CHAPTER FOUR

ASSESSING THE EFFECT OF DIFFERENT IRRIGATION SYSTEMS AND FERTILIZER APPLICATIONS ON BELL PEPPER UNDER GREENHOUSE CONDITIONS.

Introduction

The global demand for agricultural products has been driven by the increased consumption of biofuels, resource-intensive diets, and a growing population (Cassidy et al., 2013). According to Beltran-Pena et al. (2020), the economic yield from crops needs to increase by more than double by 2100 to support the present population growth. Furthermore, the increase in competition for water resources is becoming increasingly crucial (Seekell, 2017; Bjornlund, 2020), as such it is essential to develop, test and adopt innovative technologies that effectively utilize water and ensure food security as agriculture is a major consumer of Global water resources (Ansari, Naghedifar, & Faridhosseini, 2015; Dirwai, Mabhaudhi, Kanda & Senzanje, 2021). There is a need to strive to conserve and use water wisely to maximize production per litre of water. Abu-Zreig et al. (2006) and Siyal et al. (2009) argued that despite the potential water conservation benefits of modern irrigation techniques such as subsurface drip irrigation, their adoption is hindered by technical, economic, and societal constraints. Consequently, it is vital to develop a technique that is simple to implement and can conserve moisture at a lesser price (Batchelor et al., 1996, Bainbridge 2001). Research conducted in arid and semi-arid regions by Mondal (1974), Setiawan et al. (1998), Stein (1998), Bainbridge (2001), Siyal and

Skaggs (2009), Tesfaye et al. (2012) and Siyal et al. (2013), Vasudevan et al. (2014), has demonstrated the efficacy of pitcher irrigation. The current food security issues are substantial, and their intensity is expected to escalate in the next years due to the projected 35% population growth in the next four decades (Stewart & Roberts, 2012). Agricultural production will have to be increased to accommodate the growing population (Mahmud, Upadhyay, Srivastava, & Bhojiya 2021). Currently, food production fails to meet the world's food demand without fertilizers. At least 30 to 50% of global crop yields are produced using fertilizers, making fertilizers an important ingredient in preserving food production to keep up with an expanding world population (Zhang, Zhang, Sun, Jiang, Xu, & Yang, 2022). Fertigation is an important part of protected agriculture that affects crop yield and quality. To meet crop nutrient requirements following their developmental stage, fertigation can be used to regulate the concentration of nutrients required. The appropriate amount of nutrients must be supplied by the crop developmental stage to ensure that the quantity of nutrients supplied is sufficient (Saurabh & Singh, 2019). Gowda et al. (2002), Santos et al., (2003), Olaniyi and Ojetayo (2010), Ciba and Sadasakthi (2011), Sabli et al., (2012), Bhuvneshwari et al., (2013), Biwalkar et al., (2015), Sharma (2016), Rekha et al. (2017) and Shahein et al., (2018) all reported that fertigation boosted plant growth and yield attributes. To boost crop abundance, it's vital to underline existing irrigation systems like drip irrigation and clay tube irrigation in addition to management tactics like fertigation, which ensures the most efficient method for delivering water and nutrition. This study presents the response of bell peppers to watering, drip and SLECI systems as well as different fertilizer application methods under greenhouse conditions.

Methodology

Study area

The experiment was undertaken at the University of Cape Coast, School of Agriculture Teaching and Research farm, which falls within Latitude: 5°6'57.37" N and Longitude: -1°17'6.55" E. The experimental region is in a tropical savanna climate characterized by two extended periods of rainfall, with an annual rainfall total between 750 and 1,000mm and a mean monthly relative humidity varying between 85% and 99%. The experimental area experiences high temperatures throughout the year. The annual mean temperatures range from 23.2-33.2 ºC.

Greenhouse

The experiment was conducted in an 8 x 22 m^2 greenhouse, out of which plastic growing pots were arranged to depict the experimental layout. The greenhouse used a supplemental ventilation system (fan) powered by a solar system to control maximum temperature during hot periods of the day (11:30 am - 3:30 pm) to maintain temperature. The mean minimum and maximum temperature recorded in the greenhouse were 39.6^{0}C and 25.7^{0}C, whereas the mean minimum and maximum relative humidity were 52% and 96%, respectively. The greenhouse was fumigated with Plan D general-purpose insecticide and wood vinegar 1 week before the transplanting of bell pepper plants. Fumigation was carried out with the sole purpose of eradicating fungal spores, pests and diseases that might have accumulated in the greenhouse.

Figure 10: Greenhouse layout before transplanting

Preparation of growth media

The growth media used for the experiment was made of coconut fibre, vermiculite and perlite and formulated on a 50%, 25%, and 25% weight basis. The bell pepper plants were cultivated in cylindrical plastic pots measuring 25 cm in diameter and 30 cm in height. This implies that each plastic pot held a total volume of 0.059 m3 of growing media.

Nursery and transplanting

Bell pepper (yolo wonder) seeds were nursed in a seed tray filled with growth media (coconut fibre, vermiculite and perlite). 3 weeks old seedlings were hardened odd 1 week before transplanting by reducing the amount of water applied. Healthy vigorous seedlings were transplanted, and one seedling was planted in one plastic growing pot.

Figure 11: Transplanted bell pepper plant

Experimental Design and Treatment

The experiment was conducted using a factorial design (A^3 x B^2) and a completely randomized layout with five replications. The experiment involved six treatment combinations, which were obtained by combining three levels of irrigation systems (watering, drip irrigation, and SLECI system) with two levels of fertiliser administration methods (basal application and fertigation). A plot in the greenhouse is represented by 6 plastic pots. A gap of 1 meter was permitted between the plots. The drip irrigation system consisted of a water storage unit, filter valve and drip tape tube, with irrigation water being supplied with a single line of drip irrigation tubing (30cm emitter spacing) through gravity flow. The SLECI system consisted of a water tank (200 litres), valve, filter, clay tube, connectors, coupling, PE- tubes, and an end cap. Manual irrigation was carried out using a watering can with a capacity of 10 litres. The amount of water (ETo) to be supplied through drip and manual was determined by evaporation pan.

Fertilizer schedule

The fertigation system consisted of a fertilizer tank, valves, PE tubes and drip tubes. An application rate of 105 kg/ha was adopted by Kanneh et al. (2017). Three NPK fertilizers were adopted for the study. Phosphorus-based Plantifol NPK 10-50-10 was applied 2 and 10 days after transplanting to supply phosphorus to bell pepper plants which are required for root establishment & growth and enhance water use efficiency. General purpose Plantifol NPK 20-20-20 was applied 15, 22 and 29 days after transplanting to promote vegetative growth and initiation of flower formation. Potassium-based Plantifol NPK 12-6-36 was applied 36, 43, and 50 days after transplanting to enhance fruit set and fruit development. Can-17 Calcium nitrate (17-0-0 N 12 CaO) was applied 40 and 47 days after transplanting to supply calcium to bell pepper plants. Fertilizer was applied through two methods, that is basal application and fertigation. The basal application was carried out by placing the fertiliser 5 centimetres away from the base of the plant and at a depth of 10 centimetres. The process of fertigation involved the dissolution of the fertiliser in the water provided to the plants.

Data Collection

Plant height

Plant height was determined by measuring the distance from the highest point of the growing media to the topmost part of the plant. The average plant height was measured in centimetres (cm).

Leaf area (Individual leaf area)

The length of the leaf was measured as the longest segment along the petiole line of the leaf on the lateral bud below the shoot tip. The breadth of the leaf was measured as the widest width across the leaf. The product was scaled down by a factor of 0.75 to obtain the leaf area.

Number of fruits

The fruits harvested from the tagged plants at various growth stages were tallied and quantified as the number of fruits per plant.

Average fruit weight

The fruits harvested from the tagged plants were weighed, recorded and expressed as grams.

Yield per hectare

In each plot, an area of the plastic growing pot was determined. The total plant yield for the selected was then derived by weighing all fruits from the tagged plants after which the total fruit weight in the selected plot was added to generate the total yield for the selected plot. The total area for the plots was then converted from square meters to a hectare basis. Yield per hectare was then derived using the formula below (Equ. 10).

$$\frac{1\ hectare}{Selected\ area\ containing\ tagged\ plants\ (hectare)} x\ total\ yield\ from\ tagged\ plants\ (kg)$$

Equ. (10)

Water use efficiency

Water use efficiency was calculated through the proportion of the total plant yield and the total water applied under each treatment (Equ. 11).

$$\frac{\textbf{Total yeild per plant (g)}}{\textbf{Total amount of water applied (mm)}} \qquad \text{Equ (11)}$$

Fertilizer use efficiency

Fertilizer use efficiency was calculated through the proportion of the total plant yield and the total fertilizer applied under each treatment (Equ. 12).

$$\frac{\textbf{Total yeild per plant (g)}}{\textbf{Total amount of fertilizer applied (kg)}} \qquad \text{Equ (12)}$$

Marketable Fruits (%)

Physically sound fruits, free from diseases, deformity injury and damages were counted after harvest and the percentage was calculated as shown in Equ 13;

$$\frac{\textbf{Number of physically sound fruits per plant}}{\textbf{Number of harvested fruits per plant}} \times \mathbf{100} \qquad \text{Equ (13)}$$

Incidence of Blossom End Rot (%)

Incidence was recorded after harvesting by counting the number of fruits with symptoms of BER (brown to black dry patch at the blossom end of the bell pepper fruit) and the data was converted to represent % disease incidence.

$$\frac{\textbf{Number of diseased fruits per plant}}{\textbf{Number of harvested fruits per plant}} \times \mathbf{100} \qquad \text{Equ (14)}$$

Data analysis

Analyses of variance (ANOVA) of data collected were performed to evaluate the effect of various treatment factors, using Genstat statistical software

(Introduction to GenStat for Windows 18th Ed, VSN International, Rothamsted Experimental Station, Reading University, United Kingdom). Significant mean differences among treatments were compared using Tukey's least significant difference test at a probability level of 5%.

Results & Discussion

Cumulative water use

Figure 12 displays the total quantity of water used in different irrigation methods. The quantities of water utilized for watering, SLECI system, and drip irrigation system were 764.1 mm, 573.9 mm, and 664.3 mm, respectively. This aligns with the results of Ansari et al. (2015), which showed that the total water volume used for pitcher irrigation was lower compared to both drip irrigation and traditional irrigation systems. Results from Figure 12, indicate that the SLECI system saves up to 15.8% and 33.1% of water compared to the drip irrigation system and watering, while drip irrigation saves 19.5% of water when compared to the watering. The difference in cumulative water applied among the irrigation systems could be attributed to the rate of water movement from the irrigation systems to the plant. SLECI system irrigated plants were comparatively slower compared to drip irrigation systems and watering. This could be attributed to the fact that the SLECI system is a subsurface irrigation system with an auto-regulation ability (van Sen et al. 2007, Abu-Zreig et al. 2006, Stein, 1997), this ability is a result of the close interaction between the clay tube, plant roots, the soil and soil water tension. SLECI system supplies water to the soil when soil water tension is high which indicates a dry soil and water-stressed plant (Dührkoop, 2020). When the soil moisture increases, water is induced to flow through the walls of the SLECI system. As a result, the soil water tension decreases, causing the water flow to automatically reduce or cease altogether (Dührkoop, 2011; Dührkoop, 2008). Therefore, validating the self-regulating capabilities of the SLECI system to minimize irrigation losses. Watering supplied a greater amount of water compared to SLECI systems and drip irrigation systems due to a larger portion of the soil surface being wetted and higher levels of evaporation.

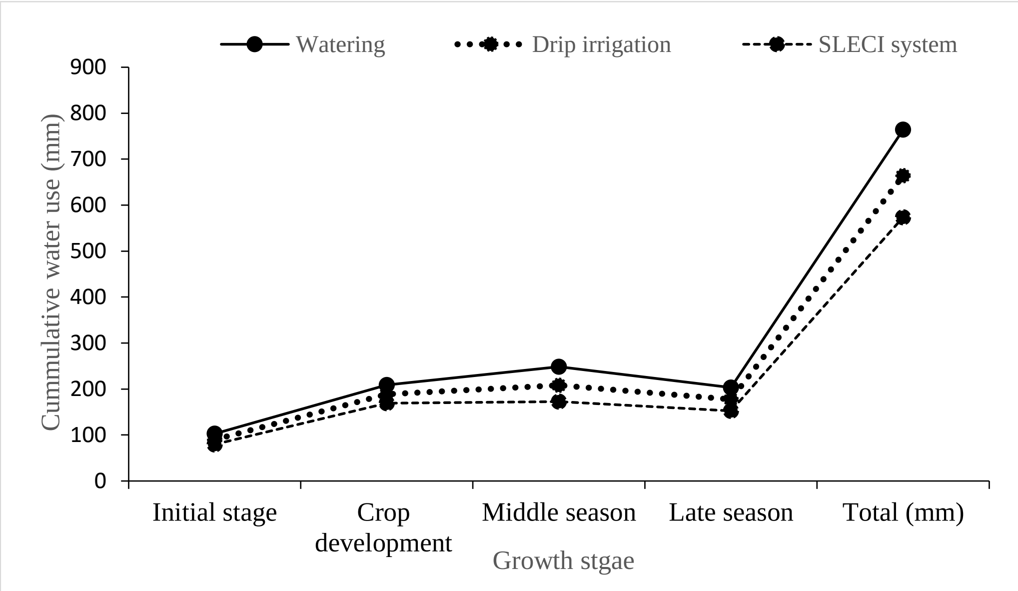

Figure 12: Crop water requirement of bell pepper under different irrigation systems.

Bell pepper plant height as influenced by irrigation system and fertilizer application method

Bell pepper plant height was significantly affected by different irrigation schemes, with a p-value of less than 0.05. (Figure 13). At 2 wat, Bell pepper plant height did show a significant difference among the drip irrigation system

(27.83 cm) and the SLECI system (29.20 cm) but both were significantly superior to watering (21.15 cm). A consistent trend was observed at 4 wat, drip irrigation system (49.28 cm); SLECI system (50.68 cm) and watering (45.84 cm), 6 wat, drip irrigation system (67.39 cm); SLECI system (67.95 cm) and watering (56.54 cm), 8 wat drip irrigation system (83.36 cm); SLECI system (84.57 cm) and watering (67.01 cm), 10 wat, drip irrigation system (95.88 cm); SLECI system (96.06 cm) and watering (77.92 cm), 12 wat, drip irrigation system (99.18 cm); SLECI system (100.31 cm) and watering (86.33 cm) Figure 13. In general, plant height increased with an increasing number of weeks in the irrigation system with the highest plant height recorded at week 12 for each system. Compared to watering, the plant height of bell pepper cultivated on drip and SLECI systems had a 19.2 % and 20.9 % increase in plant height respectively (Figure 13). Bell pepper cultivated on the SLECI system had higher plant height compared to the drip irrigation system however this difference was statistically insignificant.

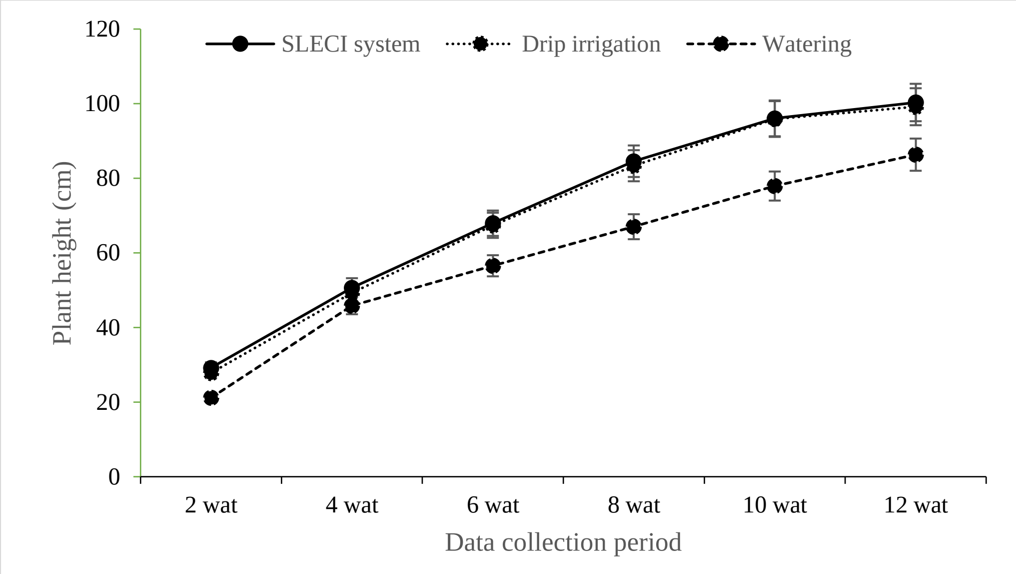

Figure 13: Bell pepper plant height as influenced by different irrigation systems at varying periods.

The response of bell pepper plant height to different fertilizer methods is presented in Figure 14. Fertilizer application methods significantly ($p < 0.001$) affected bell pepper plant height at 2 wat Basal application (24.77 cm) Fertigation (27.35 cm), 4 wat Basal application (44.55 cm) Fertigation (52.64 cm), 6 wat Basal application (58.20 cm) Fertigation (69.72 cm), 8 wat Basal application (72.26 cm) Fertigation (84.36 cm), 10 wat Basal application (81.24 cm) Fertigation (98.67 cm) and 12 wat Basal application (88.25cm) Fertigation (102.29 cm). An increasing trend in plant height was observed under various fertilizer application methods within several days. At the end of the study, fertigation resulted in a plant height increase of around 17.8% compared to the basal fertilizer application method (Figure 14).

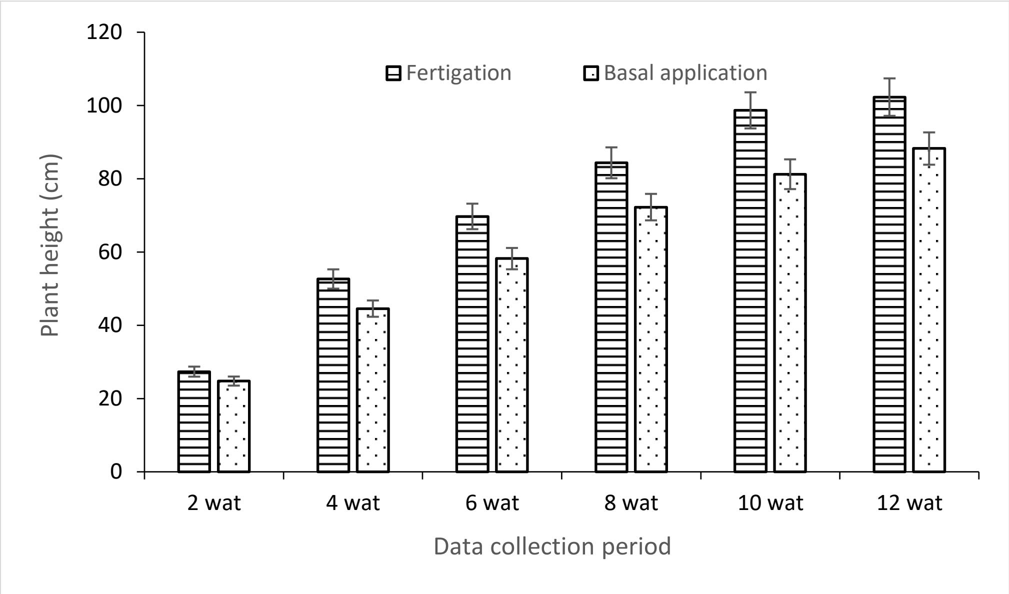

Figure 14: Bell pepper plant height as influenced by different fertilizer application methods at varying periods.

Figure 15 illustrates bell pepper plant height response to the interactive effect of different irrigation systems and fertilizer application methods, indicating a statistically significant variation ($P < 0.05$) at various growth periods of data collection. Significant differences existed among bell pepper plant heights under treatment combination of different irrigation systems and fertilizer application methods at 2 weeks after transplanting (wat) except plants grown under the SLECI system; Fertigation (30.04 cm) and drip irrigation system; fertigation (29.29 cm) as well as SLECI system; basal application (28.36 cm) and drip irrigation system; basal application (26.38 cm). Significantly lower plant height of 19.59 cm and 22.71 cm was observed in bell pepper plants grown under watering; basal application and watering system; fertigation (Figure 15). At 4 wat, the best-performing plant heights of 54.80 cm and 53.39 cm with no significant difference recorded in plant height grown under the SLECI system; fertigation and drip irrigation system; and fertigation, and were significantly higher than the remaining treatment combinations. The second-best performing plant height of 49.74 cm was recorded in watering; and fertigation. There was no significant difference between the plant height of bell pepper grown under the SLECI system; basal application (46.56 cm) and drip irrigation system; basal application (45.18 cm). Significantly lowest plant height of 41.93 cm, was recorded in watering; basal application. A similar trend of results was exhibited at 8 wat. Analysis of bell pepper plant height data, as influenced by the interactive effect of irrigation systems and fertilizer application methods, showed a consistent pattern 6, 10 and 12 wat. At 12 wat, the significantly highest plant height (108.8 cm) was recorded in bell pepper cultivated under the SLECI system and fertigation treatment and statistically not different from plant height (106.83 cm) of bell pepper plants grown under drip irrigation and fertigation. The second-best performing plant heights of 91.78cm, 91.52cm and 91.21cm that were statistically at par were recorded in the SLECI system; basal application, drip irrigation system; basal application and watering; fertigation. The worst-performing plant height (81.44 cm) was recorded in bell pepper plants grown under watering and basal application. Bell pepper cultivated under the SLECI system and fertigation resulted in a 1.8% and 19.3% increase in plant height when compared to bell pepper plants grown under drip irrigation system; fertigation and watering; fertigation (Figure 15).

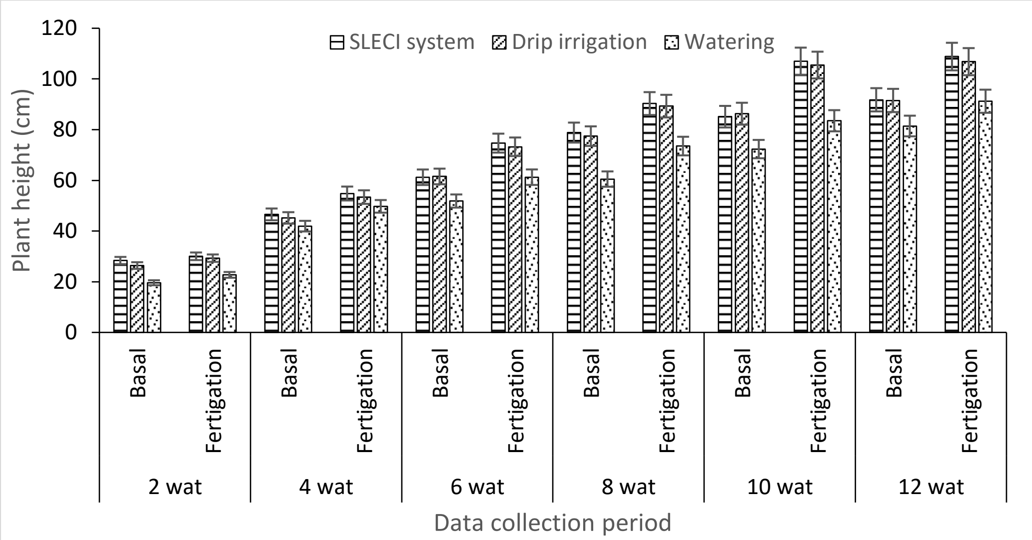

Figure 15: Bell pepper plant height as affected by the combination of different irrigation systems and fertilizer application methods at varying periods.

Bell pepper leaf area as influenced by irrigation system and fertilizer application method

Figure 16 illustrates the significant response of bell pepper leaf area to different irrigation systems. At 2 wat, the leaf area of bell pepper did show a significant difference between the SLECI system (16.99 cm^2) and drip irrigation system (16.70 cm^2) but both were significantly superior to watering (11.15 cm^2). A consistent trend was observed at 4 wat, SLECI system (30.84 cm^2); drip irrigation system (31.37 cm^2) and watering (21.64 cm^2), 6 wat, SLECI system (48.76 cm^2); drip irrigation system (47.67 cm^2) and watering (37.54 cm^2), 8 wat SLECI system (59.45 cm^2); drip irrigation system (58.95 cm^2) and watering (49.71 cm^2), 10 wat, SLECI system (66.41 cm^2); drip irrigation system (65.59 cm^2); and watering (56.18 cm^2), 12 wat, SLECI system (72.18 cm^2); drip irrigation system (71.40cm^2); and watering (65.61 cm^2) Figure 16. Compared to the watering, a 22 % and 20 % increase in leaf area was recorded for both the SLECI system and drip irrigation system respectively (Figure 16).

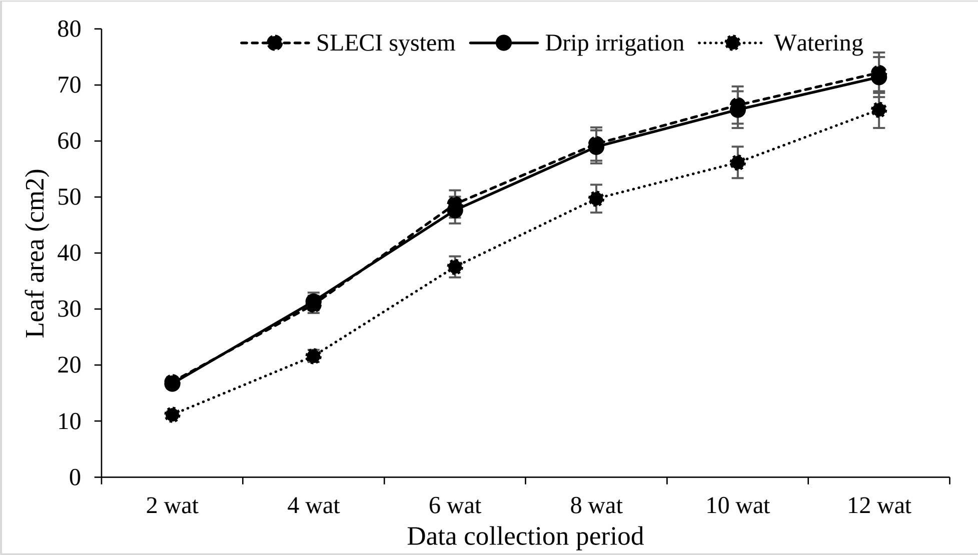

Figure 16: Bell pepper leaf area as influenced by different irrigation systems at varying periods.

Figure 17 illustrates the impact of the fertilizer application method on the bell pepper leaf area. Bell pepper leaf area significantly varied among methods of fertilizer application. Fertilizer application methods significantly ($p < 0.001$) affected the leaf area of a bell pepper at 2 wat basal application (14.58 cm^2) Fertigation (15.31 cm^2), 4 wat Basal application (27.29 cm^2) Fertigation (28.61 cm^2), 6 wat Basal application (41.04 cm^2) Fertigation (48.27 cm^2), 8 wat Basal application (52.37 cm^2) Fertigation (59.71 cm^2), 10 wat Basal application (57.33 cm^2) Fertigation (68.13 cm^2) and 12 wat Basal application (61.65cm^2) Fertigation (77.81 cm^2). More than a 1.2-fold increase in leaf area was observed between bell peppers cultivated under the fertigation system compared to the basal fertilizer application method (Figure 17).

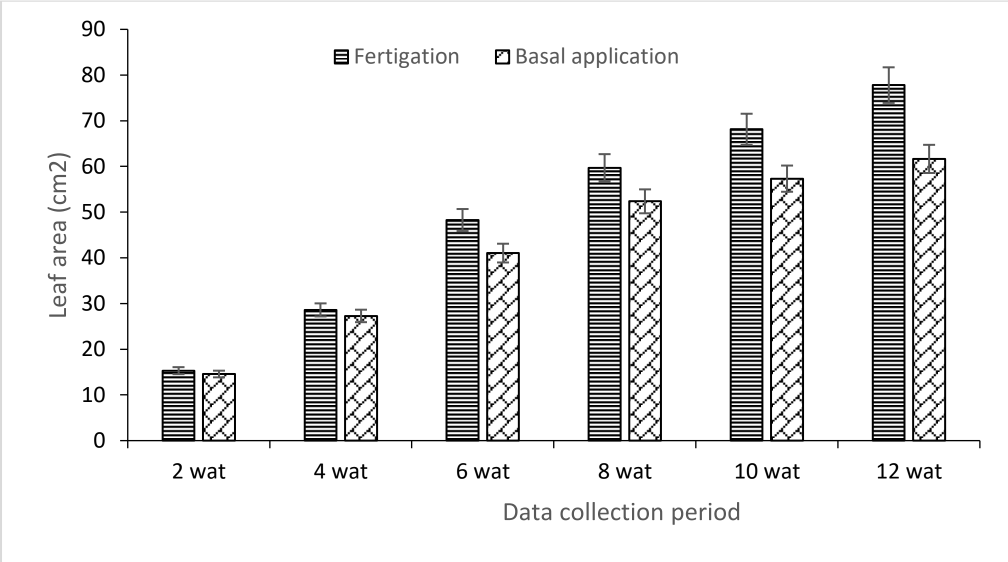

Figure 17: Bell pepper leaf area as influenced by fertilizer application methods at varying periods.

The bell pepper leaf area as influenced by the combination of different irrigation systems and fertilizer application methods is presented in Figure 18. At 2 wat, the leaf area of bell pepper grown under watering; basal application 10.91 cm^2 and watering; fertigation 11.38 cm^2 was statistically at par and lower than the leaf area of bell pepper grown under drip irrigation system; basal application (16.34 cm^2), SLECI system; basal application (16.50 cm^2), drip irrigation system; fertigation (17.06 cm^2) and SLECI system; fertigation (17.49 cm^2). At 4 wat, the significantly lowest leaf area of 20.09 cm^2 and 23.18 cm^2 was exhibited in bell pepper grown under watering; basal application and fertigation compared to the remaining treatment combinations. There was no significant difference between the SLECI system; basal application (30.73 cm^2) and fertigation (30.96 cm^2) as well as drip irrigation system; basal application (31.05 cm^2) fertigation (31.69 cm^2). At 6 wat, bell pepper is grown under manual irrigation; basal application leaf area of 31.66 cm^2 was significantly lower than the remaining treatment combinations. There was no significant difference between the leaf area of bell pepper grown under watering; fertigation (43.42 cm^2) drip irrigation system; basal application (45.22 cm^2) SLECI system; and basal application (46.24 cm^2). The leaf area of bell pepper grown under drip irrigation system; fertigation (50.12 cm^2) SLECI system; and fertigation (51.27 cm^2) was statistically at par and superior to the remaining treatment combinations. A consistent trend was observed 8 wat and 10 wat. At 12 wat, there were no significant differences between the interactive effect of manual irrigation; basal application 61.37 cm2, drip irrigation system; basal application 61.42 cm^2 and SLECI system; basal application (62.17 cm^2). Interactive effects of the drip irrigation system; fertigation 81.38 cm^2 and SLECI system; fertigation 82.19 cm^2 were statistically at par and superior to the remaining treatment combinations. At the end of the study the lowest leaf area 61.37 cm^2, was recorded, this represents a 33.9 % decrease, compared to the significantly highest leaf area (82.19 cm^2) that was recorded in bell pepper plants grown under the SLECI system and fertigation (Figure 18).

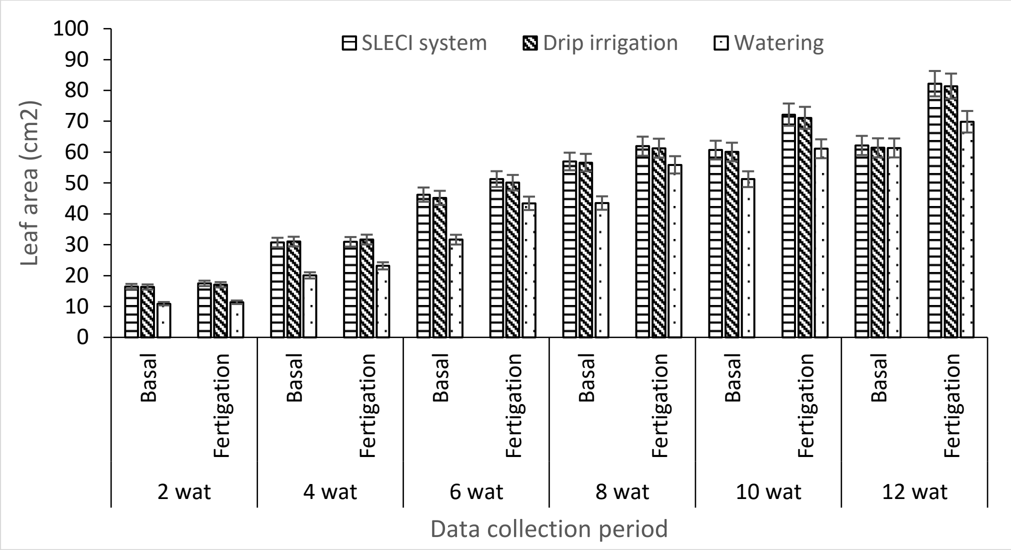

Figure 18: Bell pepper leaf area as influenced by the combination of different irrigation systems and fertilizer application methods at varying periods.

Discussion

Vegetative growth of bell pepper as influenced by different irrigation systems and fertilizer application methods

Different Irrigation systems

The analysis of variance for bell pepper vegetative growth attributes such as plant height and leaf area response to different irrigation methods, revealed substantial variations in both plant height and leaf area. These results align with the previous research conducted by Antony & Singhdhupe (2004), which showed that bell pepper plants grown using drip irrigation had greater growth attributes compared to surface irrigation. The findings of Lodhi (2009) supported this claim since they indicated that bell pepper plants produced using drip irrigation had greater vegetative attributes compared to those grown using furrow irrigation. Al-Omran et al. (2005) and Al-Harbi et al. (2008) found notable disparities between sub-surface and surface irrigation in terms of vegetative attributes like plant height and leaf area. These differences suggest that the main benefit of subsurface irrigation is the reduction of salt accumulation in the root distribution zone and the enhancement of moisture levels in the effective root zone of the crop. Bainbridge (1986) concluded that pitcher irrigation is superior to drip systems due to its reduced susceptibility to clogging compared to drip emitters. Additionally, the precise water delivery of pitcher irrigation minimizes weed-related issues in comparison to drip irrigation.

Fertilizer application method

In their study, Gowda et al. (2002) found that plants treated with fertigation had the highest plant height and leaf area measurements. The study conducted by Brahma et al. in 2010 found that fertigation resulted in the most significant growth features of the crop. Furthermore, according to Ciba's (2011) findings, fertigation was found to have the greatest impact on plant height. The study conducted by Pandey et al. (2013) found that using fertigation, a method of applying fertiliser through irrigation, resulted in increased growth of bell peppers compared to the traditional top-dressing method of fertiliser application. The acquisition of water and nutrients by plants, as well as the establishment of a deficient zone around the roots, are the primary factors that drive the flow of solutes towards the roots for uptake. Fertigation, a process where water and nutrients are combined, results in a reduced water flow rate. This slower flow rate allows the water and nutrients to remain in the root zone for a longer period. Consequently, this extended duration can contribute to enhancing plant growth. Silber et al. (2003) stated that fertigation enhances nutrient uptake by continuously replenishing nutrients in the depletion zone near the root interface. It also improves the movement of dissolved nutrients by mass flow, thanks to the higher average water content in the soil.

Interaction of Irrigation system and fertilizer application method

In their study, Gupta et al. (2010) found that bell pepper plants exhibited superior growth attributes when subjected to drip irrigation systems and fertigation. In drip fertigation, water is supplied directly to the effective root zone of the soil, where plant roots are located. This is different from manual irrigation, where the entire soil profile is saturated with water. Therefore, drip fertigation creates an advantageous setting where plants can thrive due to the presence of abundant moisture. Singh & Ghosal (2015) reported that pitcher irrigation systems and fertigation on crop performance revealed a significant increase in vegetative growth parameters. SLECI systems can release nutrient solutions at a slow rate devoid of leaching or evaporation losses. of fertilizer. Hemantoro et al. (2003) reported that soil moisture distribution from pitcher or clay tubes in the soil is sufficient to transport the solution available for crop growth and development. The nutrient content diminishes horizontally but instead tends to accumulate uniformly in the moist section of the soil where the vast majority of plant roots are clustered.

The number of fruits per plant is influenced by different irrigation systems and fertilizer application methods.

The influence of different irrigation systems on the number of fruits per plant is depicted in (Figure 19). Different irrigation systems had a significant impact on the number of bell pepper fruits, with average counts of 8.7, 11.3, and 13.2 observed for manual irrigation, drip irrigation, and SLECI system, respectively. The implementation of the SLECI system resulted in a 16.5% increase in the yield of bell peppers compared to the drip irrigation method. Figure 19 shows a 23% increase in the number of bell pepper fruits when cultivated using the drip irrigation method compared to watering.

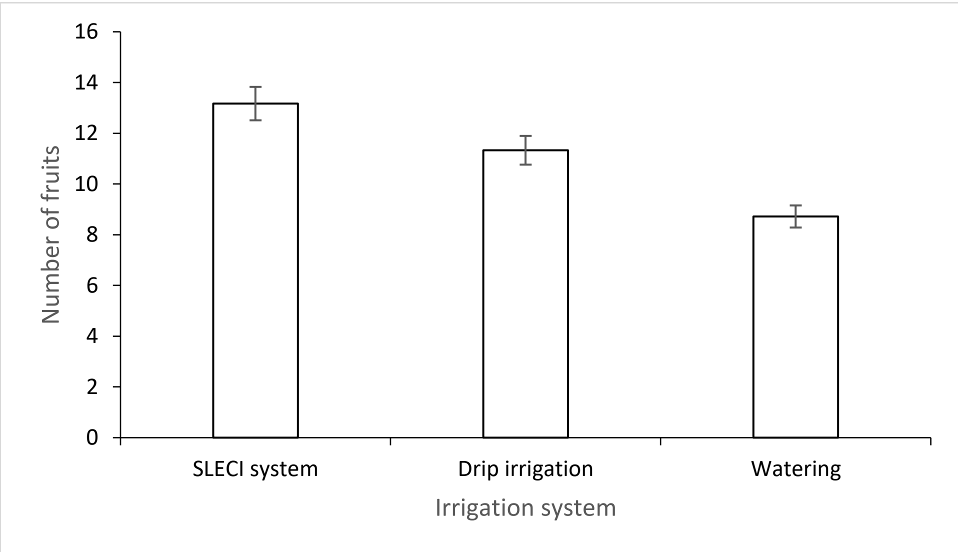

Figure 19: Number of fruits per bell pepper plant as influenced by different irrigation systems.

The number of fruits per bell pepper plant exhibited substantial variation across different ways of fertiliser treatment (Figure 20). The bell pepper grown with fertigation treatment (13.26) showed a 33% increase in the number of fruits per bell pepper plant in comparison with the basal fertilizer application method (8.89).

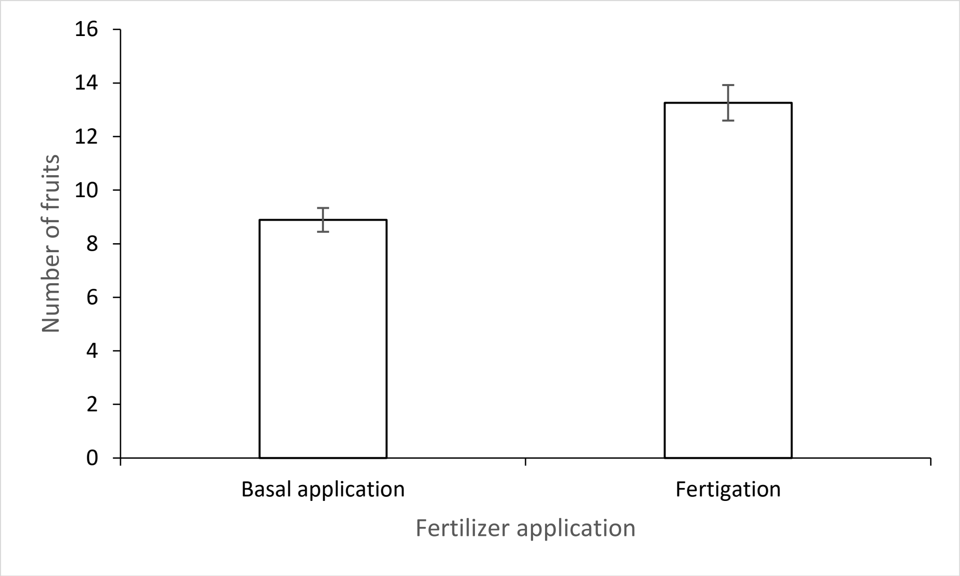

Figure 20: Number of fruits per bell pepper plant as influenced by different fertilizer application methods.

The combination of different irrigation systems and fertilizer applications resulted in significant variation in the number of fruits per bell pepper plant (Figure 21). The top three worst-performing recorded numbers of fruits (7.1, 9.2 and 10.3) were derived from bell pepper plants under treatment combinations that included basal application, whereas the best-performing bell pepper plants (10.4, 13.4 and 16) were grown under treatment combinations that included fertigation. The significantly highest number of bell pepper fruits of 16 was exhibited by plants grown under the SLECI system and fertigation.

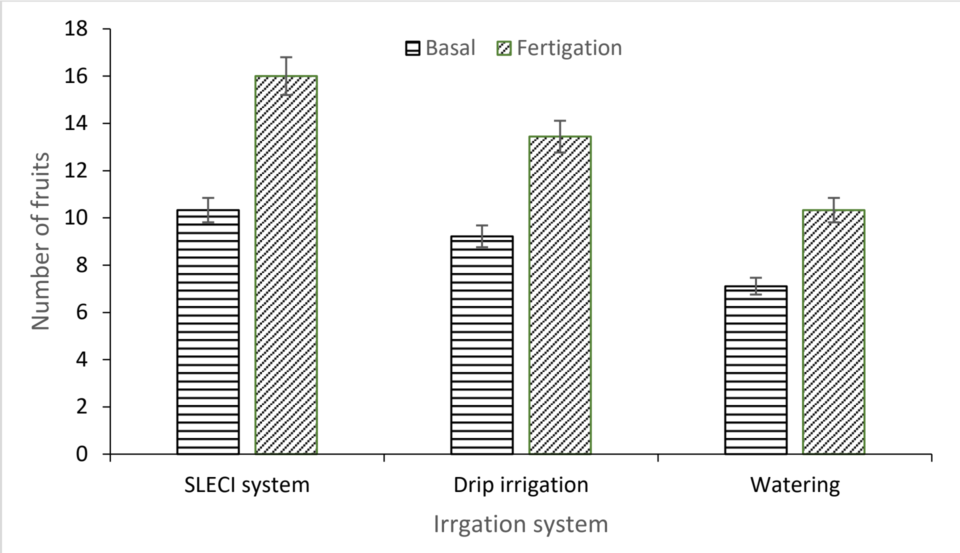

Figure 21: Number of fruits per bell pepper plant as influenced by the combination of different irrigation systems and fertilizer application methods at varying periods.

Bell pepper average fruit weight as influenced by different irrigation systems and fertilizer application methods.

Different irrigation systems resulted in significant differences in bell pepper plants' average fruit weight (Figure 22). The drip irrigation system had an average fruit weight of 106.02g, which was statistically at par with the average fruit weight of 107.53g recorded under the SLECI system. The worst-performing average fruit weight of 81.30g was recorded in bell pepper plants grown under watering. Comparing the average fruit weight obtained under drip and SLECI system with watering, an average increase of 30 % and 32 % was observed for the fruit weight of bell pepper (Figure 22).

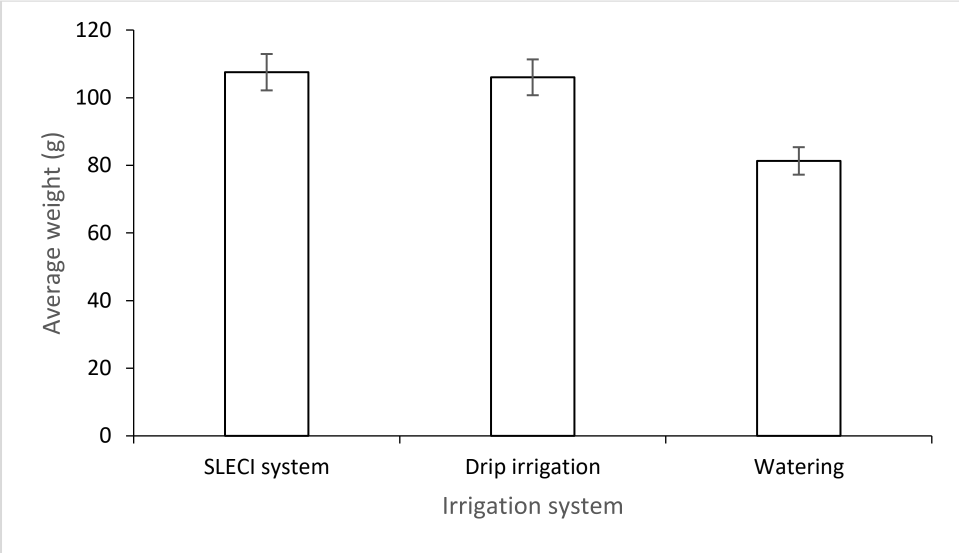

Figure 22: Bell pepper plant average fruit weight as influenced by different irrigation systems.

The mean fruit weight of bell pepper fruits influenced by various fertiliser application methods is displayed in (Figure 23). The mean fruit weight of bell peppers grown using fertigation (105.7g) was significantly greater than the mean fruit weight achieved when using basal fertiliser treatment (90.92g).

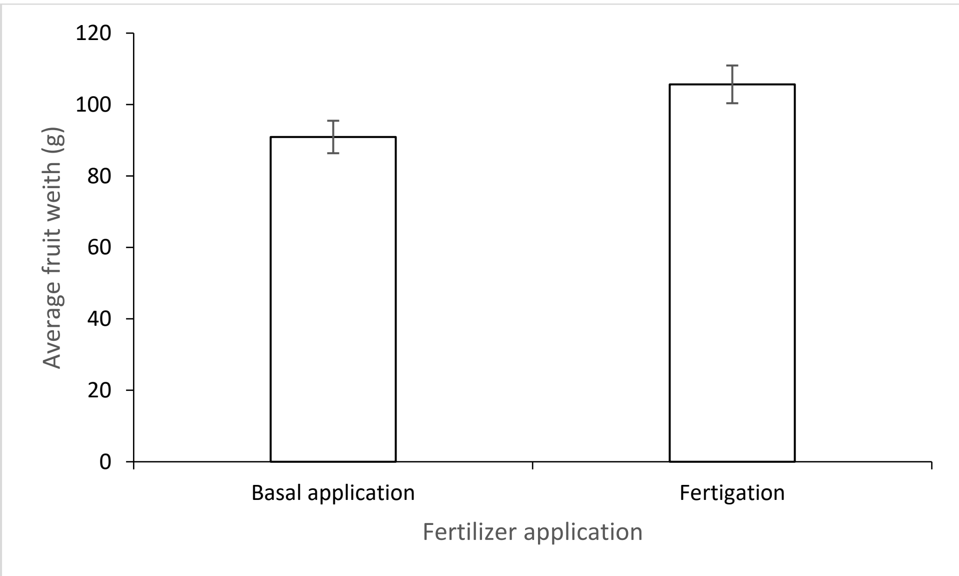

Figure 23: Bell pepper plant average fruit weight as influenced by fertilizer application methods.

The interaction of the SLECI system with fertigation recorded the significantly highest average fruit weight of 114.9g compared to the watering and basal application which recorded the lowest average fruit weight (Figure 24). Furthermore, the drip irrigation system combined with fertigation recorded a higher average fruit weight of 113.6g compared to 98.5 g obtained under the drip irrigation system and basal fertilizer application (Figure 24).

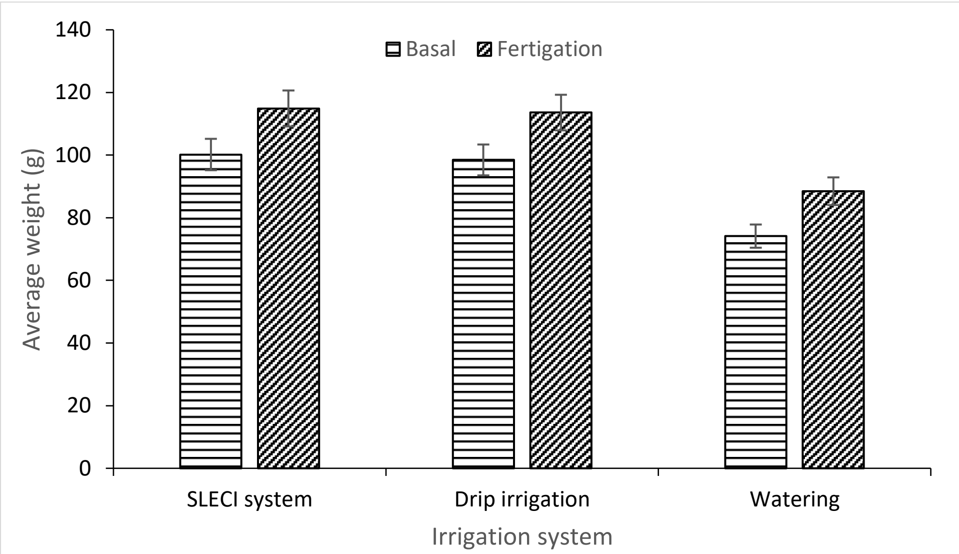

Figure 24: Bell pepper plant's average fruit weight as affected by the combination of different irrigation systems and fertilizer application methods.

Bell pepper plants' yield per hectare as influenced by the combination of different irrigation systems and fertilizer application methods.

Different irrigation systems resulted in significant variations concerning bell pepper plants' yields per hectare (Figure 25). Yield/hectare of bell pepper grown under the SLECI system (50840 t/h) and drip irrigation system (43117 t/h) increased more than 49 % and 41 % compared to watering (25491 t/h). The SLECI system recorded 15 % more yield/hectare compared to the drip irrigation system (Figure 25). Batchelor et al.1996 reached some results as far as pitcher irrigation and subsurface irrigation using the SLECI system are concerned. Evidence from (Figure 25) has demonstrated that the utilisation of the SLECI system for subsurface irrigation is highly efficient in enhancing crop yields.

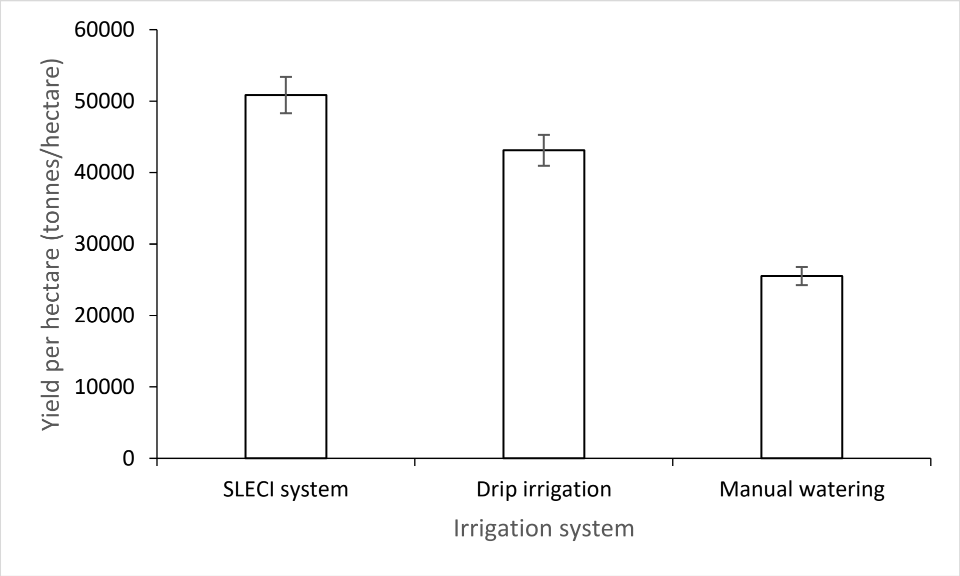

Figure 25: Bell pepper yield per hectare as influenced by different irrigation systems.

Figure 26 illustrates the bell pepper yield per hectare response to varying fertilizer application methods. The fertigation system (50459 t/h) of fertilizer application significantly increased yield per hectare of bell pepper by 42.2 % compared to the basal method of fertilizer application (29173 t/h) Figure 26.

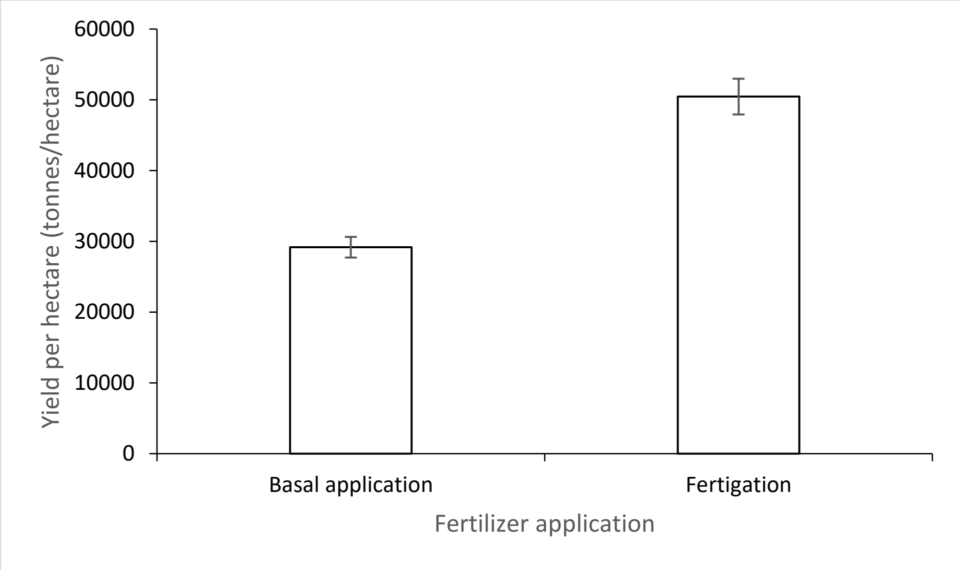

Figure 26: Bell pepper yield per hectare as influenced by fertilizer application methods at varying periods.

Figure 27 portrays bell pepper yield per hectare response to the combined effect of different irrigation systems and fertilizer application methods. Bell pepper cultivated under the SLECI system and fertigation (65037 t/h) produced the significantly highest yield which resulted in a 17 % and 50 % increase in yield per hectare of bell pepper compared to drip irrigation system; fertigation (54070 t/h) and watering; fertigation (32269 t/h). However, the SLECI system combined with fertigation produced 44 % more yield per hectare compared to the SLECI system combined with basal fertilizer application. Furthermore, a 12 % increase in yield per hectare of bell pepper was observed under the SLECI system combined with basal application compared to the drip line irrigation system combined with the basal application. The least performing yield of 18713 t/h was exhibited by bell pepper plants cultivated under watering and basal application method (Figure 27).

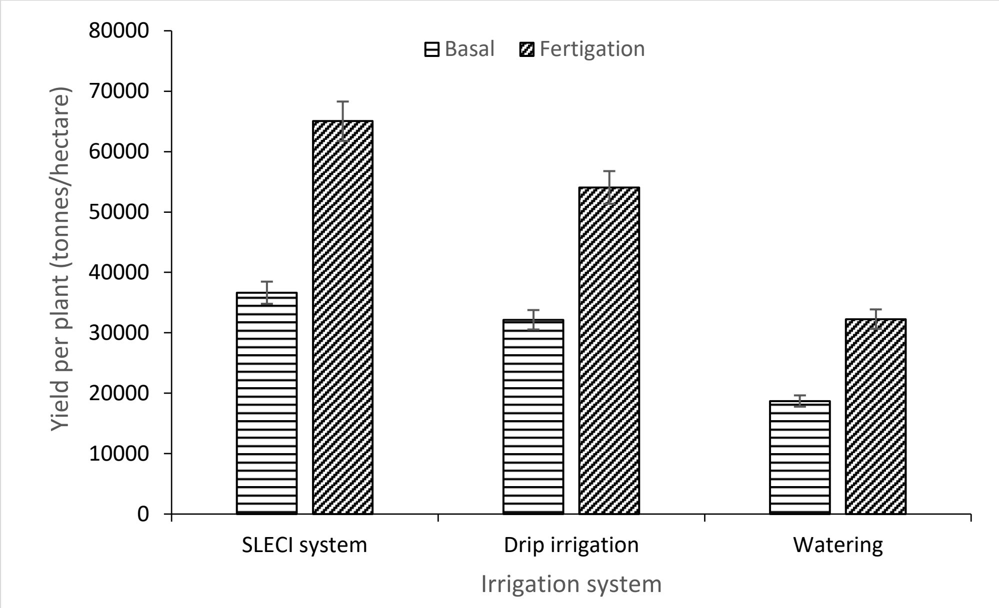

Figure 27: Bell pepper yield per hectare as influenced by the combination of different irrigation systems and fertilizer application methods

Discussion

Bell pepper yield response to the different irrigation system and fertilizer application methods

Irrigation systems

According to Antony and Singhdhupe (2004), Lodhi (2009), Kaushal et al. (2012), and Pandey et al. (2013), the use of drip irrigation resulted in a considerable increase in bell pepper yield attributes compared to plants that were surface irrigated. The superior efficacy of drip irrigation in comparison to manual irrigation can be ascribed to the efficiency of the drip irrigation system in supplying water and nutrients directly to the effective root zone of plants, ensuring that each plant receives the exact amount of water necessary for optimal growth. The SLECI system led to a significantly higher bell pepper yield in comparison to surface drip irrigation. The findings are consistent with the findings reported by Sammis (1980), Hutmacher et al. (1985), Bar-Yosef et al. (1991), Camp et al. (1993), El-Gindy and El-Araby (1996), Camp (1998), Ayars et al., (1999), Machado et al., (2003), Al-Omran et al. (2005), and Al-Harbi et al (2008). They reported that subsurface irrigation yielded higher results in comparison to surface drip irrigation. This phenomenon can be ascribed to the variables that impact the process of evaporation from the uppermost layer of soil. The act of burying irrigation pipes with sub-irrigation serves to diminish the amount of water lost through evaporation, so ensuring that water is accessible to the crops. In addition, Shlomo (2022) found that fertigation can cause an increase in the electrical conductivity of the soil solution. This is due to the buildup of salts in the root zone of the soil. Elevated salt levels tend to diminish the rate at which fruits grow and result in smaller fruits. The SLECI system facilitates the accumulation of salt on the walls of the clay tube, resulting in a reduced salt concentration in the water within the plant root zone compared to the water inside the SLECI system.

Fertilizer application method

Gupta et al. (2010), Ciba (2011), and Kaushal et al. (2012) saw a notable increase in the crop production of pepper when fertigation was applied. In their study, Brahma et al. (2010) found that fertigation resulted in the maximum yield attributes for bell peppers cultivated in a greenhouse. Sabli et al. (2012) provided more evidence by demonstrating that fertigation has a substantial impact on increasing the yield of bell pepper fruits. Fertigation delivers dissolved fertiliser to the root zone of plants via the irrigation system. When used with an efficient irrigation system like the SLECI system, both water and nutrients may be applied to achieve the highest possible crop output. The efficacy of manually applying fertiliser by side dressing or top dressing is impeded due to the leaching of fertilizers below the root zone or their removal from the crop during run-off.

Interaction of Irrigation system and fertilizer application method

In their study, Gupta et al. (2010) found that the application of both drip irrigation and fertigation resulted in a significant increase in the fruit output of bell peppers. These findings were supported by Biwalkar et al. (2015), who found that the use of both drip irrigation and fertigation resulted in the highest yield characteristics in bell peppers. This could be attributed to the fact that when fertigation is carried out through a drip irrigation system fertilizer is evenly distributed among plants. The availability of plant nutrients is consistent therefore fertilizer use efficiency is high. High fertilizer use efficiency suggests superior crop growth by delivering optimal feeding while minimizing nutrient losses. The improved performance of bell pepper plants, when the SLECI system and fertigation are combined, can be attributed to the gradual infiltration of water into the soil, which provides a consistent water supply to the plant's roots. The SLECI system enables plants to utilize water with greater efficiency compared to drip irrigation and watering methods. This is because the SLECI system delivers water straight to the crop's effective root zone.

Bell pepper water use efficiency as influenced by different irrigation systems and fertilizer applications.

Figure 28 presents the impact of different irrigation systems on the bell pepper water use efficiency. Analysis of variance revealed that different irrigation systems had a significant impact on the water use efficiency of bell peppers. The water use efficiency was reported as 0.2874 kg/l, 0.1354 kg/l, and 0.2874 kg/l for the SLECI system, drip irrigation system, and watering, respectively. SLECI system improved the water use efficiency of drip irrigation systems and watering by 53 % and 72 % respectively (Figure 28). Antony and Singhdhupe (2004) indicated that drip irrigation significantly improves water use efficiency (WUE) compared to surface irrigation. This was further substantiated by Lodhi (2009) and Kaushal et al. (2012) indicated that drip irrigation resulted in a better WUE in sweet pepper compared to conventional irrigation. Pandey et al. (2013) results revealed that drip irrigation saved water compared to flood irrigation of Capsicum. The growth of plant roots, which are the main organs for absorbing water, is enhanced in the region beneath or around the emitters of drip irrigation and SLECI system, thus bell pepper plants grown under drip and SLECI system were able to fully utilize irrigation water leading to an increase in water use efficiency. Sharma et al. (2012) found that the conventional irrigation system had the lowest water use efficiency (WUE). This is because, in conventional irrigation systems, a significant amount of water can be lost through evaporation, surface runoff, or percolation, which deprives plants of the necessary water for growth. Martínez and Reca (2014) showed that sub-surface irrigation improved water use efficiency compared to conventional or traditional systems. The SLECI system resulted in increased yields with similar water use. The study achieved water savings of 5-20% with the SLECI system. The significant increase in water savings with the SLECI system can be attributed to the absence of water losses from soil evaporation and better water distribution in the crop's root zone.

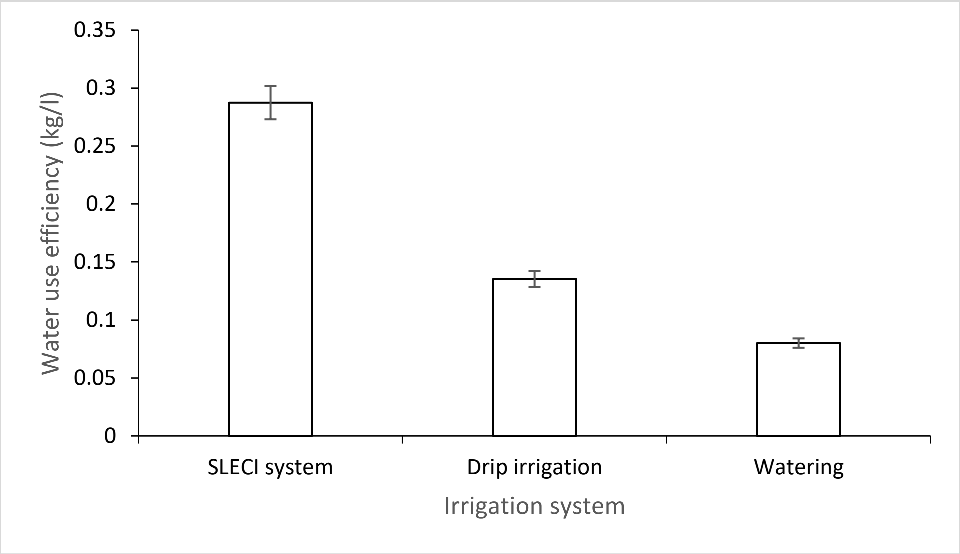

Figure 28: Response of bell pepper water use efficiency to different irrigation systems.

The fertilizer application method had a significant effect on the water use efficiency of bell pepper plants. Fertigation (0.2130 kg/l) significantly increased water use efficiency in bell peppers by 43 % compared to the basal application method (0.1223 kg/l) Figure 29. Solaimalai et al. (2005), Gupta et al. (2010) and Tanaskovik et al. (2011) reported that the water use efficiency of bell peppers under fertigation recorded higher use efficiency of water compared to manual application of fertilizer. Sharma et al. (2012) further indicated water use efficiency is significantly influenced by fertigation. Douh and Boujelben (2011). Subsurface drip irrigation ensures consistent soil moisture, reduces evaporation, and provides water directly to the plant's root zone. This allows the plant to efficiently absorb and use the nutrients provided by irrigation, ultimately improving water use efficiency.

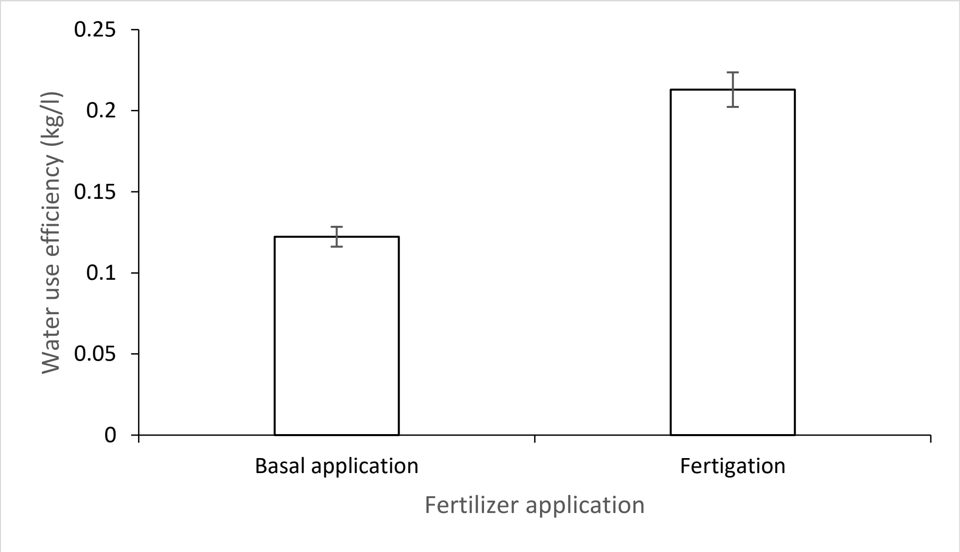

Figure 29: Response of bell pepper water use efficiency to different fertilizer application methods.

The interactive effect of different irrigation systems and fertilizer application methods on the water use efficiency of the bell pepper plant is presented in Figure 30. Significantly highest water use efficiency was exhibited by bell pepper plants under the SLECI system with fertigation (0.3677 kg/l) which is 53.8 % and 72.4 % better compared to drip irrigation system; fertigation (0.1698 kg/l) and watering; fertigation (0.1014 kg/l). Similarly, high water use efficiency was recorded under the SLECI system combined with basal application (0.2072 kg/l) compared to drip irrigation system; basal application (0.1010 kg/l) and watering; basal application (0.0588 kg/l). The result from Figure 30, indicates that regardless of the fertilizer application method chosen, the SLECI system resulted in the best-performing water use efficiency compared to the remaining treatment combination. The lowest water use efficiency of 0.0588 kg/l was recorded in a combination of watering and basal application methods. Gupta et al. (2010) reported a significantly higher water use efficiency of bell peppers when drip irrigation is combined with fertigation. This was validated by the findings of Tanaskovik et al. (2011) and Sharma et al. (2012) who indicated that treatment combination of fertigation and drip irrigation system exhibited better water use efficiency in comparison with a combination of drip irrigation system and conventional application of fertilizer as well as the combination of furrow irrigation and conventional methods of application of fertilizer. The best-performing treatment combination was the SLECI system and fertigation When the surrounding area around the clay tube becomes saturated, water stops seeping out of the clay tube, and water seepage returns when the moisture level in the soil drops, thus making the system self-regulatory. The surrounding region around the clay tube is almost always at field capacity thus deep percolation losses are negligible and the rate of water loss can be controlled. Water requirements in clay tube irrigation are less than that of drip irrigation and other irrigation system due to the very low permeability of the clay tube, as well as reduced evaporation losses.

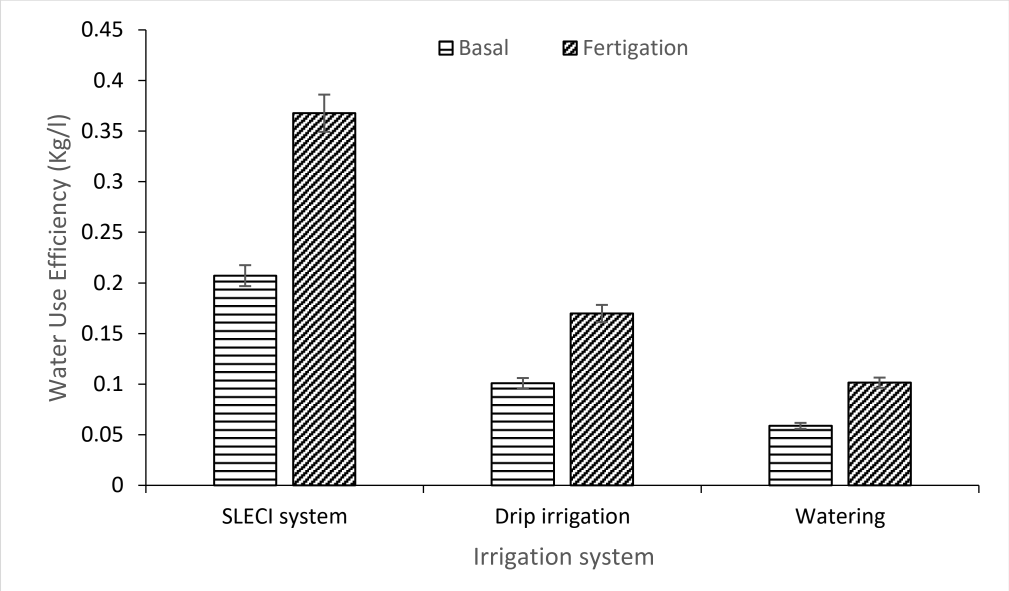

Figure 30: Response of bell pepper water use efficiency to the combination of different irrigation systems and fertilizer application methods.

Bell pepper fertilizer use efficiency response to different irrigation systems and fertilizer application methods.

Bell pepper plant fertilizer use efficiency varied significantly ($P < 0.001$) among different irrigation systems (Figure 31). The SLECI system recorded the highest fertilizer use efficiency (11.9 kg/kg) compared to the drip irrigation system (10.2 kg/kg) and watering (6.1 kg/kg). SLECI system improved fertilizer use efficiency by 14.2 % and 48.7 % compared to drip irrigation systems and watering (Figure 31). Batchelor et al.1996 reached some results as far as pitcher irrigation and subsurface irrigation using SLECI systems are concerned. It was proved that subsurface irrigation using clay pipes was particularly effective in improving fertilizer use efficiency. Gupta et al. (2010) revealed that drip irrigation resulted in significant improvement in fertilizer use efficiencies of bell pepper. This was further substantiated by Kaushal et al. (2012) who reported that drip irrigation reduces fertilization requirements. Al-Harbi et al. (2008)

indicated that subsurface irrigation significantly increases root length, and width compared to the surface irrigation system. Under the SLECI system, the density of roots in a concentrated root zone is substantially higher per unit of soil, thus fertigation is far more effective. In the SLECI system, fertilizer is administered to the plant root zone, fertigation goes on uninterrupted thereby increasing crop performance and subsequently fertilizer usage efficiency. Additionally, the lower application rate of water using the pitcher irrigation system averts minerals from being leached out of the plant's root zone.

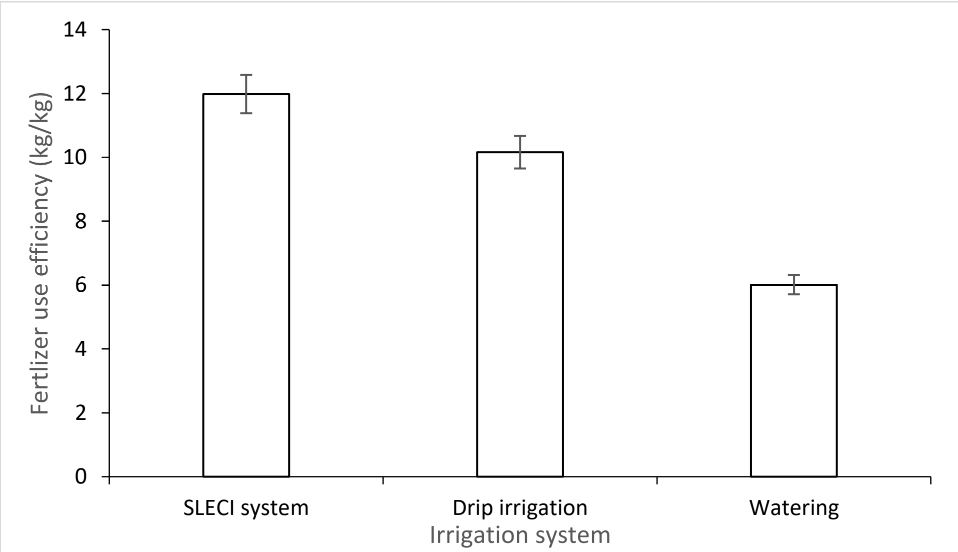

Figure 31: Bell pepper fertilizer use efficiency as influenced by different irrigation systems.

Significant variations ($P < 0.001$) existed among bell pepper fertilizer use efficiency as a result of the fertilizer application method. Fertigation (11.9 kg/kg) resulted in a 42% increase in fertilizer use efficiency compared to basal fertilizer application (6.8 kg/kg) Figure 32. Gupta et al. (2010) revealed that fertigation resulted in significant improvement in fertilizer use efficiencies of bell pepper. This was further affirmed by Kaushal et al. (2012) who reported that fertigation, reduces fertilizer requirement by 20-33% thereby increasing fertilizer use efficiency. Pandey et al. (2013) explained that fertigation saved water compared to top dressing and basal methods of applying fertilizers. Fertigation results in better fertilizer use efficiency due to the minutest losses of nutrients as a result of leaching, the direct supply of available forms of nutrients to the root zone of crops.

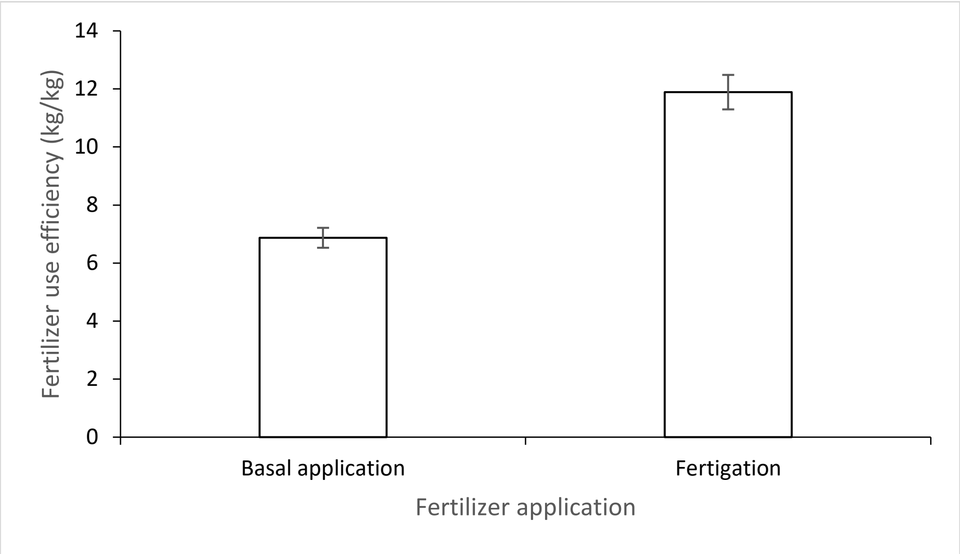

Figure 32: Bell pepper fertilizer use efficiency as influenced by fertilizer application method.

The combination of different irrigation systems and fertilizer application methods resulted in significant fertilizer use efficiency of bell pepper plants (Figure 33). Fertigation through a SLECI system exhibited the highest fertilizer use efficiency of 15.322 kg/kg followed by fertigation through a drip irrigation system (12.738 kg/kg). The following treatment combinations drip irrigation system; basal application, watering; fertigation and SLECI system; basal application exhibited fertilizer use efficiency of 7.6 kg/kg, 7.6 kg/kg and 8.6

kg/kg that were statistically at par with each other. The significantly lowest fertilizer use efficiency of 4.408 kg/kg was recorded under watering and basal application methods. Under the basal application method SLECI system resulted in a 48 % increase in fertilizer use efficiency of bell pepper compared to the manual application system (Figure 33). Solaimalai et al. (2005), reported that drip irrigation and fertigation resulted in greater fertiliser use efficiency. Gupta et al. (2010) discovered a notable enhancement in the effectiveness of fertiliser utilisation in capsicum plants when drip irrigation and fertigation techniques were employed. This can be attributed to the fact that fertigation, which involves supplying nutrients through a drip irrigation system, enhances fertiliser use efficiency (Thompson et al., 2018). By delivering nutrients using irrigation water, they are uniformly distributed to the crop's root zone and readily available for plant uptake in soluble forms (Shirgure, 2013). The fertilizer use efficiency was significantly higher when using the SLECI system for fertigation compared to surface drip irrigation systems. According to Elhindi et al. (2016), a subsurface irrigation system is more effective than a surface drip irrigation system with regard to fertiliser use efficiency because it allows for a higher concentration of nutrients in the root zone of plants.

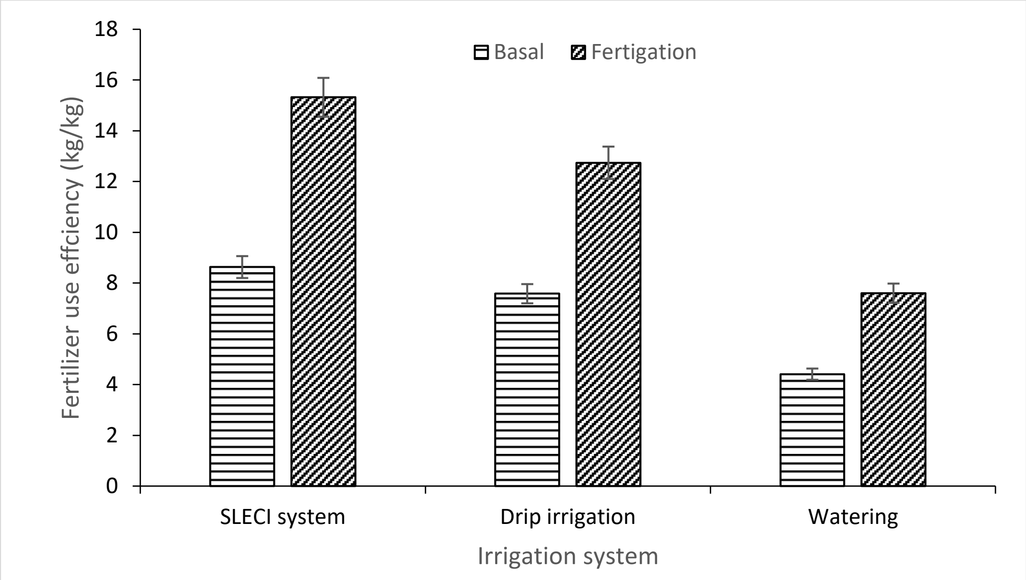

Figure 33: Response of bell pepper fertilizer use efficiency to the combination of different irrigation systems and fertilizer application methods.

Incidence of Blossom end rot (BER) bell pepper fruits has influenced different irrigation systems and fertilizer application methods.

Different irrigation systems significantly influenced BER incidence in bell pepper plants (Figure 34). The highest BER incidence of 7.6 % was recorded in bell pepper fruits under watering, whereas the lowest BER incidence of 1.6 % was recorded in bell pepper fruits from the SLECI system. SLECI system and drip irrigation system reduced BER incidence by 78.9 % and 44.8 % compared to watering (Figure 34). Tadesse et al. (2001), Taylor et al. (2004), Taylor and Locascio (2004) and Diaz-Perez and Hook (2017) indicated that irrigation regimes have been reported to influence BER in bell pepper. Fluctuating soil moisture due to inconsistent watering, shallow watering or overwatering as a result of manual irrigation is conducive to blossom end rot. Under drip irrigation, a zone of very high salinity can occur beneath the emitters, above the drip tape. The source of this phenomenon is the accumulation of salt resulting from the evaporation of water, transpiration by plants, and the gradual application of water at low pressure. Increased salinity levels contribute to the development of blossom end rot (BER) (Ehret & Ho, 1986; Adams & Ho, 1992; Adams & Holder, 1992). Sonneveld (1979) found that the incidence of blossom end rot (BER) in bell peppers rises as the electrical conductivity (EC) surpasses 1.0 dS/m. Bar-Tal et al. (2003) and Aktas et al. (2005) provided additional evidence that salt leads to a significant rise in the proportion of fruits affected by BER. The surge in the incidence of fruits affected by blossom-end rot (BER) in the presence of saline is connected to a decrease in the absorption of calcium and its subsequent transportation into the fruits.

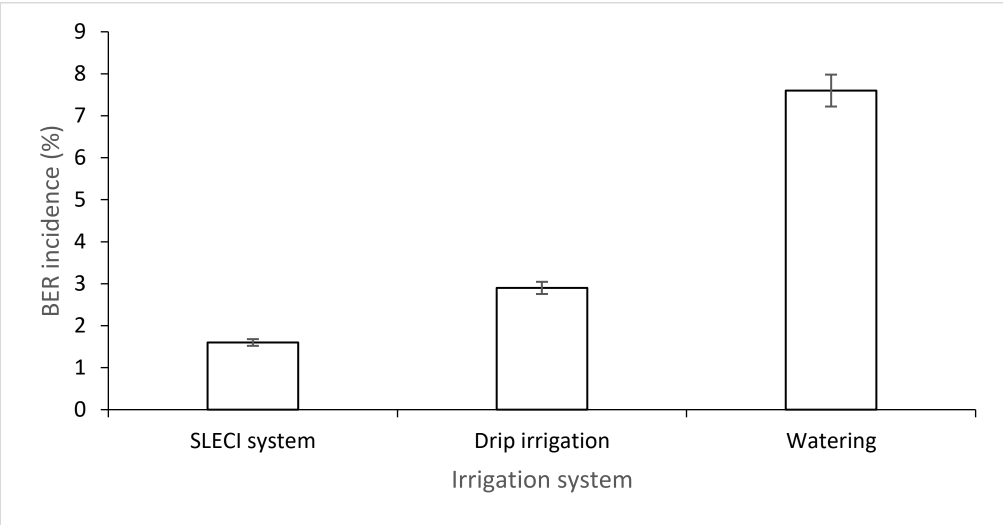

Figure 34: Effect of different irrigation systems on BER incidence of bell pepper fruits

The incidence of BER was significantly lower under fertigation (2.9 %) compared to the basal application (5.1 %) of fertilizer (Figure 35). Bell pepper cultivated under fertigation treatment resulted in a 76 % decrease in the incidence of BER compared to the basal fertilizer application. In bell pepper fruit, BER is a symptom of calcium deficiency occurring early in development

(Bangerth, 1979; Marcelis & Ho, 1999). Coolong, Ribeiro da Silva, and Shealey (2019) and Putti et al (2022) indicated that fertigation reduced the incidence of blossom end rot. Fertigation is a fertilizer application method that ensures the precise placement of fertilizer in the optimal root zone, where the roots of plants grow and have a high density. Additionally, the frequent application of fertilizer in small doses under low pressure, thereby, increases fertilizer use efficiency. Furthermore, fertigation reduces leaching, while ensuring better fruit quality with less fertilizer compared to the top dressing or side dressing method of fertilizer application.

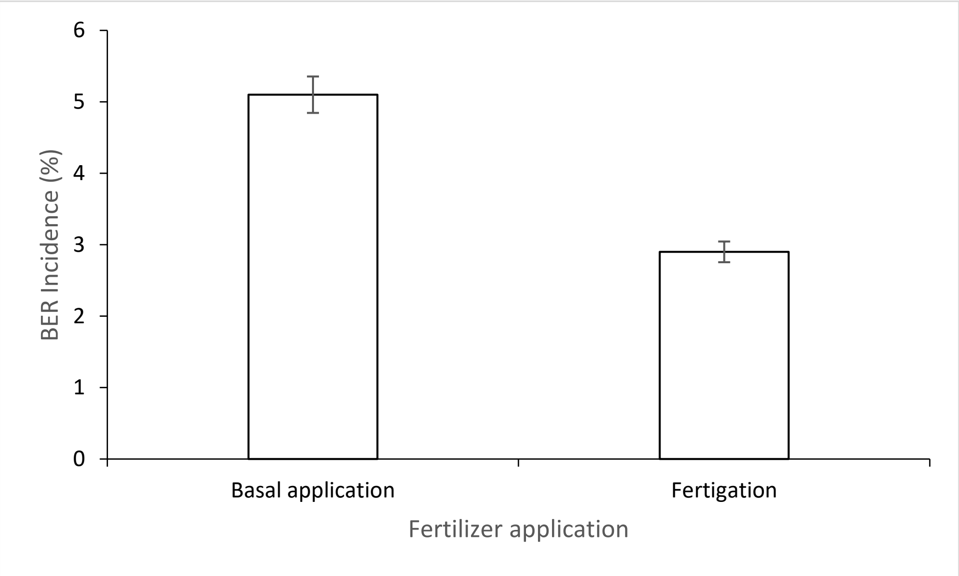

Figure 35: BER incidence of bell pepper fruits as influenced by fertilizer application method

The combination of different irrigation systems and fertilizer application methods significantly influenced the incidence of BER in bell pepper (Figure 36). The interaction of the SLECI system with fertigation resulted in the lowest incidence of BER (0.6%). The combined effect of the drip irrigation system, fertigation, and SLECI system resulted in a basal application that reported a

1.8% and 2.5% incidence of BER, which were statistically similar. When bell peppers were grown using the SLECI system paired with basal fertiliser treatment, there was a 3.2-fold reduction in the occurrence of blossom-end rot (BER) compared to using watering and basal fertiliser application. However, an approximately 3-fold increase in BER incidence was observed in bell pepper cultivated under a drip irrigation system combined with fertigation compared to a SLECI system combined with fertigation. Manual irrigation combined with fertigation led to a 3.6-fold increase in the incidence of BER compared to drip irrigation combined with the fertigation method (Figure 36). The highest BER incidence of 8.8 % was recorded in bell pepper plants grown under watering and basal application. Blossom-end rot (BER) is a physiological condition that occurs due to a lack of calcium in the fruit. Water stress and severe soil moisture variations are factors that might hinder the absorption and transportation of calcium within the plant (Putti et al., 2022). BER is inhibited under fertigation combined with a SLECI system. The SLECI system facilitates the gradual release of water to the plant roots. As the plants absorb the water, additional water flows out, ensuring that the plants receive the precise amount of water they require.

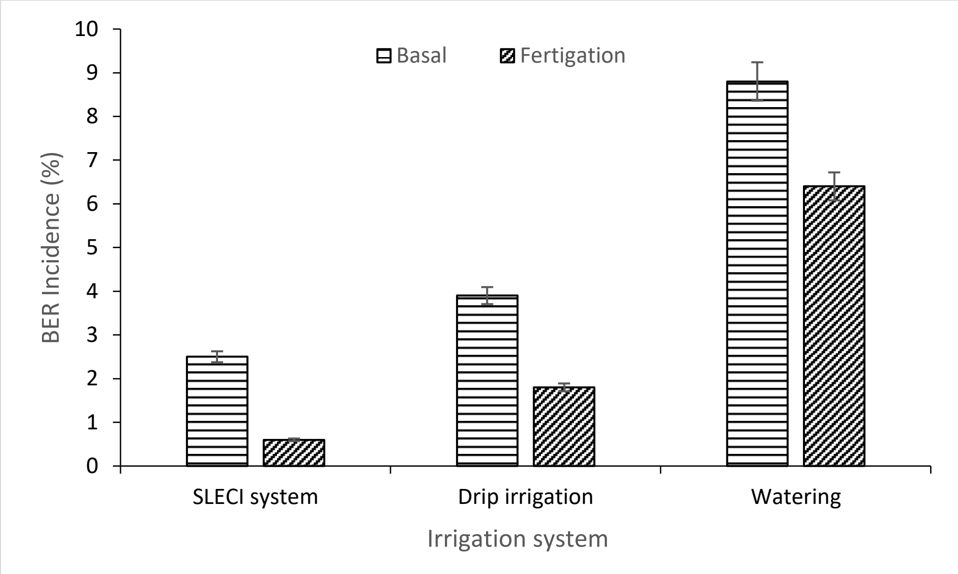

Figure 36: Response of bell pepper fruit BER incidence to the combination of different irrigation systems and fertilizer application methods.

Combination effect of irrigation systems and fertilizer application methods on the incidence of BER in bell pepper fruit

Figure 37 illustrates the highest marketable yield of 98.2 % was recorded in bell pepper fruits under the SLECI system, whereas the least marketable yield of 91.8 % was recorded in bell pepper fruits from watering. SLECI systems enhanced marketable yield by 3.5 % and 6.5 % compared to drip irrigation systems and watering (Figure 37). Sezen et al. (2006) reported that the drip irrigation system improved the quality of bell pepper fruits. This could be attributed to the fact that the design of the drip irrigation system permits improved fertilizer and water management thereby reducing the incidence of pests, diseases as well as weed pressure. Dastorani, Heshmati Sadeghzadeh (2010) reported that subsurface irrigation system improves fruit quality attributes such as wholesomeness and size compared to surface irrigation systems. Plants' growth and yield processes are at their optimum when soil moisture saturation is within the range of 40-80%. A SLECI system ensures that soil moisture is maintained within this range, thus bell pepper plants have more vitality and better fruit with minimum stress. Additionally, for crops to uptake nutrients from the soil, oxygen is required. SLECI system ensures optimal moisture in the soil and optimal air concentration due to its auto-regulate capacity, that is the soil moisture deficit and soil tension (pressure head gradient) determine the release of water from the clay tube. This attribute of the SLECI system ensures that the quality of crop yield is maximized.

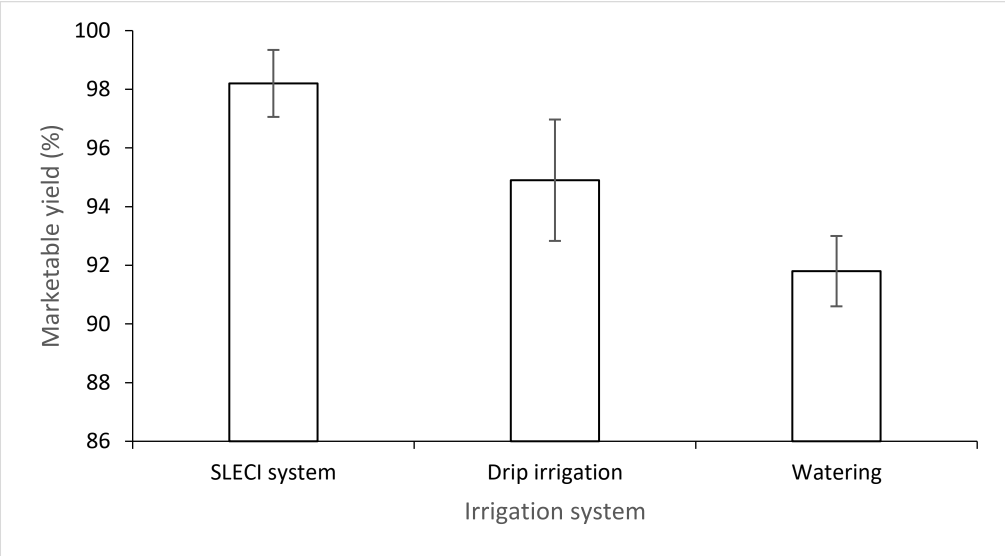

Figure 37: Response of bell pepper marketable yield to different irrigation systems.

The marketable yield of bell pepper fruit was significantly higher under fertigation (96.3 %) compared to the basal application (93.7 %) (Figure 38). Bell pepper cultivated under fertigation treatment increased marketable yield by 2.7 % compared to the basal fertilizer application. Brahma et al. (2010) fertigation, recorded significantly higher yield quality attributes over conventional fertilization. Therefore, it can be inferred that the application of fertilizer through the irrigation system did improve the growth quality of the crop. This was affirmed by Kaushal et al. (2012) reported that fertigation results in better-quality crops compared with conventional fertilizer application methods. Through fertigation nutrient supply and crop nutrient requirement are synchronized, thus crops are relieved from nutrient unavailability stress during crucial growth stages and yield formation processes. Additionally, the precise distribution of fertilizers in the effective rootzone of crops through fertigation, makes nutrients immediately accessible to the root system of crops.

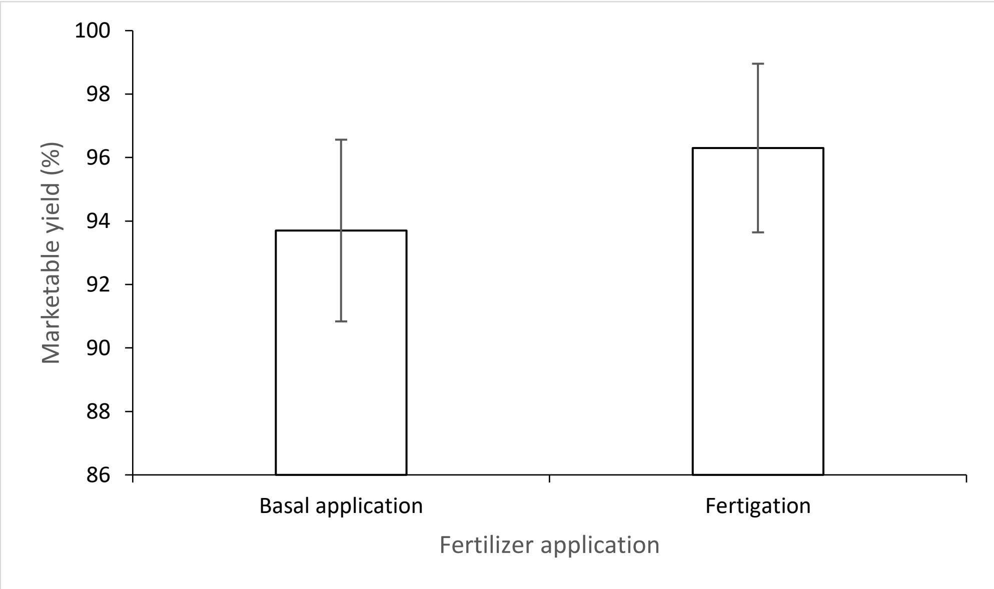

Figure 38: Bell pepper marketable yield as influenced by fertilizer application.

The combination of irrigation system and fertilizer application caused significant variations in the marketable yield of bell pepper fruits (Figure 39). The least marketable yield of 90.7 % was recorded in the interaction of the watering and basal application. The interactive effect of the watering; fertigation and drip irrigation system; basal application recorded a marketable yield of 92.9 % and 93.1 % were statistically at par, a similar trend was observed between the interaction of drip irrigation system; fertigation (96.6 %) and SLECI system; basal application (97.2 %). The highest marketable yield of 99.2 % was recorded in bell pepper fruits under the SLECI system; fertigation (Figure 39). Batchelor et al. (1996) reported that subsurface irrigation using clay tubes proved particularly effective in improving crop quality. The imbalance between vegetative growth and fruiting, inhibition of fruit bud production, and poor fruit set, which is a result of the unfavourable environment caused by water stress and lack of nutrients are eradicated by fertigation through the SLECI system.

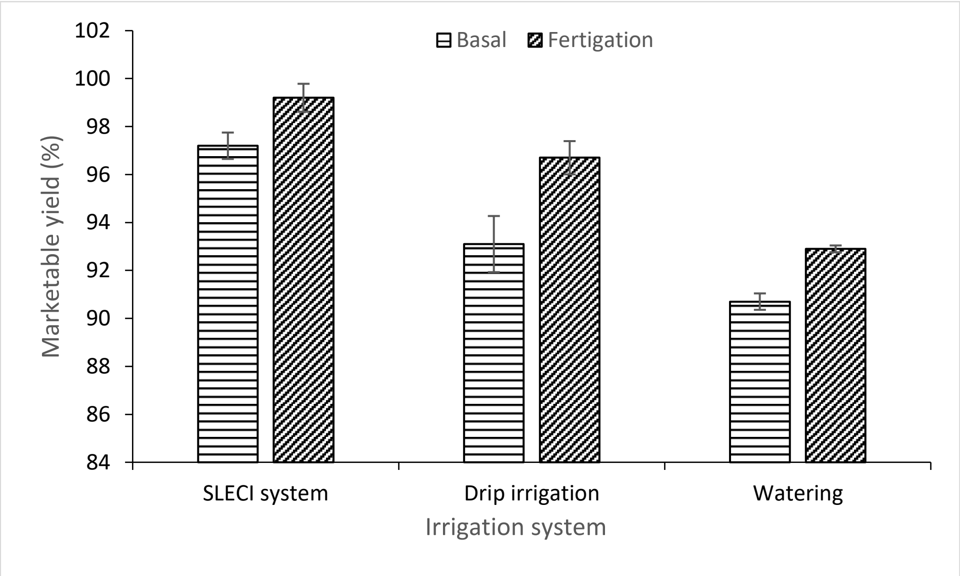

Figure 39: Bell pepper fruits marketable yield as influenced by different irrigation systems and fertilizer application methods.

Conclusion

This study was undertaken to investigate the effects of different irrigation systems and fertilizer application methods on the growth, yield, productivity, and quality of bell pepper plants. The analysis of variance and subsequent Tukey pairwise test showed that different irrigation systems and fertilizer application methods resulted in significant differences in the growth parameters, yield attributes, productivity indicators, and quality parameters.

SLECI system resulted in the growth of significantly higher plant growth, yield, and productivity attributes while significantly bell pepper fruit quality compared to watering and drip irrigation system. The adoption of a SLECI system provides an opportunity to save water and irrigate when best suited for the plant.

Among the fertilizer application methods, fertigation was significantly superior concerning plant growth and yield attributes. In terms of productivity water and fertilizer use efficiency was significantly higher for fertigation compared to basal application. Fertigation improved bell pepper quality parameters. Fertigation aids in the production of vigorous, healthy plants of consistent quality since it enables fertilizer to be directly applied to the effective root zone, where plant root rapidly absorbs the nutrients thereby taking better advantage of the fertilizer supplied.

The interaction of the SLECI system and fertigation outperformed all the remaining interactions of the irrigation system and fertilizer application method for plant growth, yield, and productivity attributes. The combination of fertigation and the SLECI system allows farmers an opportunity to fertilize and irrigate their plants since the system is auto-regulative and requires little or no human intervention to irrigate.

CHAPTER FIVE

EFFECTS OF SELF-REGULATING LOW ENERGY CLAY-BASED IRRIGATION SYSTEM BURYING DEPTH AND FERTIGATION LEVEL ON BELL PEPPER

Introduction

Water scarcity is the main natural factor that limits agriculture expansion in arid and semiarid regions (Bozkurt & Mansuroğlu 2011). Water scarcity is anticipated to increase due to industrialization and intensive horticulture resulting from the growing population's increased food and fibre demands (Sabli, 2012). Irrigation is crucial to increasing crop yields, and agriculture consumes 70 percent of the world's available water resources (Li et al., 2020). Agricultural development in Africa has been determined by an increase in cultivable areas instead of productivity gains in the last couple of years. Because urbanization is rapidly consuming available agricultural land, soil fertility and soil degradation, poor farming practices, and soil erosion limit the availability of land (Fuglie & Rada 2013). As water and fertilizer costs rise and the environment begins to suffer from nutrient leaching, farmers are searching for new strategies to manage these inputs. Crop production systems that enable the adoption of fertigation, enables the close control of both water and fertilizer use, as well as the timing, amounts, and ratios of fertilizers Sabli (2012). According to Sabli (2012) applying fertilizers at the right time, in the right amounts, and the right proportions maximizes yield and crop quality. Fertigation is the application of fertilizers to plants in conjunction with irrigation water. This technique allows fertilizers to be added to the ground without incurring additional labour or difficulty (Bozkurt & Mansuroğlu 2011; Frizzone, Freitas, Rezende, & Faria 2012; Lorenzoni et al., 2016). Fertilizer application is effective and convenient in fertigation compared to broadcast and band fertilizer application as a result of the following; fertilizer is provided in a constant flow, so nutrient concentrations fluctuate less in soil; nutrients are efficiently used and precisely applied following the plant's nutritional requirements and nutrients may be applied in soils, where conditions would normally prevent conventional application (Kafkafi & Kant 2005). Subsurface irrigation makes it possible to deliver nutrients specifically and uniformly to the effective root zone of crops in the soil. High fertilizer use efficiency is recorded in sub-surface fertigation systems since the negative effect of wind and runoff on fertilizer application is eradicated Locascio (2005). Kumar et al. (2018). An efficient subsurface irrigation system guarantees that water is applied directly to the root zone, avoiding evaporation and runoff, resulting in water conservation and saving time and money (Suarez-Rey et al., 2006; Elmaloglou & Diamanto-Poulos, 2009). According to Patel and Rajput (2007) and Bozkurt and Mansuroğlu (2011), it is vitally important to install emitters of sub-surface irrigation systems at the proper depth. The installation depth of subsurface irrigation systems varies as a result of soil, crop, and soil moisture distribution (Patel & Rajput 2007; Sariyev et al., 2007; Kandelous & Suimunek 2010; Bozkurt & Mansurolu 2011). Soil evaporation is reduced with moderate lateral depths, but a deep emitter installation may cause water loss through percolation (Dukes & Scholberg 2005). Because SLECI systems and fertigation have not been adequately investigated as treatment variables, there is limited information regarding their effect on crop growth, yield, and productivity, with fertigation and SLECI system burying depth. To address these issues, bell pepper was used as a test crop in this study to gain conclusions.

Methodology

The study area

The experiment was carried out at the A. G. Carson Teaching and Research farm, School of Agriculture University of Cape Coast, Cape Coast which falls within Latitude: 5°6'57.37" N and Longitude: -1°17'6.55" E. The experimental area falls within the tropical savanna climate with two distinct rainfall seasons, that is wet season and dry season, with annual rainfall total between 750 and 1,000mm and a mean monthly relative humidity varying between 85% and 99%. The experimental area experiences high temperatures throughout the year, with an annual mean temperature range from 23.2-33.2 ºC (Adu et al., 2017). According to Asamoah (1973), the soil of the experimental field is classified as a sandy clayey loam of the Benya series (Stagnic Lixisol) (IUSS Working Group WRB. 2015).

Soil analysis

Before clearing the field for the experiment, soils were sampled. Two opposite quadrants of each of the four samples were removed. This was done several times, removing one opposite quadrant each time, until a sizeable amount was achieved. The soil samples were then dried by air for four days, after which it was crushed, sieved, and bagged for soil analysis. Soil chemical and physical properties were determined. The result of the soil properties analysis (Table 1) showed that the soil in the experimental area is a sandy loam, and characterized by soil salinity of 0.37 ds/m, pH of 6.9, CEC of 1.73 mg/g, Organic carbon of 1.17 g/kg^{-1}, phosphorus of 18.1 ppm, nitrogen of 0.47 g/kg^{-1}, potassium of 0.24mg/100g soil, moisture content of 4.52 % and bulk density of 1.25 g/cm^{3}.

Table 1: Experimental field soil properties

Soil chemical & physical properties	**Value**
Salinity (ds/m)	0.37
pH	6.9
CEC (mg/100g soil)	1.73
Organic carbon (g/kg^{-1})	1.17
Phosphorus (ppm)	18.1
Nitrogen (g/kg^{-1})	0.47
Potassium (mg/100g soil)	0.24
Soil moisture content (%)	4.52
Soil bulk density(g/cm3)	1.25
Clay (%)	13.17
Sand (%)	63.53
Silt (%)	23.30
Texture	Sandy loam

Land & plot preparation

The experimental field was cultivated to a fine tilth, after which it was then lined, pegged, and divided into blocks and plots. Healthy and disease-free bell pepper seedlings (Yolo wonder), five weeks old were transplanted onto 2 m x 2 m (4 m^2) plots.

Experimental Design

The field experiment was conducted using factorial (A^3 x B^3) laid out in a Randomized Complete Block Design (CRBD) and replicated three times. In all, there were 9 treatment combinations in three blocks. Using a planting distance of 0.40 m x 0.50 m, a plant population of 20 crops was recorded on each plot, however, 6 crops in the mid-section of individual plots were tagged for data collection. A distance of 1 m was allowed between the blocks and 0.6 m between the plots within the blocks.

Treatment

Treatments consisted of three levels of recommended application dosage (100% Recommended application dosage (RAD), 80% RAD & 60% RAD) and three levels of SLECI system burying depth (5cm, 10cm & 15cm) in a factorial combination to obtain 9 treatment combinations. A recommended application dosage of 105 kg/ha was adopted by Kanneh et al (2017).

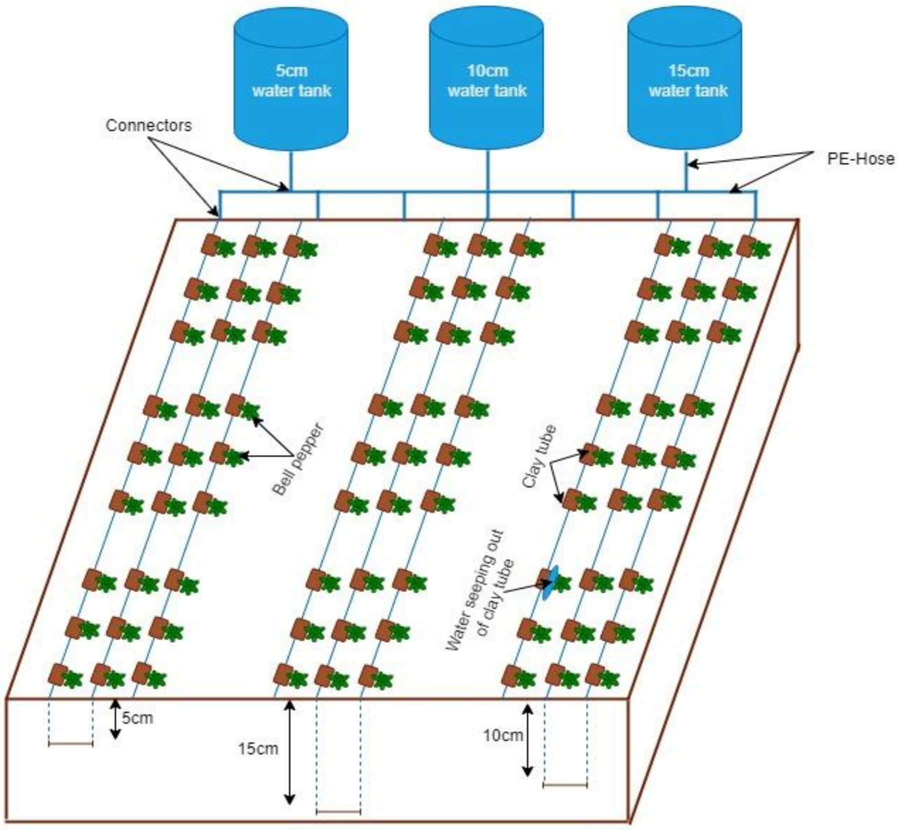

Figure 40: Schematic layout of field trial

Plant material

Bell pepper cultivars used in this study were Siempre Verde (Agriseed Seed Company). Bell pepper seedlings were planted with a planting distance of 0.40 m x 0.50 m. Plants were trained with a single stem and trimmed after the fourth cluster. Organic wood vinegar & Plan D (pesticides) and Agrithane (fungicide) were respectively used for pest and disease control.

Figure 41: Transplanted bell pepper plants using SLECI system burying depth of 5cm.

Irrigation system

The pitcher irrigation system consists of a water tank (200 litres), valve, filter, clay tube, connectors, coupling, PE- tubes, and an end cap Figure 42. The length of the clay tube was 9 cm with inner and outer diameters of 10 mm and 12 mm, indicating that each clay tube can hold 7.1^{-6} m^3 of water at a time respectively. The thickness of each clay tube was 2 mm. The core of the clay tube was mounted on a PE – hose. This line is completed with a connector to PE-hose renewal on each end of the clay tube. This was made to allow for the fitting of additional clay tubes. A PE–hose length of 50cm was allowed between 2 clay tubes. In each plot, clay pipes are joined together, and the end cap is fixed at the end of the PE tube after the desired length is achieved. The pipes are buried in the soil at different depths to depict the various treatments, and water is then supplied continuously to these pipes from the water tank or fertigation tank.

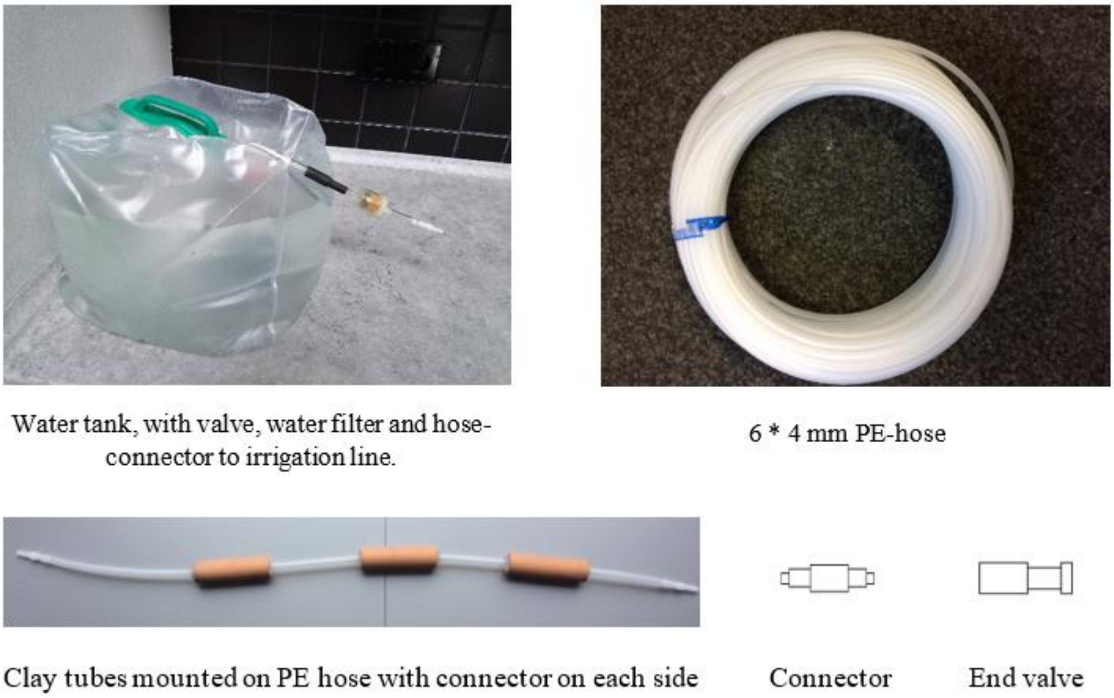

Figure 42: Components of the SLECI system

Fertigation System

The fertigation system consists of fertilizer tanks, valves and PE tubes (Figure 43). The fertigation schedule consisted of a single application of Plantifol NPK 10-50-10, Plantifol NPK 20-20-20 and Plantifol NPK 12-6-36 fertilizer (Atlantica Agricola S. A., Alicante, Spain). Plantifol NPK 10-50-10 was applied 3 days after transplanting at three different application dosages (100% RAD, 80% RAD and 60% RAD of 105 kg/hectare). Plantifol NPK 20-20-20 was applied at three different application dosages (100% RAD, 80% RAD and 60% RAD of 105 kg/hectare) 24 days after transplanting. The last application was carried out when Plantifol NPK 12-6-36 was applied at three different application dosages (100% RAD, 80% RAD and 60% RAD of 105 kg/hectare) 33 days after transplanting.

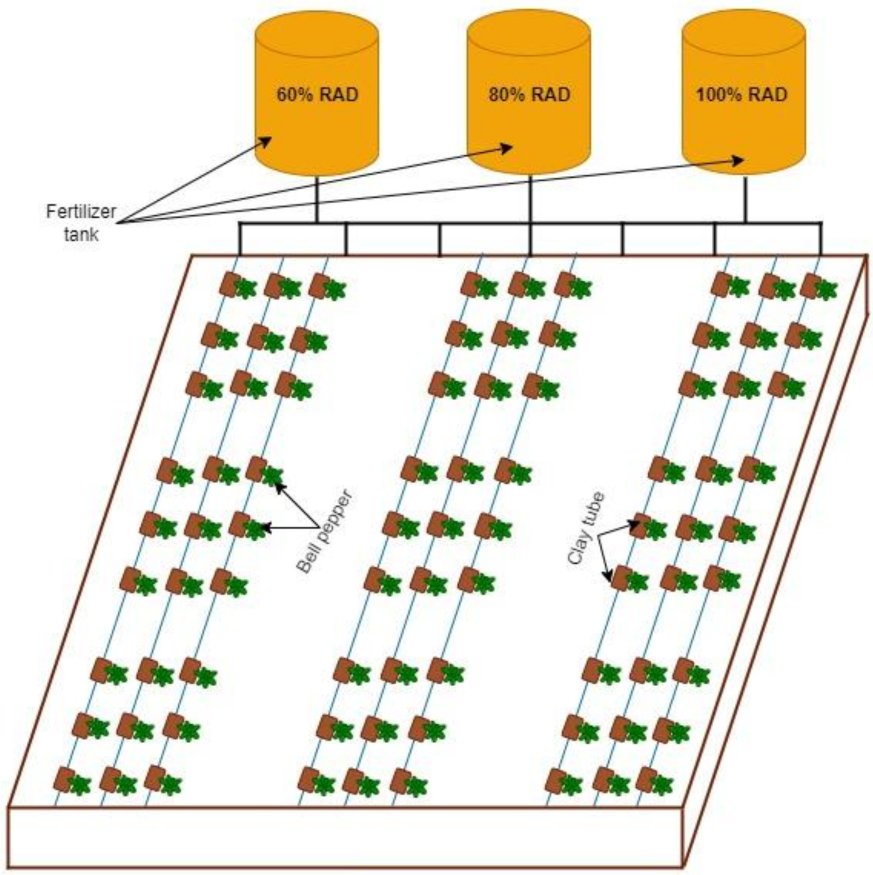

Figure 43: Schematic layout of the fertigation system

Crop water requirement and irrigation scheduling

Bell pepper plants were irrigated through a subsurface SLECI system. In this experiment, the weather sensing irrigation scheduling approach was adopted thus four plant growth stages namely, the initial stage, developmental stage, mid-season stage and the late season stage were considered. 100% crop water requirement was applied after crop evapotranspiration was determined using a US Class A evaporation pan. A variable crop coefficient was applied at the various growth stages: Initial stage 0. 60 (25 days), development stage 0. 85 (35 days), mid-season stage 1.05 (40 days), late-season stage 0.90 (20 days) harvesting 0.65 (FAO, 2020: Pepper crop information).

Crop water requirement (Crop evapotranspiration, ETc) was determined using the formula (Equ. 15)

$$\mathbf{ETc} = \mathbf{ETo} \times \mathbf{Kc} \qquad \text{Equ (15)}$$

Where,

ETc: Crop evapotranspiration [mm d^{-1}],

ETo: Reference crop evapotranspiration [mm d^{-1}] was determined using the US Class A evaporation pan. pan factor of 0.8 (Darko, 2011).

Kc: Crop coefficient [dimensionless], was adopted from FAO (2020): Pepper crop information.

Data collection

Measured parameters

Data collection was carried out bi-weekly. In each plot, data is recorded from tagged bell pepper plants comprising the mid-section of individual plots while ignoring the border crops.

Plant height

Plant height was determined by measuring the distance from the highest point of the soil surface to the topmost part of the plant. The average of plant height of plants tagged for data collection was expressed in centimetres (cm).

Leaf area (Individual leaf area)

The length of the leaf was measured as the longest segment along the petiole line of the leaf on the lateral bud below the shoot tip. The breadth of the leaf was measured as the widest width across the leaf. The product was scaled down by a factor of 0.75 to obtain the leaf area.

Number of fruits

The fruits harvested from the tagged plants at various growth stages were tallied and quantified as the number of fruits per plant.

Average fruit weight

The fruits harvested from the tagged plants were weighed, recorded and expressed as grams.

Derived parameters

Yield per hectare

In each plot, an area (tagged bell pepper plants comprising the mid-section of individual plots) was selected. The total plant yield for the selected was then derived by weighing all fruits from the tagged plants after which the total fruit weight in the selected area per plant was added to generate the total yield for the selected area. The selected area dimensions were then converted from square meters to a hectare basis. Yield per hectare was then derived using the formula below (Equ. 16).

$$\frac{1\ hectare}{Selected\ area\ containing\ tagged\ plants\ (hectare)} x\ total\ yield\ from\ tagged\ plants\ (kg)$$

Equ (16)

Water use efficiency

Water use efficiency was calculated through the proportion of the total plant yield and the total water applied under each treatment (Equ. 17).

$$\frac{\text{Total yield per plant (g)}}{\text{The total amount of water applied (mm)}} \qquad \text{Equ (17)}$$

Fertilizer use efficiency

Fertilizer use efficiency was calculated through the proportion of the total plant yield and the total fertilizer applied under each treatment (Equ. 18).

$$\frac{\text{Total yield per plant (kg)}}{\text{The total amount of fertilizer applied (kg)}} \qquad \text{Equ (18)}$$

Data analysis

Statistical analysis (Analyses of variance, ANOVA) of various recorded parameters was performed to assess the influence of various treatments in comparison with control treatments, using Genstat statistical software (Introduction to GenStat for Windows 18th Ed, VSN International, Rothamsted Experimental Station, Reading University, United Kingdom). Significant mean differences among treatments were compared using Tukey's least significant difference test at a probability level of 5%.

Result & Discussion

Crop water requirement of bell pepper

Table 2 shows the crop water consumption of bell pepper plants. The crop water requirement of bell pepper varies with crop variety, climatic conditions and irrigation system. The water requirement of bell pepper differs according to the growth stage since a developed and large plant is characterized by a bigger leaf area that will enable the plant to transpire more water. Bell pepper crop water requirement was 558.86mm (the initial growth stage required 77.08mm, the crop developmental stage required 159.75mm, the middle season stage required 186.69mm, whereas the late season stage required 134.80mm) (Table 2). The crop water requirement of bell pepper recorded was similar to observations made by Trivikrama et al. (2018) and Dimple et al. (2018) who reported 562.5 mm and 525.11 mm to be the crop water requirement of bell pepper and were within the range reported by within the range of 300 -700 mm provided by Agodzo et al. (2003) and FAO (2008). Zotarelli et al. (2011), Aladenola & Madramootoo (2013), Padrón et al. (2015) and Arya et al. (2017) recorded crop water requirements of 341 mm, 305.3 mm, 401.8 mm and 380 mm which were below 500 mm, this can be attributed to climatic condition, cropping season, variety of crop and the location. At the initial stage, crop water requirements for 5cm, 10cm and 15cm were 74.8mm, 72.8mm and 76.7mm respectively, with all being less than the crop evapotranspiration of 77.08mm. This is in line with the findings of Phene (1991) and Phene et al. (1992) who reported that a sub-irrigation system decreases crop water requirement at early stages of growth. The highest water consumption (531.4 mm) was found for a burying depth of 15 cm treatment followed by 525.1 mm recorded from a burying depth of 5 cm. The least water consumption of 489.2 mm was recorded from a burying depth of 10 cm. Burying depths of 5cm, 10cm and 15cm reduced crop water requirement by 6%, 12.5% and 4.9%. Water consumption recorded from all the treatments was lower than the crop water requirement. Burying This could be attributed to the fact that subsurface irrigation ensures that the soil surface is dry and consequently decreases evaporation, thus reducing the water consumption of bell pepper.

Table 2: Bell pepper ETc and consumptive water use.

Growth stage	ETo 100%	Kc	ETc 100%	5 cm	10 cm	15 cm
Initial stage	122.35	0.63	77.08	74.8	72.8	76.7
Crop development	138.91	1.15	159.75	148.5	135.6	149.2
Middle season	147.58	1.27	186.69	159.7	144.2	161.6
Late season	140.42	0.96	134.80	142.1	136.6	143.9
Total (mm)			558.86	525.1	489.2	531.4

Bell pepper plant height as influenced by SLECI system burying depth and fertigation level

The effect of burying depth on the plant height of bell pepper is presented in Figure 44. At 2 wat, plant height did show a significant difference among a burying depth of 5cm (19.67 cm) burying depth of 10cm (16.81 cm) and a burying depth of 15cm (14.23 cm). A similar trend was observed at 4 wats, where burying depths of 5cm, 10cm and 15cm exhibited significant plant heights of 30.14 cm, 28.88 cm and 19.92 cm. 6 wats, significant plant heights of 42.67 cm, 39.26 cm and 27.50 cm was observed under burying depth of 5cm, 10cm and 15cm. A similar trend was observed at 8 wats, significant plant heights of 50.36 cm, 53.89 cm and 34.50 cm were observed under burying depths of 5cm, 10cm and 15cm. At 10 wat, data in Figure 44 indicates that a 10cm burying depth (58.84 cm) registered significantly ($p \leq 0.05$) higher plant height compared to a burying depth of 5cm (55.93 cm) and a burying depth of 15cm (40.98 cm).

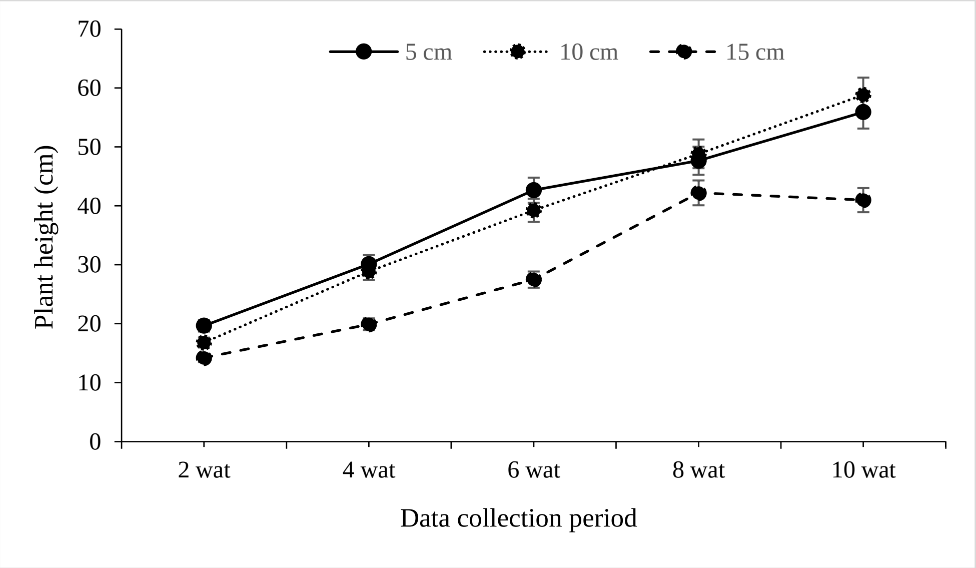

Figure 44: Bell pepper plant height as influenced by SLECI system burying depth.

The effect of fertilizer application dosage on bell pepper plant height is presented in Figure 45. At 2 wat, a plant height of 16.05 cm was observed in bell pepper plants subjected to 60 % Recommended Application Dosage, RAD which was statistically lower than the plant height of plants subjected to 100 % RAD (17.26 cm) and 80 % RAD (17.40 cm). A similar trend was observed at 4 wats, where plants subjected to 60 % RAD showed a statistically lower plant height of 24.56 cm compared to plants subjected to 100 % RAD (27.29 cm) and 80 % RAD (27.09 cm). At 6 wat, there were no significant differences between plants subjected to 80 % RAD (37.66 cm) and 100 % RAD (38.27 cm), however, both were statistically better than plants subjected to 60 % RAD (33.50 cm). After 8 wats, the plant height of plants subjected to 60 % RAD (42.22 cm) 80 % RAD (48.84 cm) and 100 % RAD (47.68 cm) statistically varied from each other. At 10 wats, data in **Figure 45** indicates that plants subjected to 80 % RAD recorded significantly ($p \leq 0.05$) higher plant height of 54.43 cm compared to plants subjected to 60 % RAD (48.24 cm) and 100 % RAD (53.08 cm).

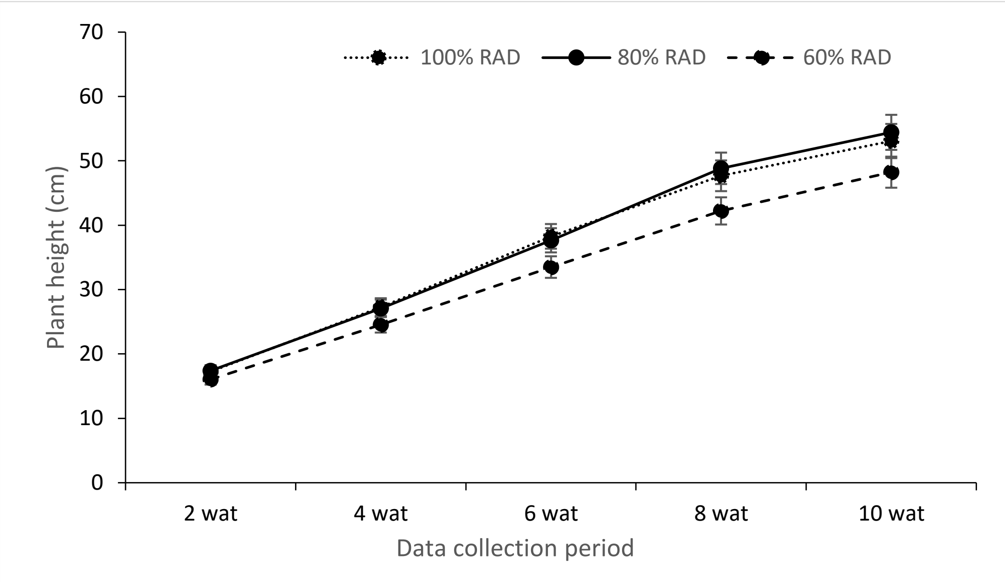

Figure 45: Bell pepper plant height as influenced by fertilizer application dosage

The interactive effect of burying depth and fertigation levels on the plant height of bell peppers is presented in **Table 3**, which showed a statistically significant variation ($P < 0.05$) at 2, 4, 6, 8 and 10 weeks after transplanting (wat). From **Table 3**, at 2 wats there were significant differences between the height of bell pepper crops under treatment combination of burying depth and fertigation levels except plants grown under burying depth of 5 cm: 80 % Recommended application dosage (RAD) (20.81 cm) and burying depth of 5cm: 100 % RAD (19.67 cm). A similar trend was observed in a plant grown under a burying depth of 10 cm: 60 % RAD (16.10 cm), 10 cm: 80 % RAD (17.17 cm) and 10cm: 100 % RAD (17.18 cm) **Table 3**, as well as at 15cm: 60 % RAD (13.52 cm) and 15 cm: 80 % RAD (14.21 cm). The highest plant height of 20.81cm was observed in plants grown under 5cm and 80 % RAD whereas the least plant height of 13.52cm was observed in plants grown under 15cm: 60 % RAD (**Table 3**). At 4 wat, there were significant differences under treatment combinations of burying depth and fertigation levels except for plants grown under a burying depth of 5 cm: 80 % RAD (31.71 cm) and burying depth of 5cm: 100 % RAD (30.58 cm). Similarly, plants grown under 10 cm: 80 % RAD (29.91 cm) and 10cm: 100 % RAD (29.98 cm), 15cm: 60 % RAD (18.78 cm) and 15cm: 80 % RAD (19.66 cm) exhibited no significant differences. The highest plant height of 31.71 cm was observed in plants grown under 5cm and 80 % RAD whereas the least plant height of 18.78 cm was observed in plants grown under 15cm: 60 % RAD **Table 3**. At 6 wat, there was no significant difference among crops grown under a burying depth of 5cm and 60 % RAD (40.53 cm), 80 % RAD (44.71 cm) and 100 % RAD (42.77 cm). A similar trend was observed in plants grown under a burying depth of 15 cm 60 % RAD (24.24 cm) and 80 % RAD (26.52 cm). The highest plant height of 44.71 cm was observed in plants grown under 5cm and 80 % RAD whereas the least plant height of 24.24 cm was observed in plants grown under 15cm: 60 % RAD **Table 3**. At 8 wat, there were significant differences between the height of bell pepper crops under the interaction of burying depth and fertigation levels except for plants grown under burying depth of 5 cm: 80 % RAD (54.57 cm) and 10 cm: 100 % RAD (55.49 cm). A similar trend was observed in a plant grown under a burying depth of 10 cm: 80 % RAD (56.98 cm), and 10cm: 100 % RAD (55.49 cm). The highest plant height of 56.98 cm was observed in plants grown under 10 cm and 80 % RAD whereas the least plant height of 31.41 cm was observed in plants grown under 15cm: 60 % RAD **Table 3**. At the end of the experiment, 10 wats, the interactive effect of burying depth and fertigation levels resulted in significant differences, except for plants grown under burying depth of 5 cm: 100 % RAD (55.40 cm) and 10 cm: 60 % RAD (54.00 cm). A similar trend was observed in a plant grown under a burying depth of 5 cm: 80 % RAD (58.68), and 10 cm: 100 % RAD (55.49 cm). The highest plant height of 62.51 cm was observed in plants grown under 10 cm: 80 % RAD whereas the least plant height of 37.00 cm was observed in plants grown under 15cm: 60 % RAD **Table 3**.

Table 3: Interactive effect of SLECI system burying depth and fertilizer application dosage on the plant height of bell pepper

Burying depth	**Fertilizer dosage**	**2 wat (cm)**	**4 wat (cm)**	**6 wat (cm)**	**8 wat (cm)**	**10 wat (cm)**
5 cm	100% RAD	19.67 ^{ef}	30.58 ^{ef}	42.77 ^{e}	50.46 ^{e}	55.40 ^{e}
	80% RAD	20.81 ^{f}	31.71 ^{f}	44.71 ^{e}	54.57 ^{f}	58.68 ^{f}
	60% RAD	18.52 ^{e}	28.14 ^{d}	40.53 ^{de}	46.04 ^{d}	53.72 ^{d}
10 cm	100% RAD	17.18 ^{d}	29.98 ^{e}	40.31 ^{de}	55.49 ^{fg}	60.01 ^{f}
	80% RAD	17.17 ^{d}	29.91 ^{e}	41.73 ^{e}	56.98 ^{g}	62.51 ^{g}
	60% RAD	16.10 ^{cd}	26.74 ^{c}	35.72 ^{cd}	49.21 ^{e}	54.00 ^{de}
15 cm	100% RAD	14.94 ^{bc}	21.32 ^{b}	31.72 ^{bc}	37.1 ^{c}	43.83 ^{c}
	80% RAD	14.21 ^{ab}	19.66 ^{a}	26.52 ^{ab}	34.99 ^{b}	42.11 ^{b}
	60% RAD	13.52 ^{a}	18.78 ^{a}	24.24 ^{a}	31.41 ^{a}	37.00 ^{a}
Lsd (0.005)		**0.7831**	**0.8209**	**3.263**	**0.971**	**1.027**

Bell pepper leaf area

The effect of the SLECI system burying depth on the bell pepper leaf area is presented in **Figure 46**. At 2 wat, bell pepper leaf area was significantly influenced by burying depth of 5cm (13.84cm^2), 10cm (13.24cm^2) and 15cm (12.07cm^2). At 4 wat, a leaf area of 24.74cm^2 was observed in bell pepper plants grown under a burying depth of 15cm and was better than plants grown under a burying depth of 5cm (21.54cm^2) and 10cm (21.57cm^2). At 6 wat there were no significant differences between plants grown under burying depths of 5cm (33.50cm^2), 10cm (33.07cm^2) and 15 cm (32.65cm^2). At 8 wat, plants grown under a burying depth of 15cm showed a statistically lower leaf area of 44.23 cm^2 compared to plants grown under a burying depth of 5cm (51.74 cm^2) and 10cm (51.48 cm^2). At the end of the experiment, 10 wats, the highest leaf area of 61.96 cm^2 was observed in plants grown under a burying depth of 10cm whereas the least leaf area of 53.17 cm^2 was observed in plants grown under 15cm **Figure 46**.

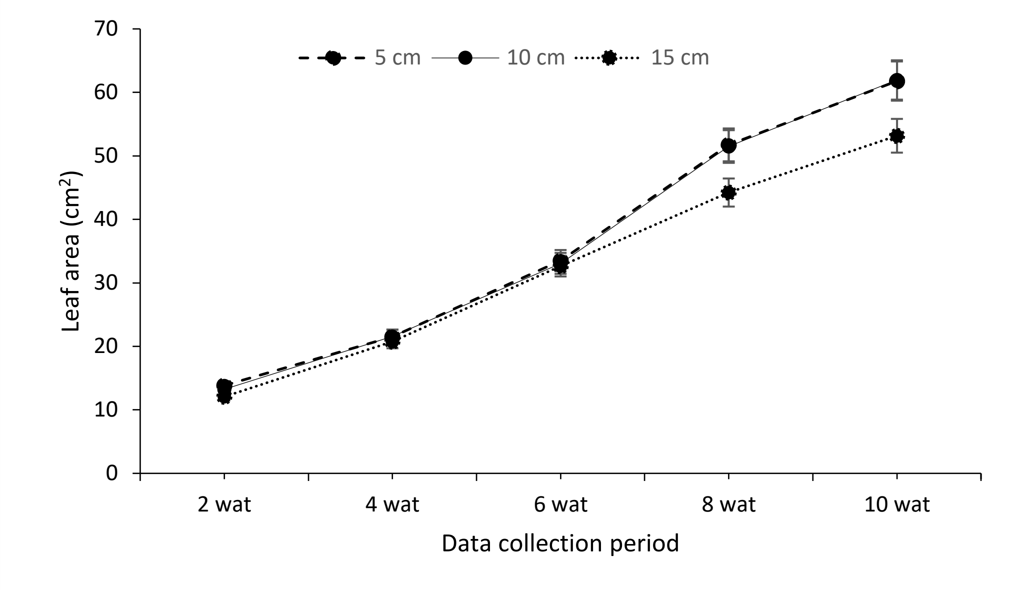

Figure 46: Bell pepper leaf area as influenced by SLECI system burying depth.

The effect of fertigation levels on the leaf area of bell pepper is presented in **Figure 47**. At 2 wat, the leaf area of plants subjected to 60 % RAD (12.54 cm^2) and 80 % RAD (13.22 cm^2) was not significantly different from each other, however, were significantly better than plants subjected to 100 % RAD 13.39 cm^2, however after 4 wat leaf area of plants subjected to 60 % RAD (21.69 cm^2) was significantly lower than crops subjected to 100 % RAD (23.02 cm^2) and 80 % RAD (23.14 cm^2), a similar trend was observed 6 wats, where plants subjected to 60 % RAD (31.26 cm^2) was significantly lower than crops subjected to 100 % RAD (33.76 cm^2) and 80 % RAD (34.20 cm^2). At 8 wat, plants exposed to 100 % RAD, 80 % RAD and 60 % RAD showed leaf areas of 51.04 cm^2, 51.92 cm^2 and 44.48 cm^2 that were significantly different from each other. At the end of the experiment, 10 wats, the significantly highest leaf area of 61.48 cm^2 was recorded in plants subjected to 80 % RAD, followed by 60.84

cm^2 recorded in plants subjected to 100 % RAD whereas the least leaf area of 54.61 cm^2 was observed in plants grown under 60 % RAD **Figure 47**.

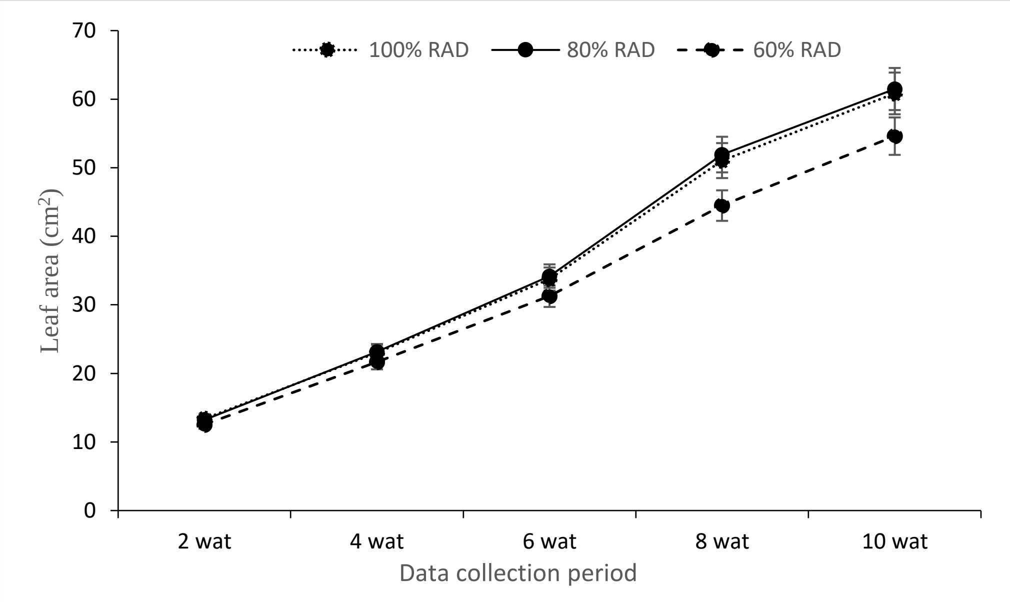

Figure 47: Bell pepper leaf area response to fertilizer application dosage

The interactive effect of burying depth and fertigation levels on bell pepper leaf area **Table 4**. At 2 wat, significant differences existed among bell pepper leaf areas due to the interactive effect of SLECI system burying depth and fertigation level treatment combinations except for 5cm: 80 % RAD (14.15 cm^2) and 5cm: 100 % RAD (14.13 cm^2), a similar trend was observed in 10cm: 80 % RAD (13.52 cm^2) and 10cm: 100 % RAD (13.84 cm^2). Results also indicate that bell pepper plants are grown under 15cm and 60 % RAD (12.02 cm^2), 80 % RAD (12.00 cm^2) and 100 % RAD (12.19 cm^2). The highest leaf area of 14.15 cm^2 was observed in bell pepper plants grown under 5cm and 80 % RAD whereas the least leaf area of 12.02 cm^2 was observed in plants grown under 15cm: 60 % RAD **Table 4**. At 4 wat, no difference existed among bell pepper leaf areas grown under burying depth of 5cm: 80 % RAD (22.16 cm^2) and 100 % RAD

(22.29 cm^2) as well as burying depth of 10cm: 80 % RAD (22.39cm^2) and 100 % RAD (22.30cm^2). Results also indicate that the leaf area of bell pepper plants grown under 15cm and 60 % RAD (24.87 cm^2), 80 % RAD (24.87 cm^2) and 100 % RAD (24.48 cm^2) were not statistically different from each other. The highest leaf area of 24.87 cm^2 was observed in bell pepper plants grown under 15cm: 60 % RAD and 80 % RAD whereas the least leaf area of 20.03 cm^2 was observed in plants grown under 10cm: 60 % RAD **Table 4**. At 6 wat, no difference existed among bell pepper leaf areas grown under a burying depth of 5cm: 60 % RAD (32.70 cm^2) and 100 % RAD (33.19 cm^2) as well as a burying depth of 10cm: 80 % RAD (35.80 cm^2) and 100 % RAD (35.38 cm^2). Results also indicate that the leaf area of bell pepper plants grown under 15cm and 60 % RAD (33.05 cm^2), 80 % RAD (32.17 cm^2) and 100 % RAD (32.72 cm^2) were not statistically different from each other. The highest leaf area of 35.80 cm^2 was observed in bell pepper plants grown under 10cm: 80 % RAD whereas the least leaf area of 28.04 cm^2 was observed in plants grown under 10cm: 60 % RAD **Table 4**. At 8 wat, there were significant differences in the leaf area of bell pepper, except for crops grown under a burying depth of 10cm: 80 % RAD (57.20 cm^2) and 100 % RAD (56.16 cm^2). Results also indicate that the leaf area of bell pepper plants grown under 15cm and 60 % RAD (44.37 cm^2), 80 % RAD (43.91 cm^2) and 100 % RAD (44.39 cm^2) were not statistically different from each other. The highest leaf area of 57.20 cm^2 was observed in bell pepper plants grown under 10cm: 80 % RAD whereas the least leaf area of 41.07 cm^2 was observed in plants grown under 10cm: 60 % RAD **Table 4**. At the end of the experiment, 10 wats, the interactive effect of burying depth and fertigation levels resulted in significant differences, except for plants grown under a burying depth of 15 cm: 60 % RAD (53.32 cm^2), 80 % RAD (52.61 cm^2), 100 % RAD (53.59 cm^2) and burying depth of 10cm: 60 % RAD (53.24 cm^2). The highest leaf area of 66.52 cm^2 was observed in plants grown under 10 cm: 80 % RAD whereas the least leaf area of 52.61 cm^2 was observed in plants grown under 15cm: 80 % RAD **Table 4**.

Table 4: SLECI system burying depth and fertilizer application dosage on the leaf area of bell pepper

Installation depth	**Fertilizer dosage**	**2 wat (cm^2)**	**4 wat (cm^2)**	**6 wat (cm^2)**	**8 wat (cm^2)**	**10 wat (cm^2)**
5 cm	100% RAD	14.13 ^{c}	22.29 ^{b}	33.19 ^{b}	52.57 ^{d}	62.79 ^{c}
	80% RAD	14.15 ^{c}	22.16 ^{b}	34.62 ^{c}	54.66 ^{e}	65.31 ^{d}
	60% RAD	13.25 ^{b}	20.16 ^{a}	32.70 ^{b}	47.99 ^{c}	57.26 ^{b}
10 cm	100% RAD	13.84 ^{bc}	22.30 ^{b}	35.38 ^{cd}	56.16 ^{ef}	66.13 ^{de}
	80% RAD	13.52 ^{bc}	22.39 ^{b}	35.80 ^{d}	57.20 ^{f}	66.52 ^{e}
	60% RAD	12.36 ^{a}	20.03 ^{a}	33.05 ^{a}	41.07 ^{a}	53.24 ^{a}
15 cm	100% RAD	12.19 ^{a}	20.48 ^{c}	32.72 ^{b}	44.39 ^{b}	53.59 ^{a}
	80% RAD	11.99 ^{a}	20.87 ^{c}	32.17 ^{b}	43.91 ^{b}	52.61 ^{a}
	60% RAD	12.02 ^{a}	19.87 ^{c}	28.04 ^{b}	44.37 ^{b}	53.32 ^{a}
Lsd (0.005)		**0.5100**	**0.7152**	**0.6867**	**0.970**	**0.7313**

Discussion

Bell pepper vegetative growth as influenced by SLECI system burying depth and fertilizer application dosage

Burying depth

The outcome aligns with the observations of Bozkurt and Mansuroğlu (2011), who demonstrated that the greatest plant height and leaf area were achieved at a depth of 10cm. Siyal and Skaggs (2009) found that the depth at which irrigation pipes are installed has an impact on evaporation. This, in turn, influences the structure of the wetted zone in the crop's root area. Cox (2001), Nemali and van Iersel (2004), Montesano et al. (2010), and Bouchaaba et al. (2015) have documented a reduction in the growth of sub-irrigated plants. This decline has been linked to an elevation in the electrical conductivity (EC) of the upper layer of the soil and an uneven dispersion of moisture across the soil profile due to evaporation. The growth indicators exhibited the weakest performance when the irrigation depth reached a depth of 15cm. Consistent with the research conducted by Al-Harbi et al. in 2008, it was shown that the irrigation depth that reached the deepest into the soil led to a notable decrease in plant height. While a greater lateral depth can decrease soil evaporation, installing irrigation pipes at a deeper level can result in increased water losses through deep percolation and reduced water availability in the crop's effective root zone, particularly during the early stages of growth. The study conducted by Dukes and Scholberg in 2005 found that it led to inadequate plant development. According to Al-Harbi, Al-Omran and El-Adgham (2008), the underperformance of the irrigation pipe at the deepest and shallowest depths can be attributed to a decrease in the amount of water applied. This reduction in water can negatively impact the physiological processes of the plants and increase their vulnerability to water stress. As a result, the absorption and distribution of water to different parts of the plant are affected. Pandey et al. (2000), Çakir (2004), and Yuan et al. (2019) have confirmed that water stress can impede cell division and differentiation, lower the rate of photosynthesis, disrupt the balance of enzyme systems, and hinder growth.

Fertigation levels

Results from the study are in contrast with the findings of Bassiony et al. (2010), where the highest fertilization rate resulted in the tallest sweet pepper plants, the highest number of leaves and leaf area. Similarly, Elhindi et al. (2015) also reported that an increase in the recommended rate of fertilizer through fertigation increased the vegetative growth of plants. The disparity in results could be attributed to the irrigation system adopted or the method of fertilizer application. Results are in tandem with the findings of Eckas (2005), Umair et al. (2019) and IWS (2022) where best-performing growth parameters were recorded when the fertilizer application rate was reduced by 20-30% and was applied through sub-surface irrigation. Fertigation through subsurface irrigation is beneficial to crops since there is more efficient usage of nutrients as a result of water being supplied uniformly to the root zone as they are required by the crop, thereby minimizing or eliminating surface runoff and evaporation from the soil surface Singh et al. (2022)

Interaction of burying depth and fertigation levels

The results are consistent with the previous findings of Gupta et al. (2009), who demonstrated that the combination of decreasing crop water requirement and applying 80% of the recommended NPK through fertigation was much more effective than other treatment combinations in promoting vegetative growth of bell pepper. With the use of subsurface irrigation, the wetted surface is virtually eliminated, ensuring that the drier ground minimizes weed development. Weeds compete with crops for water, air, sunlight and nutrients in the soil making them deficient for the crop. Additionally, chemicals can be applied directly through the clay tube system, there is no need for foliar application, thus eradicating the negative impact of foliar application, such as damage to leaves. When leaves are damaged, they lose their photosynthetic ability, which harms the growth of the crop. A burying depth of 10 cm coupled with an 80% recommended application dosage of fertilizer reduces deep leaching of plant nutrients, reduces soil salinity build and ensures the availability of moisture in the effective root zone. This creates an ideal environment for growth and development.

Bell pepper yield attributes as influenced by SLECI system burying depth and fertilizer application dosage.

Number of fruits per plant

The effect of burying depth on the number of fruits per bell pepper plant is presented in Figure 48. Data analysis indicates that the number of fruits per plant, between different burying depths of 5cm, 10cm and 15cm was statistically significant ($P<0.05$) Figure 48. Increases in the number of fruits per plant were obtained with an increase in the burying depth of the SLECI system, where a burying depth of 5cm produced 27% and 42.6% more fruits than a burying depth of 10 cm and 15 cm respectively Figure 48.

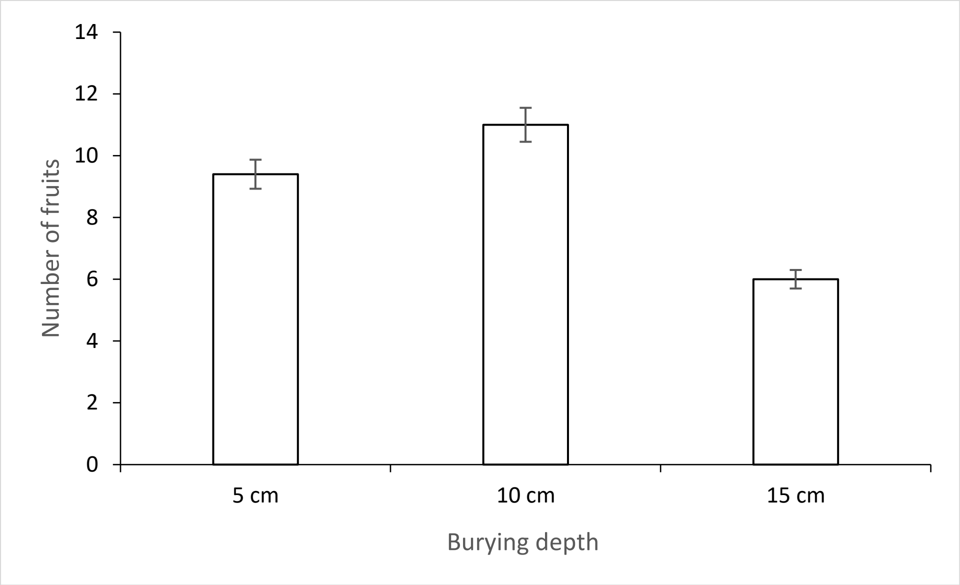

Figure 48: Bell pepper number of fruits as influenced by SLECI system burying depth

The number of fruits per bell pepper plant influenced by different fertilizer application dosages is presented in **Figure 49**. Data analysis indicates that the number of fruits per plant, among different fertilizer application dosage treatments (100% RAD, 80% RAD and 60 % RAD) was statistically significant ($P<0.05$) **Figure 49**. The highest number of fruits per plant 8.5 was recorded at 80% RAD treatment than 100% RAD and 60 % RAD treatments.

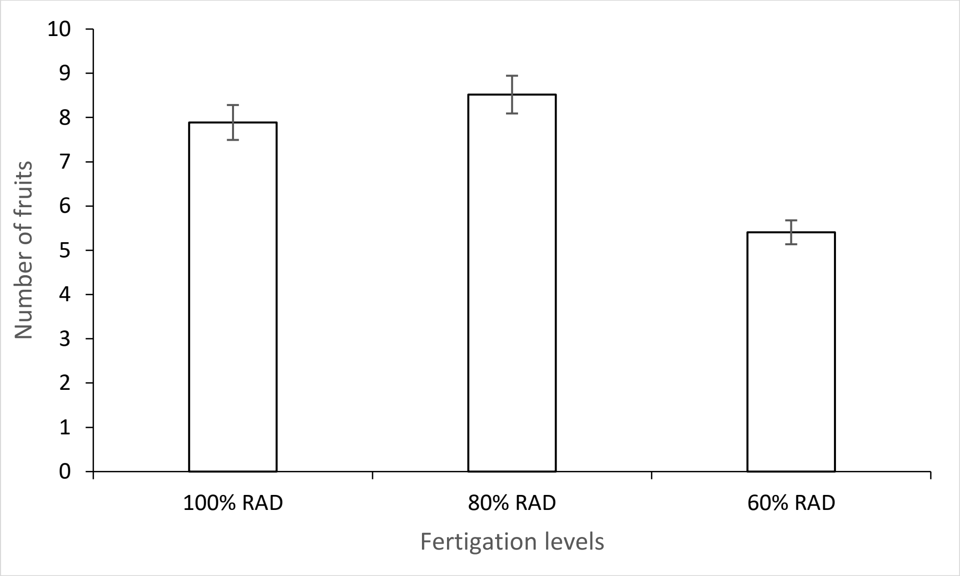

Figure 49: Bell pepper number of fruits as influenced fertilizer application dosage

Exposure to bell pepper burying depth and different fertilizer application dosages caused significant differences concerning the number of fruits per plant produced **Table 5**. The interaction between burying depth and different fertilizer application dosages exhibited significant differences in the number of fruits per plant in bell pepper. The combination of a burying depth of 10 cm and 80% recommended application dosage irrigation resulted in a significantly higher number of fruits per plant, which was statistically equivalent with the following treatment combinations, 5cm:80% RAD (11.9) and 10 cm: 100% RAD (11.8). The lowest number of fruits per plant (4.3) was recorded in plants subjected to 15cm and 60% RAD **Table 5**.

Table 5: Interactive effect of clay tube burying depth and fertilizer application dosage on the number of fruits/plants of bell pepper

Installation depth	Fertilizer dosage	Number of fruits/plants
5 cm	100% RAD	10.1 [c]
	80% RAD	11.9 [d]
	60% RAD	6.3 [b]
10 cm	100% RAD	11.8 [d]
	80% RAD	12.1 [d]
	60% RAD	5.7 [b]
15 cm	100% RAD	6.3 [b]
	80% RAD	5.8 [b]
	60% RAD	4.3 [a]
Lsd (0.005)		**0.6091**

Bell pepper average fruit weight as influenced by SLECI system burying depth and fertilizer application dosage

Bell pepper average fruit weight as affected by different burying depths is presented in **Figure 50**. Average fruit weight shows a significant difference among a burying depth of 5cm (73.00 g) burying depth of 10cm (69.08 g) and a burying depth of 15cm (47.09 g). A significant increase in average fruit weight by 5.3% and 35.3% was attained when plants grown under a burying depth of 5 cm were compared to a burying depth of 10 cm and 15 cm **Figure 50**.

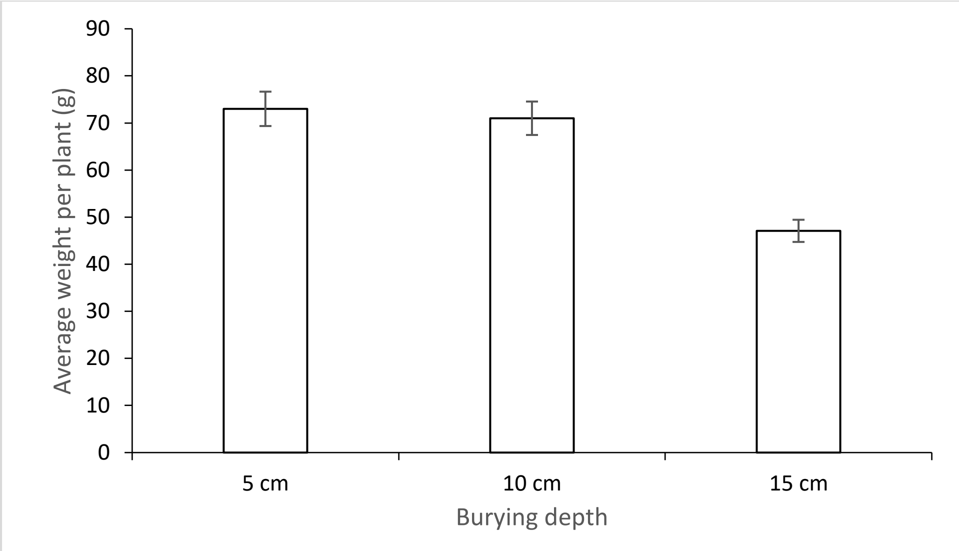

Figure 50: Bell pepper average fruit weight as influenced by SLECI system burying depth

The results (**Figure 51**) of average fruit weight show different variations by the application of different application dosages. Average fruit weight was recorded as 73.88 g, 63.46 g and 51.83 g exhibited by bell pepper plants subjected to 80 % RAD, 100 % RAD and 60 % RAD respectively **Figure 51**.

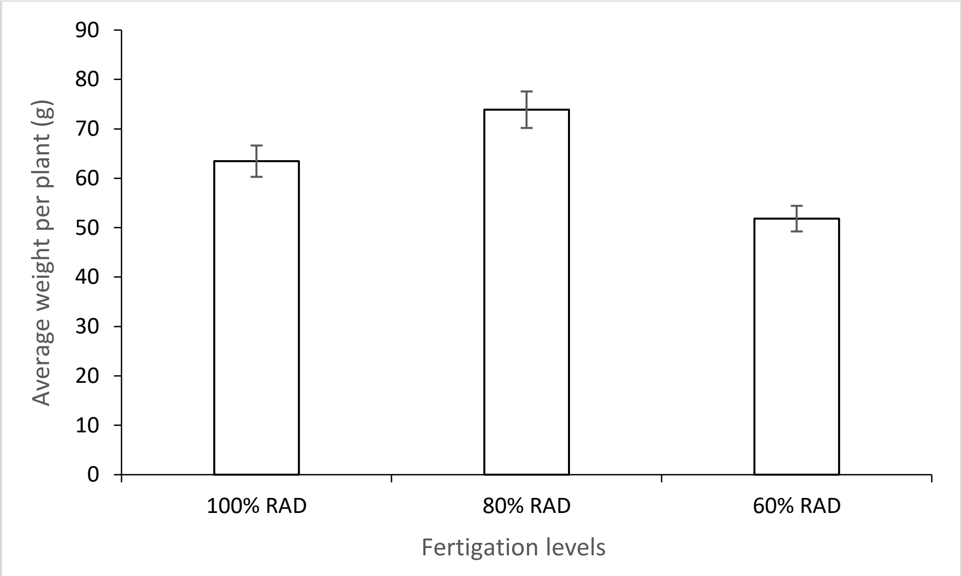

Figure 51: Bell pepper average fruit weight as influenced by fertilizer application dosage.

The interactive effect of burying depth and fertigation levels on the average fruit weight of bell pepper is presented in **Table 6**. The interaction between burying depth and different fertilizer application dosages exhibited significant differences in the average fruit weight of bell pepper. The combination of a burying depth of 10 cm and 80% RAD resulted in a significantly higher average fruit weight 86.67g, compared with the rest of the treatment combinations. The lowest number of average fruits of 40.43 g was recorded in plants subjected to 15cm and 60% RAD **Table 6**.

Table 6: Interactive effect of clay tube burying depth and fertilizer application dosage on the average fruit weight of bell pepper

Installation depth	Fertilizer dosage	Average fruit weight (g)
5 cm	100% RAD	76.31 [f]
	80% RAD	85.88 [g]
	60% RAD	56.82 [d]
10 cm	100% RAD	62.33 [e]
	80% RAD	86.67 [g]
	60% RAD	58.23 [d]
15 cm	100% RAD	51.74 [c]
	80% RAD	49.09 [b]
	60% RAD	40.43 [a]
Lsd (0.005)		**0.952**

Bell pepper yield per hectare as influenced by SLECI system burying depth and fertilizer application dosage.

The yield per hectare of bell pepper was significantly affected (P>0.05) with the imposition of different SLECI system burying depths **Figure 52**. The yield per tonne was recorded as 0.7974 t/ha, 0.7286 t/ha and 0.2872 t/ha respectively from plants grown under clay tube burying depths of 5cm, 10cm and 15cm, indicating that the yield of bell pepper showed significant (p<0.05) vary with the variation of treatments at the end of the crop growing period. The highest yield of 0.7974 t/ha was recorded in plants grown under a burying depth of 5cm which was 8.6% and 63.9% better than plants grown under 10 cm and 15 cm respectively **Figure 52**.

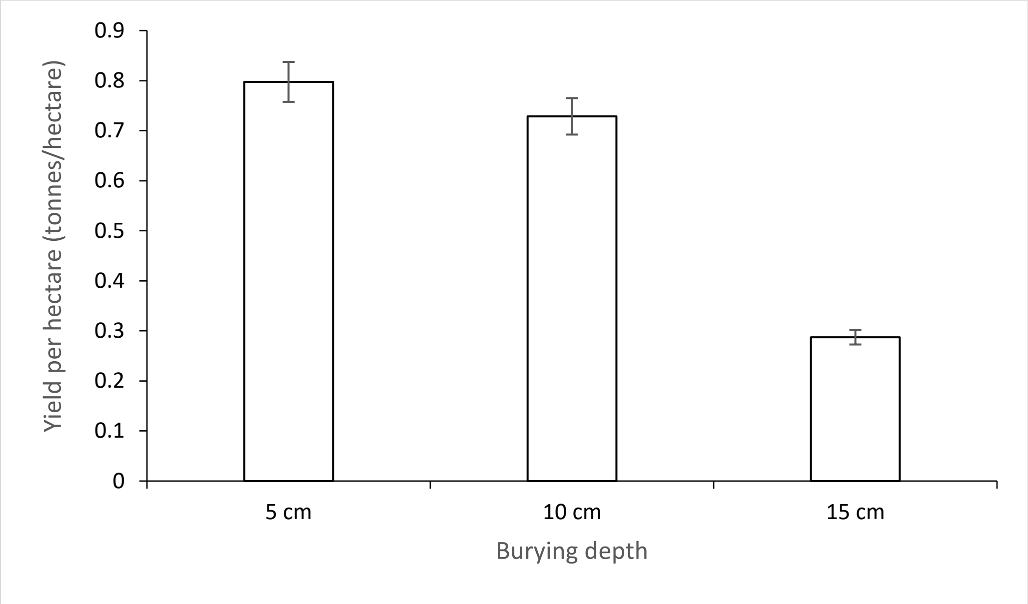

Figure 52: Bell pepper yield per hectare as influenced by SLECI system burying depth

The yield per tonne of bell pepper was significantly affected (P>0.05) with the imposition of different fertilizer application dosages **Figure 53**. The yield per tonne was recorded as 0.8772t/ha, 0.6179t/ha and 0.3181t/ha respectively from plants subjected to 80 % RAD, 100 % RAD and 60 % RAD, indicating that the yield of bell pepper showed significant variation due to different fertilizer application dosage. Data available in **Figure 53**, indicates that even though the recommended application dosage of fertilizer was reduced by 20% (80% RAD) it produced the highest yield of 0.8772t/ha which was an improvement of 29.5% and 63.7% when compared to bell plants that were subjected to 100% RAD and 60% RAD.

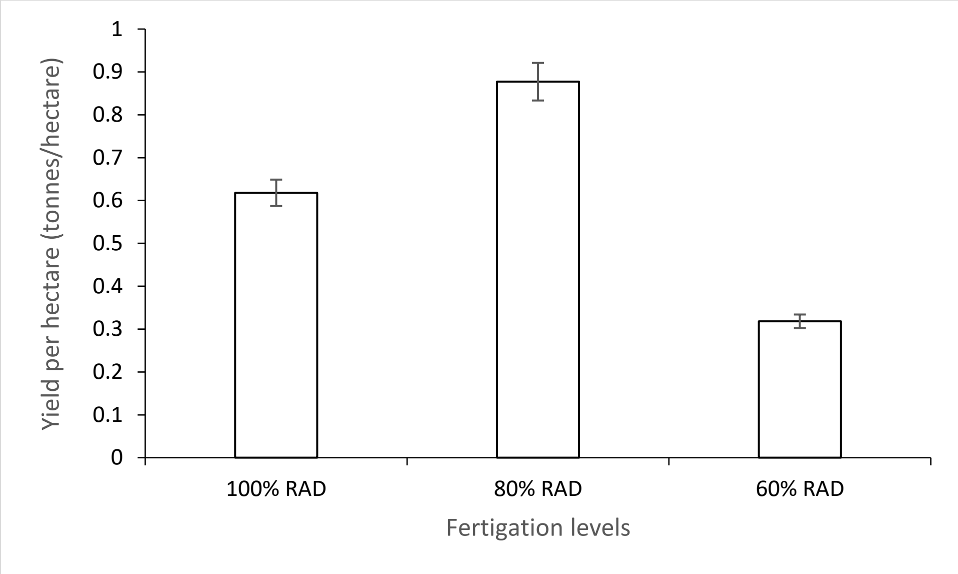

Figure 53: Bell pepper yield per hectare as influenced by fertilizer application dosage

Table 7 shows that the average fruit weight of bell pepper significantly influenced clay tube burying depth and fertilizer application dosage. The interaction of clay tube burying depth of 10 cm and 80% RAD significantly produced the highest yield of 1.1877 t/ha which was statistically equivalent to 5cm and 80% RAD treatment combination which produced a yield of 1.1350 t/ha. The lowest yield of 0.1950 t/ha was recorded in bell pepper plants subjected to 15cm and 60% RAD **Table 7**.

Table 7: Interactive effect of clay tube burying depth and fertilizer application dosage on the yield of bell pepper

Installation depth	Fertilizer dosage	Yield (tonnes/hectare)
5 cm	100% RAD	0.8574 [e]
	80% RAD	1.135 [f]
	60% RAD	0.3998 [c]
10 cm	100% RAD	0.6387 [d]
	80% RAD	1.1877 [f]
	60% RAD	0.3595 [bc]
15 cm	100% RAD	0.3576 [bc]
	80% RAD	0.309 [b]
	60% RAD	0.195 [a]
Lsd (0.005)		**0.05357**

Discussion

SLECI system burying depth

This finding disagrees with earlier findings of Lamm & Trooien 2005 and Al-Damry (2006) who reported high yields from irrigation depths of 25 - 40cm. the difference in findings could be ascribed to the type of subsurface system, different geographical temperatures which result in different evaporation losses and different types of soil which influence the potential occurrence of percolation. The best performance of 10cm is in tandem with the findings of Bozkurt and Mansuroğlu (2011) and Wang, Jiao, Guo, Lu, Bai and Wang (2018) who reported that the highest yield parameters were recorded when crops are grown at 10cm burying depth. The best performance could be attributed to the fact that at a depth of 10cm, there was a better balance in the soil moisture, aeration and plant nutrients in the effective root zone depth. The deepest burying depth resulted in a significantly lower yield; this is consistent with the findings of Lamm and Trooien (2005) who indicated that yields were significantly less for the deepest burying depth. The poor performance of the deepest depth and shallowest depth of irrigation pipe is in line with the findings of Douh and Boujelben (2011) who indicated that irrigation pipe burying depth results in significantly different yields. Mellouli, van Wesemael, Poesen and Hartmann (2000) found that evaporation from uncovered soils leads to a significant reduction in moisture and directly affects crop productivity. When the surface of the soil is devoid of moisture for an extended period, the moisture level in the top layer of soil becomes crucial, particularly during the initial growth of seedlings and the subsequent development of the young crop. At the deepest burying depth, water seeps into the ground and does not have enough time to get absorbed by the roots of the young plants. Deep percolation can result in low plant growth due to the lack of nutrients and water. Seedlings and young plants are very sensitive to water availability, as such reduction in water availability due to deep percolation can affect the yield of crops due to stunted growth as a result of remains stunted due to a lack of nutrients and water.

Fertigation levels

Bell pepper crops subjected to a 20% reduction in the recommended application dosage of fertilizer resulted in the best performance in yield this is in contrast with the findings of Bassiony et al. (2010) and Nijamudeen et al. (2013) where it was reported that the average yield of bell pepper obtained from increased fertilizer rate compared to the fertilizer application of normal dose. The disparity could be attributed to the difference in the irrigation system. Results from the study are in tandem with the findings of Kaushal et al. (2012) who reported that subsurface irrigation reduces fertilization requirement (20-33%). While ensuring an increase in yield. Tripathi et al. (2017) indicated that the adoption of a SLECI system ensures that the amount of fertilizer required by the crop during its lifecycle can be abridged as much as 25 to 40%. SLECI systems are buried beneath the soil surface, fertigation is uninterrupted. Additionally, the density of roots in a concentrated root zone is substantially higher per unit of soil, thus fertigation is far more effective. A clay tube ensures that fertilizer is administered to the plant root zone. Furthermore, the lower application rate of water using a SLECI system averts minerals from being leached out of the plant's root zone Bainbridge et al. (2006) as well as the eradication of weeds. Weed dynamics (emergence, frequency of growth and population) are highly reduced when clay tube irrigation is used in cultivating crops. According to Kakade et al. (2019), weeds compete with crops for a nutrient that is supplied, since clay tube ensures that nutrient is placed within the effective root zone of crops thus reducing nutrient resources for weeds.

Interaction of burying depth and fertigation levels

Gupta et al. (2009) indicated that reducing crop water requirement water along with 80% recommended NPK through fertigation was found to be significantly superior over all other treatment combinations with maximum fruit yield of bell pepper. The significantly better performance of interactive effects of 10 cm burying depth and 80% recommended application dosage could be attributed to the availability of water and nutrients in the effective root zone of crops. A concentrated root zone has a much higher density of roots in a given unit of soil and the effectiveness of the fertigation supplied to the soil is much better. with clay tube irrigation, fertilizer can be applied to the root zone where it is most beneficial resulting in better crop performance and improved crop yields. The lower application rate and self-regulatory ability of the SLECI system prevent the leaching of nutrients outside the domain of the effective root zone of crops. Fertilizer requirements can be reduced by as much as 25-40% fertigation can also continue without interruption (Eckas, 2005; Umair et al., 2019; IWS, 2022).

Bell pepper water use efficiency as influenced by SLECI system burying depth and fertilizer application dosage

Figure 54 gives the water use efficiency of a bell pepper at the final harvest as influenced by different clay tube burying depths. Significant differences were recorded among treatments (5cm, 10cm and 15cm burying depth). A burying depth of 10cm exhibited the highest water use efficiency of 0.1435 kg/l, in comparison with other treatments, a burying depth of 10cm outperformed a 5cm burying depth (0.1312 kg/l) and 15 cm burying depth (0.0517 kg/l) by 8.6% and 63.9%. According to Nalliah et al. (2009), the potential of most of the increased food production in the world depends on increasing WUE by using improved irrigation techniques is important for the agricultural sector Najafi and Tabatabaei (2007). The best-performing water use efficiency was recorded at a burying depth of 10cm. This is in line with the findings of Wang et al. (2018) where water use efficiency (WUE) burying depth of 10 cm) were higher than those of 5cm and Bryla et al. (2003) reported that WUE decreased at the deepest buying depth. Low WUE recorded in 5 cm and 10 cm could be attributed to high soil evaporation with crop evapotranspiration resulting in a slow early growth rate in crops. Additionally, at the early growth stage, water application does not correspond to crop demand since shallow roots of crops are unable to utilize water beyond the root zone Gallardo et al. (1996); Yazgan et al. (2008). Water application is very critical to make the most efficient use of the subsurface irrigation system, as excessive irrigation (percolation beyond the root zone, burying depth of 15cm) reduces yield, while inadequate irrigation (high evaporation losses, burying depth of 5cm) causes water stress and reduces production

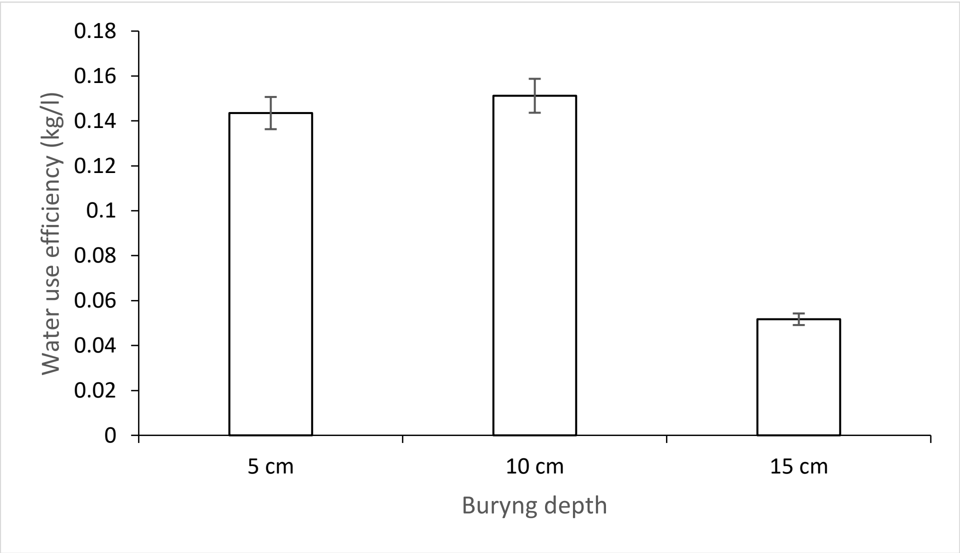

Figure 54: Bell pepper water use efficiency as influenced by SLECI system burying depth

The results relating to the water use efficiency of bell pepper as influenced by varying fertilizer application dosages are presented in Figure 55. Supplying bell pepper plants with 80% RAD was found to be significantly superior with the highest water use efficiency of 0.1579 kg/l, followed by 100% RAD (0.1112 kg/l) and 60% RAD (0.0573 kg/l). Fertilizing crops through fertigation increases WUE. Because nutrients are supplied through irrigation water, they are already in soluble forms available for plant uptake Shirgure (2013). Reducing the recommended application dosage by 20% resulted in the best yield. Fertilizer application has been shown to decrease by 33% for potatoes, 26% for wheat, 23% for maize and 23% for cotton 21% for tomatoes and pepper when supplying nutrients through fertigation and subsurface irrigation system Li et al. (2021). Lower WUE obtained from crops subjected to 100% recommended application dosage compared to WUE obtained from crops subjected to 80% recommended application dosage can be attributed to an increase in soil salinity as a result of fertigation. Shirgure (2013) and Ashrafi et al. (2020) found that soil nutrient concentration is carefully controlled within a narrow range in the root zone. Nutrients applied to this zone are efficiently absorbed by plants, along with the remaining water after evaporation. Any excess salt in the soil accumulates over time, as noted by Ziganshin, Galiev, Khusainov and Abdelfattah (2020). Fertigation poses a potential risk of excessive salinization of the soil, which can have detrimental consequences on plant growth and soil quality. If salt is not removed, it will build up in the soil and cause salinization. Adamchuk and Rossel (2010) and Sabirov, Valiev, Karimova, Dmitriev and Khaliullin (2019) showed that salinization is characterized by a higher concentration of solutes in the soil compared to that of crop roots. Due to osmosis, water exits the plants root system, reducing its availability to plants. Barradas, Matula and Dolezal (2012) state that an excessive amount of salt in the soil has a detrimental impact on both plants and soil characteristics. Cultivated crops exhibit varying responses to soil salt. Crops are highly susceptible to salt due to their inability to adjust to osmotic fluctuations, which hinders their capacity to take additional water from the soil.

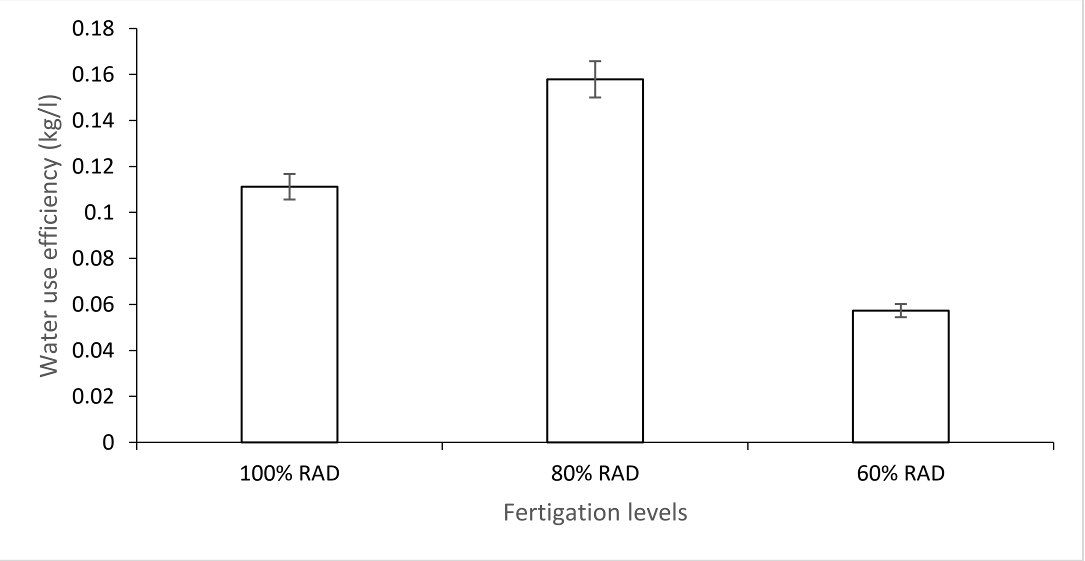

Figure 55: Bell pepper water use efficiency as influenced by fertilizer application dosage

The results relating to the water use efficiency of bell pepper plants as influenced by the interaction of clay tube burying depth and fertilizer application dosage are presented in **Table 8**. The analysis of the interaction of treatments imposed, showed that bell pepper plants that were grown under clay tube burying depth of 10cm and received 80% RAD were characterized by the highest water use efficiency of 0.214 kg/l, resulting in an 83.6% increase in comparison to the least water use efficiency of 0.035 kg/l recorded in plants subjected to clay tube burying depth of 15cm and 60% RAD. The second-best performing treatment combinations were 5 cm: 80% RAD (0.204 kg/l) and 10cm: 100% RAD **Table 8**. Results are in line with the findings of Gupta et al. (2010) who reported that the highest water use efficiency was observed with the treatment combination of reduced crop water requirement and 80% recommended NPK through fertigation. Water use efficiency is the quantity of economic yield produced per unit of water used by the crop. Bell pepper cultivated under clay tube burying depth of 10cm and 80% recommended application rate recorded the highest yield while being subjected to the least crop water requirement. This could be attributed to the fact that clay tube fertigation synchronizes nutrient supply and crop nutrient requirement, which enhances water-use efficiency and yield. Furthermore, Water is applied directly to the root zone of the crop and not to the soil surface where most weed seeds germinate after cultivation, thus competition for water, nutrients and sunlight is eliminated.

Table 8: Interactive effect of clay tube burying depth and fertilizer application dosage on the water use efficiency of bell pepper

Installation depth	Fertilizer dosage	Water use efficiency (kg/l)
5 cm	100% RAD	0.154 ^{e}
	80% RAD	0.204 ^{f}
	60% RAD	0.072 ^{c}
10 cm	100% RAD	0.204 ^{d}
	80% RAD	0.214 ^{f}
	60% RAD	0.065 ^{bc}

15 cm	100% RAD	0.072 [bc]
	80% RAD	0.056 [b]
	60% RAD	0.035 [a]
Lsd (0.005)		0.00964

Bell pepper fertilizer use efficiency as influenced by the SLECI system burying depth and fertilizer application dosage

Figure 56 portrays results related to fertilizer use efficiency as influenced by clay tube burying depth. Clay tube burying depth of 5cm (5.980 kg/kg) exhibited significantly greater ($P \leq 0.05$) fertilizer use efficiency over a burying depth of 15 cm (2.154 kg/kg) by 64% at final harvest. This was followed by a clay tube burying depth of 10 cm (5.465 kg/kg) having significantly greater ($p \leq 0.05$) fertilizer use efficiency over a burying depth of 15 cm **Figure 56**. The significantly lower FUE recorded in plants grown under 5cm burying depth could be attributed to the effect of evaporation on nutrient uptake. Evaporation is needed for the plant's cooling down processes and it is a pulling force enabling the transport of water and nutrients within the plant. However, evaporation itself can significantly reduce the quantity or volume of water in the soil, thus subjecting the plant to water stress. Plants absorb nutrients in soil water, when soil is dry, they are unable to absorb soil nutrients. A depth of 10cm ensured that nutrients and water were supplied to the effective root zone of crops regardless of the stage of plant growth, devoid of the negative impact of evaporation as well as leaching. An effective root zone is a potential depth down to which plant roots can take up the maximum amount of plant-available water from the soil even in dry periods. According to Suarez-Rey et al. (2006) and Elmaloglou and Diamantopoulos (2009) subsurface irrigation systems ensure that water is directly applied to the root zone without losses due to evaporation. Thus, plants grown at a depth of 10cm were not exposed to conditions that would limit their nutrient uptake. The poor performance of bell pepper FUE when compared to crops grown under 10cm and 5cm could be attributed to the leaching of nutrients outside the effective root zone of crops. Soil water is redistributed below the root zone due to the force of gravity and is not available to plants until the plants have developed deep penetrating roots. Soil water provides a medium of dissolved nutrients that are readily available for plant uptake, as such when the soil water is not available, for plant uptake, nutrient uptake is hindered resulting in poor fertilizer use efficiency.

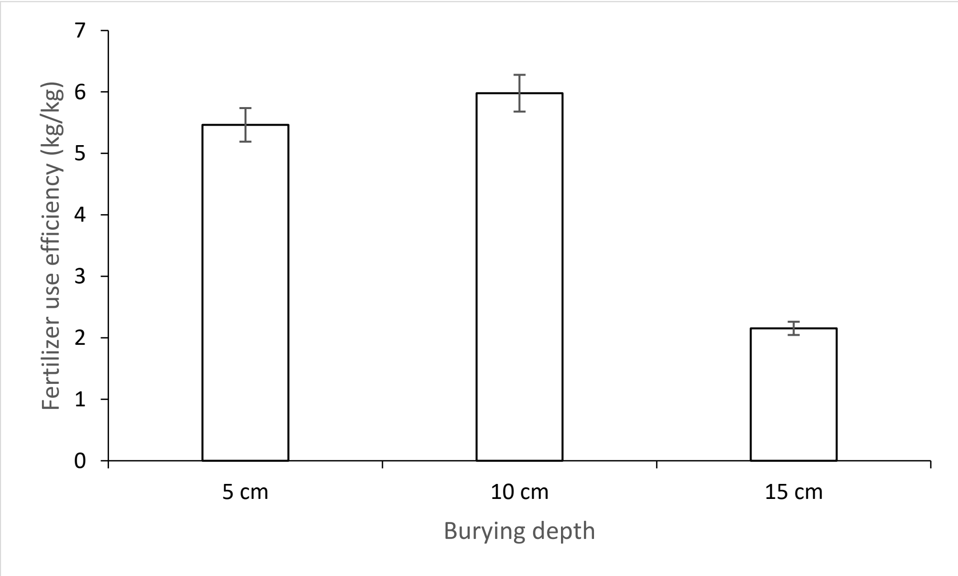

Figure 56: Bell pepper fertilizer use efficiency as influenced by SLECI system burying depth

Figure 57 portrays results related to fertilizer use efficiency as influenced by fertilizer application dosage. Bell pepper plants that were supplied with 80% RAD exhibited a fertilizer use efficiency of 6.579 kg/kg which was significantly superior compared to the fertilizer use efficiency of bell pepper plants that received 100% RAD (4.634 kg/kg) and 60% RAD (6.579 kg/kg). There were significant differences between 100 % RAD and 60 % RAD Figure 57. Fertilizer use efficiency is the fraction of harvested crop per unit of nutrient supplied by fertilizer. Lower FUE obtained from crops subjected to 100% RAD compared to FUE obtained from crops subjected to 80% RAD could be attributed to the increase in EC soil water resulting in soil salinity. Bano and Fatima (2009) stated that soil salinity induces osmotic stress, ion toxicity, oxidative stress, and nutritional deficit in plants, hence restricting water absorption from the soil. The excessive buildup of salt in the cell walls of plants can quickly result in osmotic stress and the death of cells (Munns, 2002). Plants that are sensitive to salinity may have negative effects even at low salt concentrations if the soil has a significant amount of saline toxicity. Excessive salt levels in the soil can disrupt the nutrient balance in plants or hinder the absorption of certain nutrients, as salts can also serve as plant nutrients (Blaylock, 1994). According to Netondo et al. (2004), salinity has a negative impact on photosynthesis by decreasing leaf area, chlorophyll content, and stomatal conductance. The crop's yield is directly proportional to its FUE (Field Use Efficiency). According to Shrivastava and Kumar (2015), salinity has a negative impact on reproductive development. It hinders the formation of microspores and the elongation of stamen filaments. Salinity also increases programmed cell death in some tissues, leads to the abortion of ovules, and causes the ageing of fertilized embryos. Salinity has a detrimental effect on crop productivity, which in turn has a potential impact on FUE. The decrease in FUE observed in crops exposed to 60% RAD, as opposed to those exposed to 80% RAD, can be explained by stunted growth resulting from insufficient nutrition supply to the crops. In their study, Morgan and Connolly (2013) found that a deficient supply of nutrients to crops leads to impaired growth, necrosis of plant tissue, and less chlorophyll production, which is crucial for photosynthesis. Consequently, this ultimately leads to a decrease in crop yield. Decreasing the number of nutrients delivered leads to a decrease in crop output, resulting in a decreased FUE.

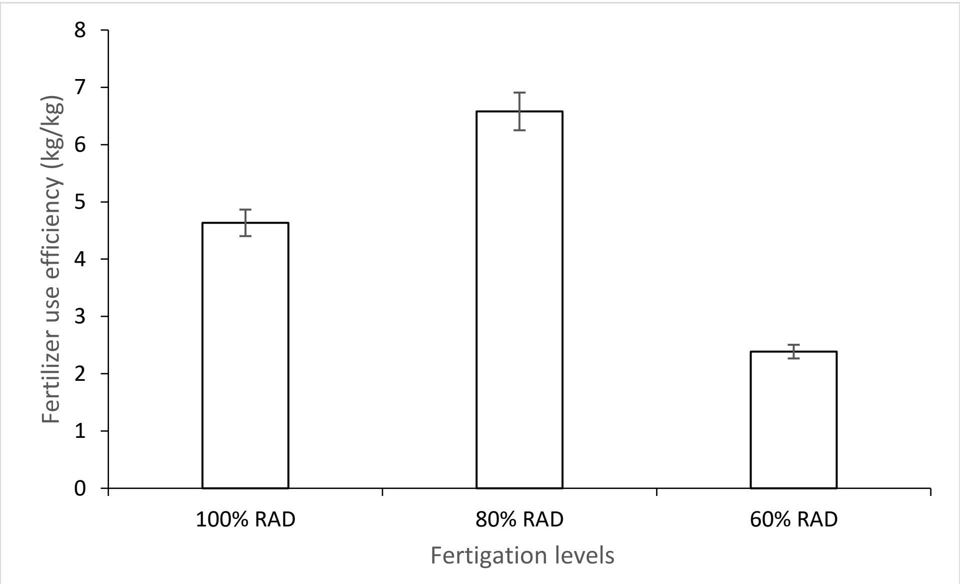

Figure 57: Bell pepper fertilizer use efficiency as influenced by fertilizer application dosage

The results of fertilizer use efficiency of bell pepper concerning the interactive effect of clay tube burying depth and fertilizer application dosage at final harvest are presented in Table 9. It indicates that the bell pepper plants grown under burying depth of 10cm: 80% RAD (8.908 kg/kg) and 5 cm: 80% RAD (8.512 kg/kg) recorded the highest fertilizer use efficiency which was significantly superior to the remaining treatment combinations. Bell pepper plants grown under 15cm and 60% RAD 42 kg recorded the least fertilizer use efficiency of 1.462 kg/kg. The best-performing fertilizer use efficiency being recorded under clay tube burying depth of 10 cm and 80% recommended application dosage could be attributed to the form of fertilizer application, that is fertigation. Badr and El-Yazied (2007) fertilizer application through irrigation systems and fertigation can reduce fertilizer usage and minimize groundwater pollution due to fertilizer leaching from excessive irrigation. Additionally, Dhotre et al. (2017) indicated that clay tube subsurface fertigation can synchronize nutrient supply and crop nutrient requirement, which enhances fertilizer use efficiency, by reducing nutrient losses via leaching, ammonia volatilization, denitrification, and weed pressure. This guarantees about 40% savings in irrigation water and 25% applied fertilizers with increased productivity. Gunarathna et al. (2017) indicated that water availability directly influences the efficient use of all other inputs such as fertilizer, thus better water availability, in turn, ensures optimum yields.

Table 9: Bell pepper fertilizer use efficiency as influenced by the interactive effect of the SLECI system burying depth and fertilizer application dosage

Installation depth	**Fertilizer dosage**	**Fertilizer use efficiency (kg/kg)**
5 cm	100% RAD	6.43 e
	80% RAD	8.51 f
	60% RAD	2.99 c

10 cm	100% RAD	4.79 [d]
	80% RAD	8.91 [f]
	60% RAD	2.70 [bc]
15 cm	100% RAD	2.68 [bc]
	80% RAD	2.32 [b]
	60% RAD	1.46 [a]
Lsd (0.005)		0.4018

Conclusion

This study was conducted to investigate the effects of SLECI system burying depth and fertilizer application dosage on the growth, yield, and productivity of bell pepper plants. The analysed results indicated that different SLECI system burying depths, varying fertilizer applications and their interaction had significant effects on the growth, yield, and productivity parameters.

The best performing growth parameters, plant height, and leaf were recorded under bell pepper plant grown under a burying depth of 10cm and 80% recommended application dosage. The best-performing interaction of treatment was; a SLECI system burying depth of 10cm and 80% recommended application dosage was recorded as the best-performing plant height and leaf area.

For yield parameters clay tube burying depth of 10cm produces a significantly higher number of fruits/plants, average fruit weight and yield/hectare compared to burying depth of 5cm and 15 cm, concerning recommended application dosage, reducing the recommended application dosage of fertilizer by 20% (80% RAD) resulted in a significantly higher number of fruits/plants, average fruit weight, and yield/hectare compared 100% RAD and 60% RAD treatment. Yield parameters (number of fruits/plants, average fruit weight, and yield/hectare) were significantly higher in bell pepper plants that were subjected to the interaction of 10cm burying depth and 80% recommended application dosage of fertilizer.

Bell pepper plants grown under the SLECI system burying depths of 10cm exhibited the highest water use efficiency and fertilizer use efficiency when compared to crops grown under burying depths of 5cm and 15cm. with regards to the recommended application dosage of fertilizer treatment, a reduction of 20% resulted in a significantly higher water use efficiency and fertilizer use efficiency. The interaction of 10cm burying depth and 80% recommended application dosage of fertilizer resulted in a significantly higher water use efficiency and fertilizer use efficiency compared to the remaining treatment combination.

CHAPTER SIX

ASSESSMENT OF THE GROWTH, YIELD, WATER PRODUCTIVITY, AND QUALITY OF BELL PEPPER UNDER VARYING WATER SALINITY LEVELS USING SELF-REGULATING LOW ENERGY CLAY-BASED IRRIGATION SYSTEM.

Introduction

Freshwater is unequally distributed across the globe, making some regions of the world water abundant while others receive less water than the demand thus falling into a water scarcity condition. The unequal distribution of water coupled with higher demands in certain areas for domestic consumption, industrial use, and food production poses a severe threat to its sustainable use (Salman, Abdelfattah, Ahmad & Simongini, 2022). Soil salinity poses a significant challenge for agriculture when using irrigation, making it a major obstacle to global agricultural productivity. Crops cultivated in saline soils experience adverse effects due to elevated osmotic stress, nutritional imbalances, toxicities, unfavourable soil physical conditions, and decreased crop output (Shrivastava & Kumar, 2015). According to the FAO (2021), soil salinity is responsible for rendering around 0.3–1.5 million hectares of agriculture unproductive annually, while also causing a decrease in productivity on an additional 20–46 million hectares. Increased evapotranspiration is anticipated to worsen the buildup of salts in the upper layers of soil, although the severity of subsurface salinity is particularly noticeable at depths ranging from 30 to 100 cm (FAO, 2021). Indiscriminate use of saline irrigation water in the absence of proper management poses a grave risk of endangering the development of salt-affected soils accompanied by serious crop damage. Options are available to deal with salinity issues and drainage of salt-affected soils vital to future food security in arid and semi-arid environments. Several studies indicate that saline water is to be irrigated in such amount and quality that meets the evapotranspiration demands of the crop, minimizes root zone salinity, and selection of suitable crops and varieties tolerant to water and salinity stress (Katerji, Van Hoorn, Hamdy & Mastrorilli 2003). Additionally, the design, choice, and management of irrigation systems influence soil salinity levels since inadequate irrigation management leads to secondary salinization that affects 20% of irrigated land worldwide (Glick et al., 2007). If well planned and executed, this adaptive approach can reduce environmental degradation due to soil salinity. Mondal, (1978), Bainbridge (1987), Bhatt et al. (2013), and Thingujam, Adhikary, Senjam, Pal, Kundu, and Kuma (2017) found that pitcher's irrigation system could be successfully adopted as it is simple, and enables the growth of various crops and offers the benefits of using saline water which is not applicable in conventional irrigation for alleviating root-zone salinity. The self-regulative ability of the pitcher irrigation system offers the benefit of alleviating root zone salinity to maintain favourable soil moisture (Adhikary, Bera, Kumar & Pal 2020). Crops can be grown in only 10-15cm of water to achieve economically viable yield. With surface irrigation, most crops would tolerate saline water up to2-3dS/m. Highly saline water ranging from 4 -15 dS/m could be used with pitcher irrigation to get as many yields as with freshwater (Dubey, 2020). High tomato yields were observed when pitcher irrigation was adopted to cultivate tomatoes, with saline water of salinity of 10.2 mmhos/cm indicating that a pitcher irrigation system may be valuable when irrigating with saline water, likewise, Mondal, Dubey, and Gupta (1992) observed a 10% reduction in the yield of cauliflower and brinjal when irrigated through pitcher irrigation system with saline irrigation water. Similarly, Adhikary, Bera, Kumar De, and Pal (2020) suggested that the application of saline water through pitcher irrigation increases the growth and yield of the brinjal crop. Kurunc, Unlukara, and Cemek (2011) stated that bell peppers had a moderate sensitivity to salt, with a range of 1.2 – 1.8 ds/m and a threshold of 2 ds/m. Water conservation and the utilisation of low-quality water resources are crucial areas of current research, particularly in regions facing a scarcity of water for agricultural reasons (Naik, Panda, Nayak, & Sharma, 2008; Adhikary, Bera, Kumar De & Pal, 2020). Despite much research conducted on irrigation management, the issue of salinity in agriculture is progressively worsening due to the extensive utilisation of non-saline soils and non-saline water. Given the circumstances, the prudent use of marginal and low-quality water supplies can be an alternative approach. The objective of this study was to evaluate the growth, yield, water productivity, and quality of bell pepper plants under various levels of water salinity using an SLECI system.

Materials & Methods

Study area

The experiment was carried out at the Research field of CSIR Institute of Industrial Research, which falls within Latitude: 5.65774 and Longitude: -

0.15013, with an altitude of 71m. The experimental area falls within the tropical savanna climate with two types of rainy seasons: the first major season is from April to July while the second minor season is from September to November. The bi-modal rainfall pattern provides a suitable environment for farming activities in most months (8 months) of the year as residents can cultivate and harvest different types of crops in each season. Temperatures are generally high throughout the year. The high temperatures warm up the air, which rises to condense contributing to the second type of precipitation called Conventional rainfall for the area. March to April is usually the hottest period with temperatures reaching 32°C during the day and 27°C at night. Cooler temperatures occur from May to September, with a high of 27-29°C during the day and 22-24°C at night.

Soil sampling

Soil samples were taken from the experimental field before, five days after initiation of the irrigation, and after harvest from soil depths 0-30, cm for determining soil physicochemical properties.

Research design

The experiment was laid out in a Randomized Complete Block Design with three replications. In addition to the control, four irrigation water salinity levels were considered in the experiment resulting in five different treatments in the experiment. Treatments T1, T2, T3, T4 and T5 correspond to the control, 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m. Each treatment was replicated three times, which resulted in a total of 15 experimental plots (units) with dimensions of 2 x 3 m. The experimental plots were randomly distributed within each block. With a planting distance of 0.5 x 0.5 m, each experimental plot had a plant population of 24. Border plants were ignored while mid-section plants were tagged for data collection.

Figure 58: Field layout depicting various irrigation water salinity levels

Irrigation System

The SLECI system consists of a water tank (100 litres), valve, filter, clay tubes, connectors, coupling, PE- tubes, and an end cap. The length of the clay tube was 9 cm with inner and outer diameters of 10 mm and 12 mm, indicating that each clay tube can hold 7.1-6 m3 of water at a time respectively. The thickness of each clay tube was 2 mm. The core of the clay tube was mounted on a PE – hose. This line is completed with a connector to PE-hose renewal on each end of the clay tube. This was made to allow for the fitting of additional clay tubes. A PE–hose length of 50cm was allowed between 2 clay tubes. In each plot, clay pipes are joined together or laid end to end to form long tubes of a desired length of 2m, an end cap is fixed at the end of the PE tube after the desired length is achieved. The clay pipes were buried at a depth of 5cm. The water tank was filled with fresh and saline water according to the experimental treatments.

Treatments and Preparation of treatment (irrigation water salinity levels)

There were five different saline irrigation water with electrical conductivities (Ec) of; 0.55 dS/m (control), 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m. The saline water of the required EC was prepared artificially by mixing the Sodium Chloride (NaCl) salt in fresh water in buckets. Different salinity levels for each treatment were prepared by mixing calculated amounts of Sodium chloride (NaCl) salts to achieve desired salinity concentrations. The amount of sodium chloride to be dissolved in 1 litre of water was determined by Salt (mg/l) = 640 × EC (dS/m) adopted from Michael (1998). Thus 1.3, 2.6, 3.8, and 5.12 g amounts of NaCl dissolved in 1 litre of water to prepare saline water of concentrations 2.0 dS/m, 4.0 dS/m, 6.0 dS/m, and 8.0 dS/m respectively. Each time the EC of the saline water was checked with an EC meter before filling the water storage tank as per treatments.

Figure 59: Transplanted bell pepper plants

Plant material and cultural practices

Bell pepper cultivars used in this study were Siempre Verde (Agriseed Seed Company). Organic wood vinegar & Plan D (pesticides) and Agrithane (fungicide) were respectively used for pest and disease control. Weeding of the experimental field was carried out for 3 weeks using a hand hoe.

Data collection

Data collected included growth parameters such as plant height, leaf area, and stem girth), yield parameters (number of fruits, average fruit weight, and yield per hectare), water productivity (water use efficiency), and quality (blossom end rot).

Plant height

Plant height was determined by measuring the distance from the highest point of the soil surface to the topmost part of the plant. The average of plant height of plants tagged for data collection was expressed in centimeters (cm).

Leaf area (Individual leaf area)

The length of the leaf was measured as the longest segment along the petiole line of the leaf on the lateral bud below the shoot tip. The breadth of the leaf was measured as the widest width across the leaf. The product was scaled down by a factor of 0.75 to obtain the leaf area.

Number of fruits

The fruits harvested from the tagged plants at various growth stages were tallied and quantified as the number of fruits per plant.

Average fruit weight

The fruits harvested from the tagged plants were weighed, recorded and expressed as grams.

Derived parameters

Yield per hectare

In each plot, an area (tagged bell pepper plants comprising the mid-section of individual plots) was selected. The total plant yield for the selected was then derived by weighing all fruits from the tagged plants after which the total fruit weight in the selected area per plant was added to generate the total yield for the selected area. The selected area dimensions were then converted from square meters to a hectare basis. Yield per hectare was then derived using the formula below (Equ. 19).

$$\frac{1\ hectare}{Selected\ area\ containing\ tagged\ plants\ (hectare)} x\ total\ yield\ from\ tagged\ plants\ (kg)$$

Equ (19)

Water use efficiency

Water use efficiency was calculated through the proportion of the total plant yield and the total water applied under each treatment (Equ. 20).

$$\frac{\text{Total yield per plant (g)}}{\text{The total amount of water applied (mm)}} \qquad \text{Equ. 20}$$

Incidence of Blossom End Rot (%)

Incidence was recorded after harvesting by counting the number of fruits with symptoms of BER (brown to black dry patch at the blossom end of the bell pepper fruit) and the data was converted to represent % disease incidence (Equ. 21).

$$\frac{\textbf{Total yeild per plant (g)}}{\textbf{Total amount of fertilizer applied (kg)}} \qquad \text{Equ (21)}$$

Salt dynamics in the soil

The soil was sampled at depths of 5cm, 10cm, 15cm and 20cm from the wetted zone around the clay tubes. Soil salinity was determined using a conductivity meter used to determine the electrical conductivity (EC) using a ratio of 1:5 distilled water: soil dilution.

Moisture dynamics in the soil

The moisture distribution in the soil around the clay tube was determined using a HOLDAll 3 in1 soil meter, model 60182L, to determine the moisture content, the switch is pushed to the moist position on the instrument. The probe of the instrument was inserted to the desired depth of 5cm, 10cm, 15cm and 20cm. The probe was allowed to sit for 5 seconds and readings were recorded.

Data analysis

Analyses of variance (ANOVA) of data collected were performed to evaluate the effect of irrigation water salinity levels, using Genstat statistical software (Introduction to GenStat for Windows 18th Ed, VSN International, Rothamsted Experimental Station, Reading University, United Kingdom). Significant mean differences among treatments were compared using Tukey's least significant difference test at a probability level of 5%.

Results & discussion

Consumptive water use

Consumptive water use or reference evapotranspiration of the control, 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m is presented in Table 10. Under saline water levels of 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m, 25.40 mm (4.2%), 65.16 mm (10.6%), 101.33 mm (16.6%) and 140.83 mm (23%) less water seeped from the clay tube compared to irrigation with fresh water (control). Results from (Table 10) are in line with earlier findings of Vasudaven et al. (2011) who indicated that the depletion of water from clay tubes has slightly decreased with the increase in salinity. The reference evapotranspiration of bell pepper was 643.07mm when compared to the SLECI system (control: 611.87mm), and irrigation water savings of 11.33% were achieved, agreeing with earlier findings of MINFAL (2005). Naik et al. (2008) and Vasudaven et al. (2011) explained that the decrease in seepage of water as a result of high irrigation water salinity levels might be due to blockage of some of the water-conducting microspores of the SLECI system due to partial retaining of salt in the saline water.

Table 10: Consumptive water use of different irrigation water salinity levels

Growth stage	ETo	0.55 dS/m	2.0 dS/m	4.0 dS/m	6.0 dS/m	8.0 dS/m
Initial stage	94.35	81.27	78.98	75.28	71.15	64.27
Crop development	194.72	172.51	168.46	153.15	144.46	133.42
Middle season	218.18	201.42	194.72	182.37	166.27	153.96
Late season	174.82	156.67	144.31	135.91	128.66	119.39
Total (mm)	681.25	611.87	586.47	546.71	510.54	471.04

Bell pepper plant height as influenced by irrigation water salinity level.

The plant height of bell pepper was significantly ($p < 0.05$) influenced by water salinity level (*Figure 60*). At 2 wat, the plant height of bell pepper did not show a significant difference among 2.0 dS/m (8.7 cm), 4.0 dS/m (7.9 cm), 6.0 dS/m (7.6 cm) and 8.0 dS/m (7.5 cm) compared to 0.55 dS/m, which is the control (8.6 cm). A similar trend was observed at 4 wat, where bell pepper irrigated with 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m exhibited plant height of 30.4 cm, 29.1 cm, 28.5 cm and 28.2 cm compared to the 0.55 dS/m (29.3 cm) which is the control. It was also observed that at 6 wat, bell pepper irrigated with 2.0 dS/m, 4.0 dS/m, 6.0 and 8.0 dS/m irrigation water exhibited plant height of 39.7 cm, 38.3 cm, 37.1 cm and 37.0 cm compared to the 0.55 dS/m (39.2cm) which is the control. Data available in (*Figure 60*) indicate that at 8 wat, the plant height of bell pepper decreased with increasing water salinity levels 2.0 dS/m (49.0 cm), 4.0 dS/m (47.9 cm), 6.0 dS/m (46.2 cm) and 8.0 dS/m (45.82 cm) when compared to the control (0.55 dS/m, 48.0 cm). A similar trend was observed at 10 wat, where it was observed that 10 wat, bell pepper irrigated with 2.0 dS/m, 4.0 dS/m, 6.0 and 8.0 dS/m exhibited plant height of 54.0 cm, 53.1 cm, 52.4 cm and 51.8cm compared to the 0.55 dS/m which is the control. Compared to the plant height (53.8cm) of the control (0.55 dS/m) increasing water salinity levels to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m decreased plant height of bell pepper by 0%, 3.8%, 5.4% and 6% (*Figure 60*). In general, plant height increased with an increasing number of weeks in the irrigation system with the highest plant height recorded at week 10 for each treatment. Salinity becomes problematic when a sufficient amount of salts accumulate in the root zone, leading to a detrimental impact on plant growth. High levels of salts in the root zone impede the ability of plant roots to extract water from the surrounding soil. Saline irrigation water reduces the water availability for the plant, irrespective of the actual water content in the root zone. Consequently, bell pepper plants irrigated with saline water demonstrate poor growth. The SLECI system effectively regulates soil moisture levels, allowing crops to thrive in both regular and saline soils. Additionally, it is specifically designed to utilise saline waters that cannot be used with traditional irrigation methods (Mondal et al., 1992). The use of the SLECI method, which stands for clay tube irrigation, results in the accumulation of salt on the soil surface and the reduction of salt concentration in the soil around the roots, hence increasing moisture levels (Abu-Zreig & Atoum, 2004).

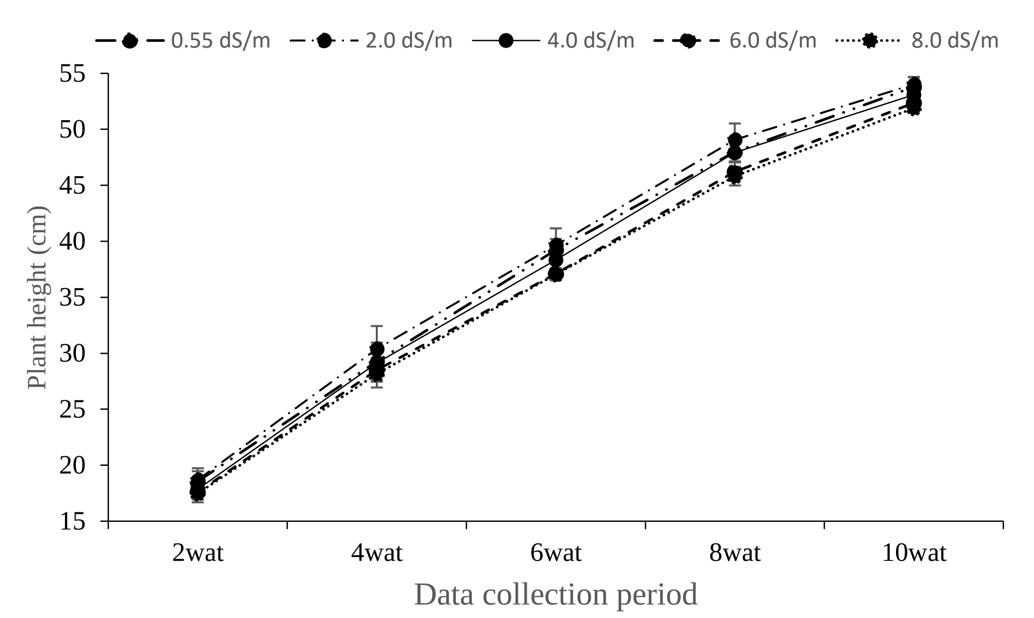

Figure 60: Bell pepper plant height influenced irrigation water salinity level

Bell pepper leaf area as influenced by irrigation water salinity level

The leaf area of bell pepper was significantly ($p < 0.05$) influenced by water salinity level (*Figure 61*). At 2 wat, the leaf area of bell pepper did not show a significant difference among 2.0 dS/m (13.3 cm), 4.0 dS/m (13.1 cm), 6.0 dS/m (13.0 cm) and 8.0 dS/m (12.7 cm) compared to 0.55 dS/m (13.1cm). A similar trend was observed at 4 wat, where bell pepper irrigated with 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m exhibited leaf areas of 23.3 cm, 23.2 cm, 22.9 cm and 22.7 cm compared to the 0.55 dS/m (23.0 cm) which is the control. It was also observed that at 6 wat, where bell pepper irrigated with 2.0 dS/m, 4.0 dS/m, 6.0 and 8.0 dS/m exhibited leaf area of 34.1 cm, 34.0 cm, 33.9 cm and 33.9 cm compared to the 0.55 dS/m (34.0 cm) which is the control. Data available in (*Figure 61*) indicate that at 8 wat, the leaf area of bell pepper decreased with increasing water salinity levels 2.0 dS/m (51.4 cm^2), 4.0 dS/m (51.3 cm^2), 6.0 dS/m (51.1 cm^2) and 8.0 dS/m (50.6 cm^2) when compared to the control (0.55

dS/m, 51.3 cm^2). A similar trend was observed at 10 wat, where it was observed that 10 wat, bell pepper irrigated with 2.0 dS/m, 4.0 dS/m, 6.0 and 8.0 dS/m exhibited leaf area of plant height of 61.4 cm^2, 61.3 cm^2, 61.0 cm^2 and 60.7cm^2 compared to the 0.55 dS/m (62.2 cm^2) which is the control. Compared to the control (0.55 dS/m) increasing water salinity levels to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m decreased the leaf area of bell pepper by 1%, 1.4%, 2% and 2.4% (*Figure 61*). In general, leaf area increased with an increasing number of weeks in the irrigation system with the highest leaf area recorded at week 10 for each treatment. Results from this study agree with earlier findings of Savvas et al. (2000) who reported that at irrigation water salinity level of 8 dS/m, leaf area was restricted. Bauder & Brock (2001) explained that plants are required to use more energy when extracting water from the soil when soil water salinity is high, thus excess salinity in soil water decreases available water exposing the plant to the negative effect of water stress.

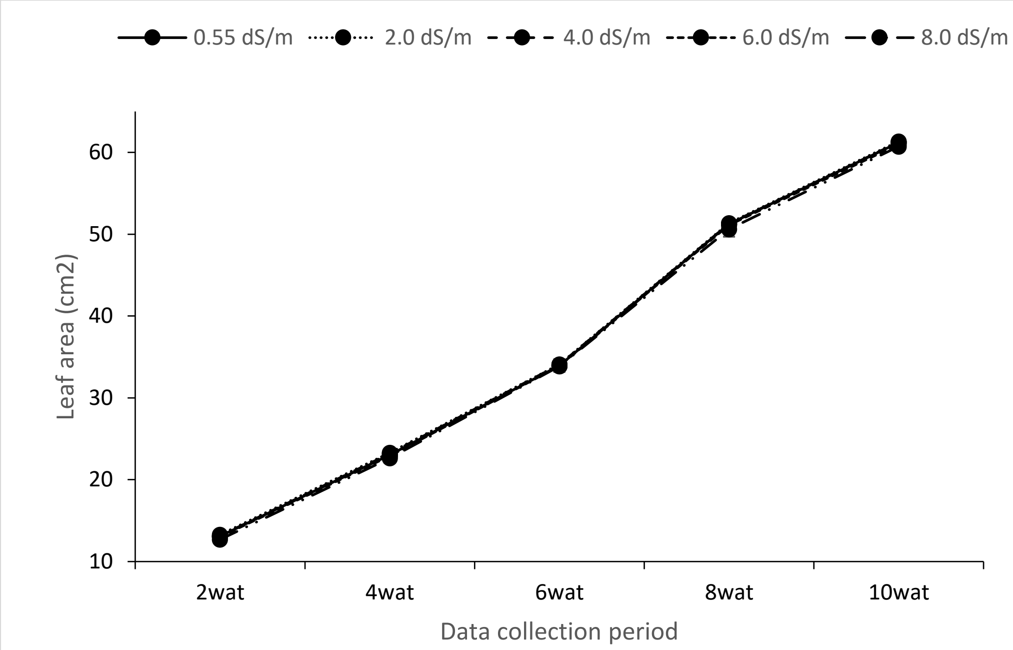

Figure 61: Effect of irrigation water salinity level on the leaf area of bell pepper.

Bell pepper stem girth as influenced by irrigation water salinity level

The stem girth of bell pepper was significantly ($p < 0.05$) influenced by water salinity level (Figure 62) At 2 wat, the stem girth of bell pepper did not show a significant difference among 2.0 dS/m (5.1 mm), 4.0 dS/m (4.6 mm), 6.0 dS/m (4.8 mm) and 8.0 dS/m (4.2m) compared to 0.55 dS/m (5.0 mm). A similar observation was made at 4 wat, where bell pepper plants irrigated with 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m exhibited stem girth of 6.9 mm, 6.8 mm, 6.5 mm, and 5.6 mm compared to the 0.55 dS/m (7.1 mm) which is the control. At 6 wat, the control (0.55 dS/m) exhibited the highest stem girth of 10.3 mm followed by 2.0 dS/m (10 mm), 4.0 dS/m (9.5 mm), 6.0 (9.4 mm) and 8.0 dS/m (9.1 mm) in that order (Figure 62). At 8 wat, a consistent reduction in stem girth was observed in bell pepper plants as salinity levels in irrigation water were increased, where the bell pepper irrigated with 0.55 dS/m, 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m exhibited stem girth of 12.0 mm, 11.5 mm, 11.3 mm, 11.0 mm and 10.5 mm. A similar trend was observed at 10 wat, where bell pepper irrigated with 0.55 dS/m, 2.0 dS/m, 4.0 dS/m, 6.0 and 8.0 dS/m exhibited stem girth of 12.4 mm, 12.3 mm, 12.2 mm, 11.9 mm and 11.3 mm. In general, stem girth increased with an increasing number of weeks in the irrigation system with the highest stem girth recorded at week 10 for each treatment. Compared to the control (0.55 dS/m) increasing water salinity levels to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m decreased the stem girth of bell pepper by 0.03%, 1.6%, 4% and 8.8% (Figure 62). Results from this study are in line with the findings of Savvas et al. (2000) at high EC of 8 dS m-1, the growth of vegetative organs of plant, plant stem inclusive was restricted. The reduced growth could be attributed to the fact that as soil is irrigated, available plant water is at its highest and soil water salinity is at its lowest, as plants absorb water, the remaining water is held tighter to the soil particles and becomes progressively more difficult for plants to utilize (Bauder, 2001)

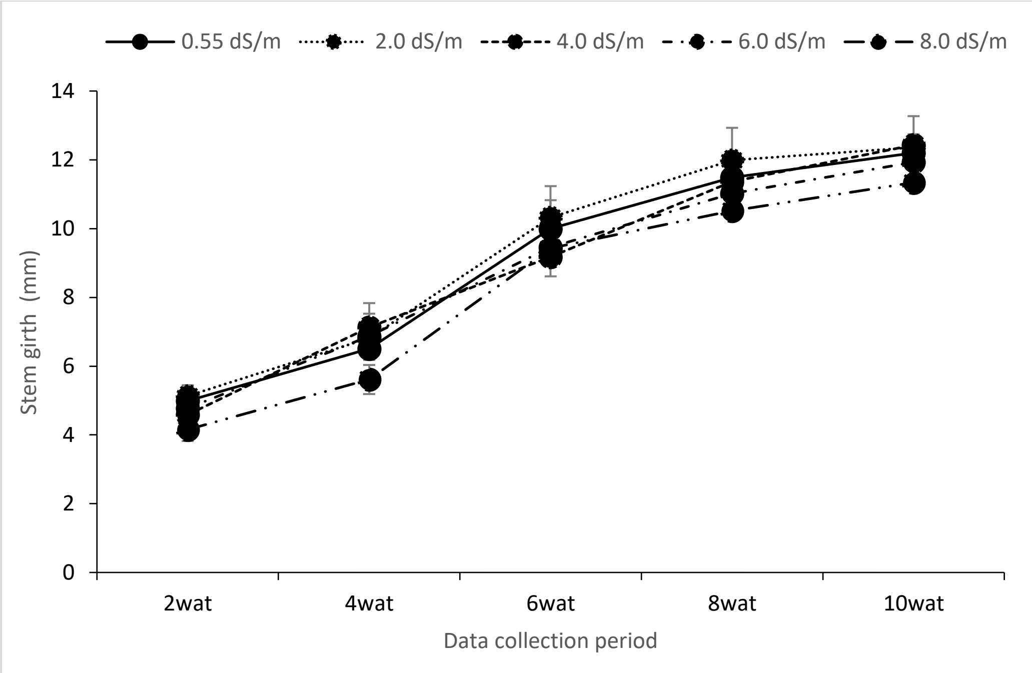

Figure 62: Bell pepper stem girth as influenced by irrigation water salinity level

Bell pepper number of fruits as influenced by irrigation water salinity level

The number of fruits of bell pepper was significantly ($p < 0.05$) influenced by water salinity level (Figure 63). A consistent reduction in the number of fruits per plant was observed in bell pepper plants as salinity levels in irrigation water were increased, with 0.55 dS/m, 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m exhibiting 13.0, 12.4, 12.1, 11.7 and 11.3 number of fruits. In comparison with the control (0.55 dS/m) increasing water salinity level from 0.55 dS/m to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m decreased the number of fruits by 4.6%, 6.9%, 10% and 13.1% (Figure 63). The poor yield exhibited by bell pepper plants irrigated with saline water could be attributed to the negative impact of soil salinity on the soil. Soil salinity causes sodium-induced soil dispersion which in turn causes loss of soil structure. When there is a loss of soil structure and hydraulic conductivity, the rate at which water flows through the soil is reduced. When water movement is restricted, portions of the soil become swollen and water-logged. This results in the creation of anaerobic soils which can reduce or prevent plant growth (Mamedov, Levy, Shainberg & Letey 2000).

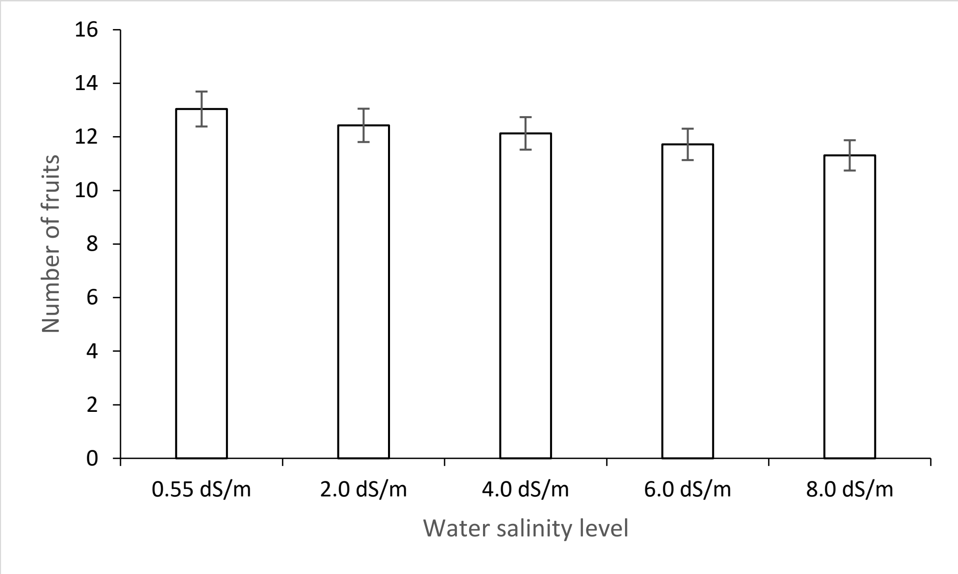

Figure 63: Bell pepper number of fruits as influenced by irrigation water salinity level

Bell pepper average fruit weight as influenced by irrigation water salinity level

The average fruit weight of bell pepper was significantly ($p < 0.05$) influenced by water salinity level (Figure 64), where bell pepper plants irrigated with 0.55 dS/m, 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m produced average fruit weight 75.2 g, 74.6 g, 73.5 g and 73.1 g. In comparison with the control (0.55 dS/m), a reduction of 0.26%, 1.1%, 2.5% and 3.1% was observed in the average fruit weight of bell pepper when water salinity level was increased from 0.55 dS/m to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m (Figure 64). This is in tandem with the findings of Savvas et al (2000) who indicated that at an irrigation water salinity level of 8 dS/m fruit weight of bell pepper fruits was severely reduced. They explained that the detrimental effects of the high salinity of irrigation water on yield can be attributed to a restriction of water accumulation in the fruit due to reduced water transport to the fruit.

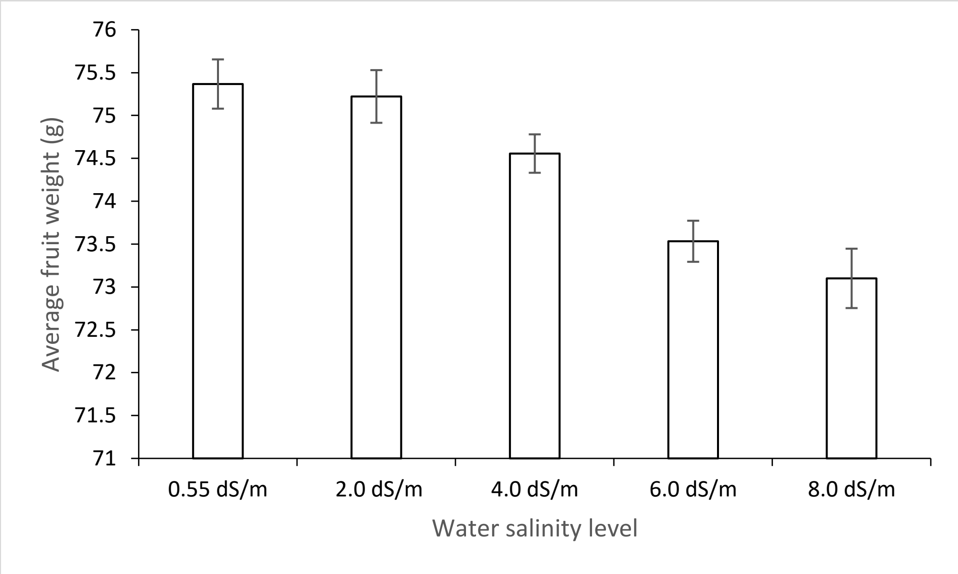

Figure 64: Bell pepper average fruit weight as influenced by irrigation water salinity level.

Bell pepper yield as influenced by irrigation water salinity level.

The yield of bell pepper was significantly ($p < 0.05$) influenced by water salinity level (Figure 65). The yield of bell pepper did show a significant difference among 0.55 dS/m (1.331 t/ha) 2.0 dS/m (1.327 t/ha), 4.0 dS/m (1.321 t/ha), 6.0 dS/m (1.315 t/ha) and 8.0 dS/m (1.313 t/ha) which resulted in a reduction of 4 t/h, 10t/h, 16/t/h and 18t/h (Figure 65). The detrimental effects of high irrigation water salinity levels on the yield of bell pepper could be attributed to the decrease in mean fruit weight even though the number of fruits per plant may not be affected (Adams, 1991, Cuartero & Fernandez-Munoz, 1999, Savvas & Lenz, 2000). Sonneveld & Welles (1988), Adams & Ho (1989) and Willumsen et al (1996) explained that the decrease in total yield due to high salinity levels is mainly due to a decrease in fresh weight fruit of bell pepper plants. Rubio, Garcia-Sanchez, Rubio, & Martinez (2008) further reiterated that the differences in the yield as a result of high salinity may be attributed to the water content of bell pepper fruits.

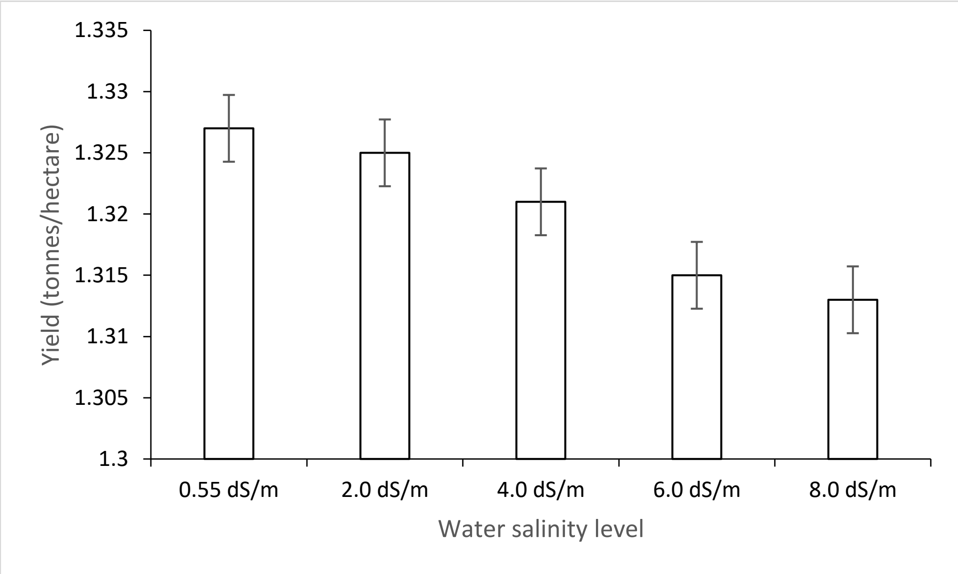

Figure 65: Bell pepper yield as influenced by irrigation water salinity level

Bell pepper water use efficiency as influenced by irrigation water salinity level

The effect of irrigation water salinity level on the water use efficiency of bell pepper is presented in Figure 66. At a significant level of 95% ($p < 0.05$) the highest water use efficiency of 1.871 kg/l was recorded in plants irrigated with 2.0 dS/m, this was followed by plants irrigated with 0.55 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m which exhibited a water use efficiency of 1.810 kg/l, 1.600 kg/l, 1.499 kg/l and 1.464 kg/l in that order. Results from the study are in line with the findings of Whitmore (2000) and Memon et al. (2010) who reported that irrigating with fresh water results in higher water productivity compared to irrigating with saline water. Within an SLECI system, the movement of water and solutes is not only limited to downward and sideways spreading but also includes an upward movement caused by capillarity and surface evaporation. This upward movement leads to the accumulation of salts at or near the soil surface (Keikha & Karandish 2015). Hussain et al. (1997), Mer et al. (2000), and Roberts et al. (2009) have demonstrated that the accumulation of salts has detrimental effects on crops.

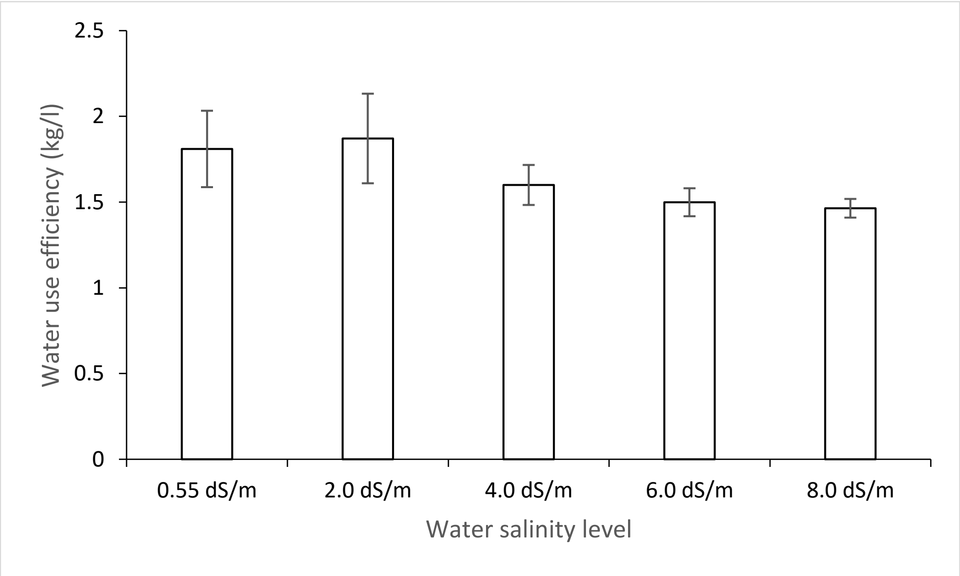

Figure 66: Bell pepper water use efficiency as influenced by irrigation water salinity level

Bell pepper BER incidence as influenced by irrigation water salinity level.

The effect of irrigation water salinity level on the incidence of the blossom end of bell pepper fruits is presented in (Figure 67). Analysis of data indicates there was no significant difference in the incidence of blossom end rot of bell pepper fruit irrigated with 0.55 dS/m (0.389%), 2.0 dS/m (0.556%) and 4.0 dS/m

(0.878%) however they were significantly lower than bell pepper plants irrigated with 6.0 dS/m and 8.0 dS/m which exhibited a blossom end rot incidence of 1.58 % and 2.03% (Figure 67). In comparison with the control (0.55 dS/m), an increase in water salinity level was from 0.55 dS/m to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m resulting in a 1.4, 2.3, 4.1, 5.2-fold increase of the incidence of blossom end rot of bell pepper fruits (Figure 67). Results are in tandem with the findings of (Ehret & Ho, 1986; Adams & Ho, 1992; Adams & Holder, 1992) who reported that irrigating with saline water heightens the incidence of BER in Solanaceae fruits. Sonneveld, (1979) and Rubio et al. (2010) reported an increase in the incidence of BER in pepper when irrigation salinity level increased above 1.0 dS/m. Bar-Tal et al. (2003) and Aktas et al. (2005) reported that irrigation with saline solution caused a substantial increase in the percentage of BER-affected fruits. The increase in the occurrence of blossom end rot-affected fruits under irrigation with saline water has been related to reduced calcium uptake and transport into the fruits

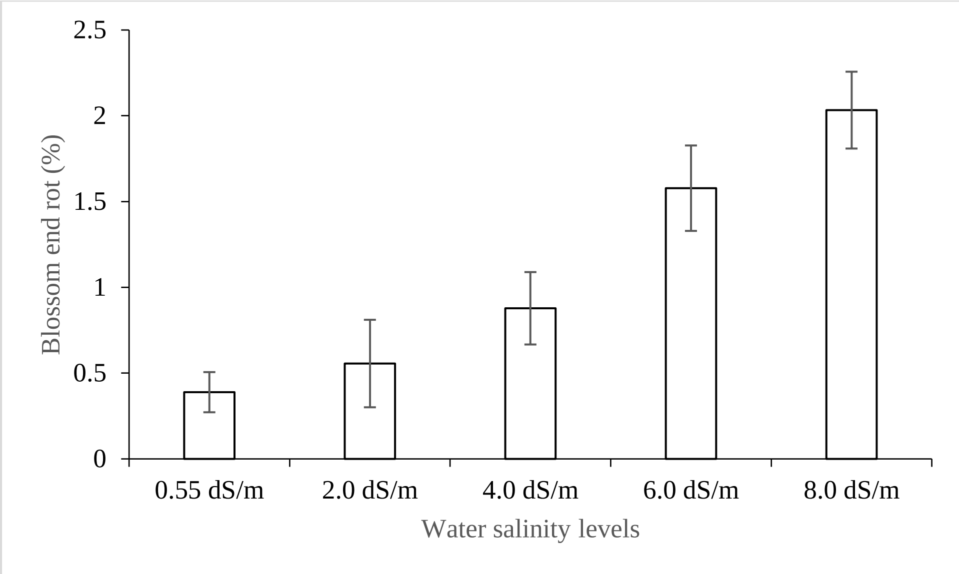

Figure 67: Bell pepper BER incidence as influenced by irrigation water salinity level.

Effect of irrigation water salinity level on salt distribution in the soil

The effect of irrigation water salinity level on soil wetting pattern is presented in Figure 68. It can be observed that soil salinity levels increased time as the experiment progressed, whereby soil salinity levels at 12 weeks were higher than at 8 weeks and 4 weeks, while at 8 weeks, soil salinity levels were higher compared to soil salinity levels at 4 weeks. As the water is taken up by plants through transpiration or lost to the atmosphere by evaporation, soil water salinity increases because salts become more concentrated in the remaining soil water. Thus, evapotranspiration (ET) through the atmosphere and plants during irrigation intervals increases soil salinity (Bauder & Brock 2001). Results from Figure 68 indicate that even high saline irrigation water was used for irrigation, however, the SLECI system was able to keep soil saline levels below the maximum threshold of 2 ds/m as indicated by Kurunc et al. (2011), additionally, they indicated that that bell pepper is moderately sensitive to salinity levels of

1.2 – 1.8 ds/m. Results from Figure 68 also indicate that salinity differences between depths of 5cm, 10cm, 15cm and 20cm increased with time, this could be attributed to the absorption of water and nutrients within the effective root zone which resulted in the accumulation of salt.

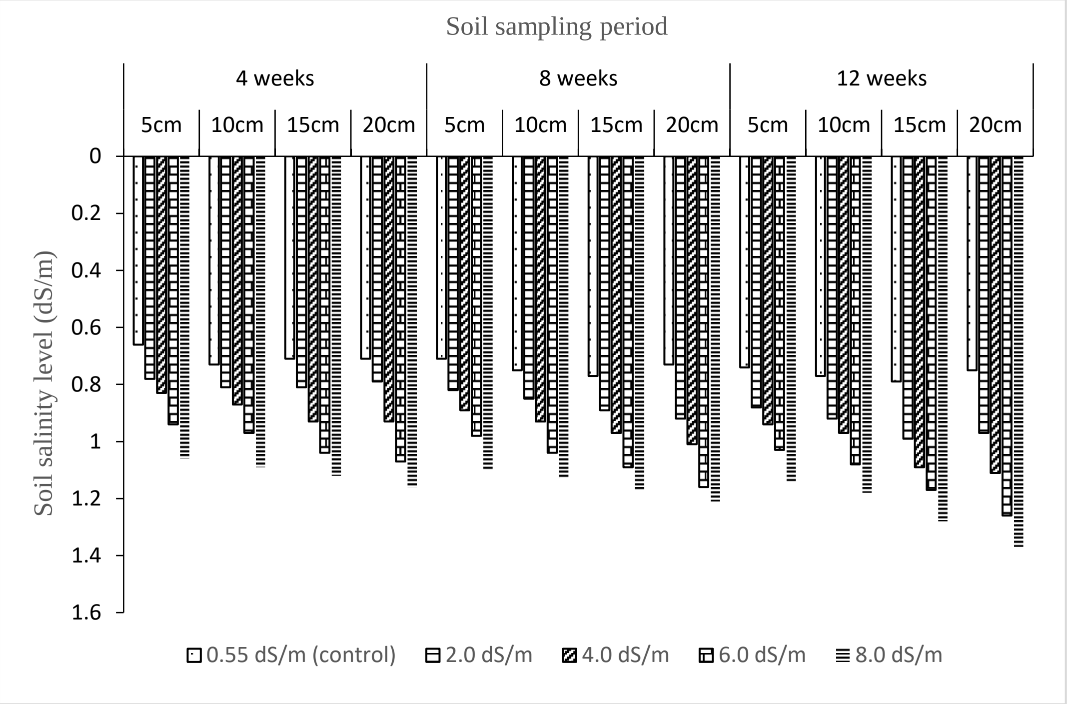

Figure 68: Effect of irrigation water salinity level on salt distribution in the soil

Effect of irrigation water salinity level on moisture distribution

The effect of irrigation water salinity level on moisture distribution is presented (Figure 69). Results in Figure 69 portray that more water seeped from the clay tubes when fresh water that is the control was used for irrigation compared to irrigation water with salinity levels of 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m. Thus, the size of the wetting front in the soil decreased with the increased salt concentration of irrigation water. This agrees with earlier findings of Naik et al. (2008) who also reported a decrease in wetting front advancement with an increase in the salinity level of water used in pitcher irrigation. The less seepage of water from clay tubes containing saline water might be due to blockage of some of the water-conducting microspores of the clay tube due to partial retaining of salt in the saline water. This was further substantiated by earlier results reported by Vasudaven et al. (2011) who found a 14% reduction in water seepage from the pitcher irrigation system due to the use of saline water. Data also indicate that there were distinct differences in moisture distribution at 12 weeks, compared to 4 weeks and 8 weeks, this could be attributed to the crop water requirement of bell pepper, as the plants grow the potential of roots to exert more energy to absorb water increases thus the increase in soil moisture, especially at a soil depth of between 10cm and 15cm.

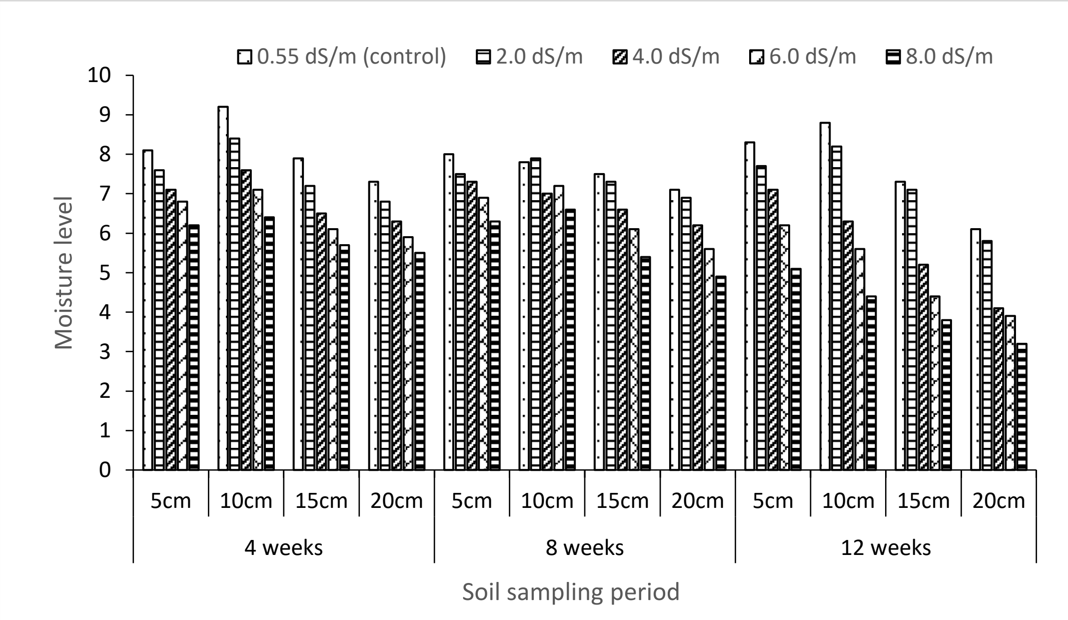

Figure 69: Effect of irrigation water salinity level on moisture distribution

Conclusion

The results of irrigating bell pepper with saline water using the SLECI system showed that with the SLECI system, irrigation water savings of 11.33% were achieved compared to the reference evapotranspiration of bell pepper. Under saline water levels of 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m, 4.2%, 10.6%, 16.6% and 23% less water seeped from the clay tube compared to irrigation with fresh water (control). Compared to the control (0.55 dS/m) increasing water salinity levels to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m decreased plant height of bell pepper by 0%, 3.8%, 5.4% and 6%, decreased leaf area of bell pepper by 1%, 1.4%, 2% and 2.4% and decreased stem girth of bell pepper by 0.3%, 1.6%, 4% and 8.8%. Increasing water salinity level from 0.55 dS/m to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m decreased the number of fruits by 4.6%, 6.9%, 10% and 13.1% and the average fruit weight by 0.26%, 1.1%, 2.5% and 3.1%. the overall yield of bell pepper did not show a significant difference even though a reduction of 4 t/h, 10t/h, 16/t/h and 18t/h of yield was recorded. Even though bell pepper plants were subjected to irrigation water salinity stress the highest water use efficiency of 1.871 kg/l was recorded in plants irrigated with 2.0 dS/m, this was followed by plants irrigated with 0.55 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m which exhibited a water use efficiency of 1.810 kg/l, 1.600 kg/l, 1.499 kg/l and 1.464 kg/l in that order. An increase in water salinity level from 0.55 dS/m to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m resulted in a 1.4, 2.3, 4.1, 5.2-fold increase of the incidence of blossom end rot of bell pepper fruits. Salinity differences between depths of 5cm, 10cm, 15cm and 20cm increased with time and increasing level of irrigation water salinity level.

Salt accumulation during irrigation is a particular concern in arid regions where annual potential evapotranspiration is much higher than precipitation. Thus, the adoption of the SLECI system will utilize poor-quality water when fresh water is scarce since it can prevent salt accumulation and the resulting harmful effects on the growth and yield of crops.

CHAPTER SEVEN

SIMULATION OF WATER AND SALT DYNAMICS IN A SELF-REGULATING LOW ENERGY CLAY-BASED IRRIGATION SYSTEM

Introduction

Agriculture facses numerous challenges in food production to ensure the provision of enough food for a growing population by 2050 (FAO, 2022). Food security, as well as water and energy security, are vital for establishing a sustainable long-term economy (Alvino & Ferreira, 2021). The agriculture sector consumes a significant amount of water, with irrigation alone accounting for approximately 70% of freshwater usage (Chen et al., 2021). As one of the primary consumers of water resources, agriculture must strive for greater efficiency, especially in arid and semiarid climates (Ahmad et al., 2022). It is crucial to prioritize the optimization of agricultural practices to enhance both food security and resource management. The physiological well-being of plants is greatly affected by water stress, particularly in terms of their photosynthetic capacity. Extended periods of water stress significantly hinder plant growth and productivity (Osakabe, Osakabe, Shinozaki & Tran 2014; Parkash & Singh 2020). The presence of irrigation-induced salinity can lead to an increase in the water requirement of plants. This is because it reduces the ability of roots to penetrate the soil, resulting in a higher water demand. In regions where there are no alternative sources of water for irrigation, this can cause excessive groundwater exploitation. Conversely, in areas where surface water is used for irrigation and the water table is shallow, waterlogging issues are often observed (Shahid, Zaman, & Heng, 2018; Minhas, Qadir, & Yadav 2019). Soil salinization, along with the changing climatic scenarios, has emerged as a significant global issue. A considerable portion of cultivable land (around 20 percent) and irrigated land (about 33 percent) is impacted by the problem of soil salinity. This, in turn, results in a substantial decline in crop yield and quality (Qadir et al 2014; Chourasia et al 2021). The adverse effects of soil salinization on agricultural productivity are particularly severe in areas with high reliance on irrigation systems. In addition to its impact on the productivity and yield of irrigated land, salinity has wide-ranging implications for socio-economic growth and food security. These implications include reduced profit margins, increased poverty, higher fertilizer requirements, and the unlikelihood of land reclamation (Thimmappa, Sharma, Dagar, & Raju 2016; Machado & Serralheiro 2017). For optimal food production in the face of challenges affecting crop yield, an irrigation system that promotes the development of plants with enhanced survivability and growth during water and salinity stress is essential. Currently, there is limited information available on moisture flow and salinity levels under clay tube conditions, specifically regarding the rate of flow in the pitcher as influenced by different levels of irrigation water salinity.

Simulation plays a crucial role in Agriculture by mimicking the operation of an existing or proposed system. It provides valuable evidence for decision-making, allowing us to test different scenarios or process changes. Simulations are highly effective in tuning up performance and optimizing processes in the field of Agriculture. MATLAB Simulink model was used to simulate moisture levels in different soils (clay, loam and sandy). Salinity and moisture levels at different depths of 5cm, 10cm, 15cm and 20cm under different irrigation water salinity levels were also investigated.

Materials & Methods

Study area

The experiment was carried out at the Research field of CSIR Institute of Industrial Research.

Laboratory experiment

The laboratory experimental set-up consisted of a SLECI system (water tank - 20 litres, valve, filter, clay tube, connectors, coupling, PE- tubes, and an end cap). 27 rectangular plastic pots (dimensions of 25 cm in length, 25 cm in width and a height of 30 cm) were filled with gravel to a height of 4cm after which clay, loamy and sandy soil was filled equally to the 30 cm mark. Thus clay, loamy and sandy soil were placed in 9 separate plastic pots. The water storage tank was mounted at a height of 50 cm, and the filter together with the valve was connected to the water storage tank. The PE – hose on which the core of the clay tube was mounted was then connected to the valve. The irrigation system was then operated.

Table 11: Key soil moisture parameters and variables

Parameter	Description	Significance
Water Content	Amount of water in soil volume	Primary measure of moisture
Water Potential	Energy state of soil water	Determines water movement
Field Capacity	Water retained after drainage	Upper limit of available water

Factors considered for soil moisture and salinity simulation

Irrigation Variables (Flow rate of irrigation system, irrigation duration and irrigation frequency).

Soil Characteristics (Texture and structure, hydraulic conductivity and water retention capacity).

Landscape Features (Topography, vegetation cover and drainable porosity).

Data for calibration and coding

To collect the required data for model calibration and validation, bell pepper was cultivated on an experimental field laid out in a Randomized Complete Block Design with three replications. Treatments T1, T2, T3, T4 and T5 correspond to the control, 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m. Each treatment was replicated three times, which resulted in a total of 15 experimental plots (units) with dimensions of 2 x 3 m. With a planting distance of 0.5 x 0.5 m, each experimental plot had a plant population of 24 (experimental plot area of 6m^2 divided by plant area of 0.5*0.5 = 0.25m^2) which corresponds to 40,008 plants per hectare (Extrapolation of number of plants per plot area of 6m^2 to land area on a hectare basis 10,000m^2). The saline water of the required EC was prepared artificially by mixing the Sodium Chloride (NaCl) salt in fresh water. Different salinity levels for each treatment were prepared by mixing calculated amounts of Sodium chloride (NaCl) salts to achieve desired salinity concentrations.

The irrigation system consisted of a water tank (100 litres), valve, filter, clay tube, connectors, coupling, PE- tubes, and an end cap. In each plot, clay pipes are joined together or laid end to end to form long tubes of a desired length of 2m, an end cap is fixed at the end of the PE tube after the desired length is achieved. The clay pipes were buried at a depth of 5cm. The water tank was filled with fresh and saline water according to the experimental treatments. Irrigation scheduling was auto-regulated since the flow rate or movement of water from the clay tube into the effective root zone of the crops depends on a water-deficient gradient in the soil. The total applied irrigation water was dependent on the treatment (Irrigation water salinity level).

Model selection

The Bucket Model treats the root zone as a single unit, where volume-balance equations are used to monitor water movement. The model considers infiltration rate, leakage rate, and transpiration as key components.

Setting Up the Simulink Environment

Adopted MATLAB toolboxes

Toolbox	Purpose	Key Components
Simscape Fluids	Fluid dynamics	Pumps, valves, pipes
Signal Processing	Data analysis	Filtering, visualisation
System Identification	Model validation	Parameter estimation

Model configuration and initialization

The model configuration process involves several critical steps:

Step 1: Solver Selection: Configure the solver to 'Variable Step Auto' for optimal performance.

Step 2: Initial Conditions: Following parameters were then set up (Initial pressure values, temperature conditions and domain-specific variables)

Step 3: The isothermal liquid domain configuration (initial pressure specifications).

The foundation of the model relies on implementing the volume-balance equation that tracks moisture movement through the root zone:

$$dS/dt = P(t) - E(t) - L(t) - R(t)$$

Where:

S represents soil moisture storage,

P(t) is irrigation,

E(t) is evaporation,

L(t) represents leakage,

R(t) is runoff.

These individual components are implemented using integrator blocks connected through sum blocks.

Implementing soil layer interactions

Soil layer interactions require modelling vertical moisture movement between layers. The model uses Richards' equation for detailed spatial representation:

Layer Parameter	Implementation Block	Function
Hydraulic Conductivity	Gain Block	Controls water flow rate
Water Retention	Look-up Table	Defines moisture characteristics
Layer Interface	Transfer Function	Manages inter-layer exchange

These parameters were interconnected through Simulink's signal routing system, enabling dynamic moisture exchange between soil layers.

Adding environmental factor calculations

Environmental influences significantly impact soil moisture dynamics. The model incorporates these factors through:

a. Temperature effects using thermal conductivity blocks
b. Irrigation patterns via signal generators
c. Evapotranspiration through custom function blocks

The environmental calculations are integrated using Simulink's Moist Air Domain blocks, which handle the complex interactions between soil moisture and atmospheric conditions. These blocks automatically compute relative humidity and vapour pressure.

Data structure preparation

The data structure included both input and output parameters. Tabulated data included Soil moisture retention curves, hydraulic conductivity values and environmental factor correlations. The model's data structure accommodated both simulation and deployment modes. In simulation mode, Simulink source blocks was utilized to emulate soil moisture sensor inputs and environmental conditions. For deployment, the model was configured to accept real-time sensor data through input blocks. Simulink Editor was used to establish signal routing between various components, thus ensuring accurate mathematical relationships between soil moisture parameters and environmental variables.

Simulation

An .m file MATLAB R2021 software was created with the purpose of the model being indicated. The type of visual representation was then selected. Two files were then created, a training file and a text file. The training file was used to train the model to train and assess the model that has been created. Inputs (data from laboratory and field experiments) are then uploaded via the text file. The text file was then used to assess the performance of the training file. A simulation of the various experiments was run after which statistical inferences were then conducted to assess the validity of the software and simulations.

Data collection

Determination of the salt dynamics in the soil

The soil was sampled at depths of 5cm, 10cm, 15cm and 20cm from the wetted zone around the clay tubes. Soil salinity was determined using a conductivity meter used to determine the electrical conductivity (EC) using a ratio of 1:5 distilled water: soil dilution.

Determination of moisture dynamics in the soil

The moisture distribution in the soil around the clay tube was determined using a HOLDAll 3 in1 soil meter, model 60182L, to determine the moisture content, the switch is pushed to the moist position on the instrument. The probe of the instrument was inserted to the desired depth of 5cm, 10cm, 15cm and 20cm. The probe was allowed to sit for 5 seconds and readings were recorded.

Determination of moisture distribution in the soil in plastic pots

The moisture level in the soil around the clay tube was determined using a HOLDAll 3-in-1 soil meter, model 60182L. The probe of the instrument was inserted 5cm from the clay tube and at a depth of 10cm. Data was recorded 60, 120 and 180 minutes after operation of the irrigation system.

Data analysis

Statistical analysis (Analyses of variance, ANOVA) of various recorded data from field Correlation and regression analysis between measured traits was performed using the built-in function of prcomp and lm from the built-in-R stats package (Team, 2014). The results were visualized using the factorextra package (Kassambara, 2017), FactoMineR and ggbiplot2 (Vincent, 2011).

Results and Discussion

Effect of irrigation water salinity level on salt distribution in the soil

Figure 73 presents a series of three-line graphs, each representing salt accumulation concerning depth but at different time intervals of 4 weeks, 8 weeks, and 12 weeks. In each graph, the horizontal axis signifies the depth and spans from approximately 5cm to 20cm. The vertical axis denotes salt accumulation with values ranging slightly differently for each graph but roughly from around 0.6 ds/m to 1.4 ds/m. At 4 weeks (Figure 73), the lines are quite parallel to each other, indicating a steady difference in salt accumulation across the given depths for various salinity levels. There are multiple lines, each representing a different salinity level specified in ds/m. The values provided are 0.55 ds/m, 2.0 ds/m, 4.0 ds/m, 6.0 ds/m, and 8.0 ds/m. Each line is differentiated by colour, making it easier to distinguish between the varying salinity levels. At 8 weeks, the layout and trend of the lines appear similar to the 4-week graph. The salt accumulation lines for various salinity levels run parallel, covering a similar range on the vertical axis. The salinity levels, as indicated by the legend, remain consistent with 4 weeks salinity levels. At 12 weeks, the overall trend remains steady with lines for different salinity levels maintaining their parallel course. The range on the vertical axis is slightly different but remains close to that of 4 weeks and 8 weeks in the previous graphs. At 4, 8 and 12 weeks, (Figure 73) soil salinity content as influenced by irrigation water salinity levels remains relatively straight, indicating that salt accumulation is consistent across the depth for each specified salinity level. Analysis of data (Figure **74**) revealed a R^2 value of 0.99617 at 4 weeks, 0.99413 at 8 weeks and 0.99215 at 12 weeks indicating the model was able to predict over 90% of the measured data. Results are in line with earlier findings of Usman, Yakubu and Tekwa (2011) where the model developed in their study was proved to be capable of predicting water movement based on data about the pitcher, soil properties, as well as the time of water infiltration. This was further substantiated by Mguidiche, Provenzano, Douh, Khila, Rallo and Boujlbene, (2015) where results indicated that, simulated and measured soil water content in the root zone were fairly close when a model was tested to predict the salt distribution around a buried emitter when two different water qualities with electrical conductivity of 1.0 dS m^{-1} and 4.0 dS m^{-1}), was used during the growing season. The presence of high salinity levels in irrigation water can also lead to an increase in soil salinity. As the water evaporates, the salts are left behind, gradually accumulating in the soil. This accumulation can have detrimental effects on the soil structure and fertility, posing challenges to agricultural productivity.

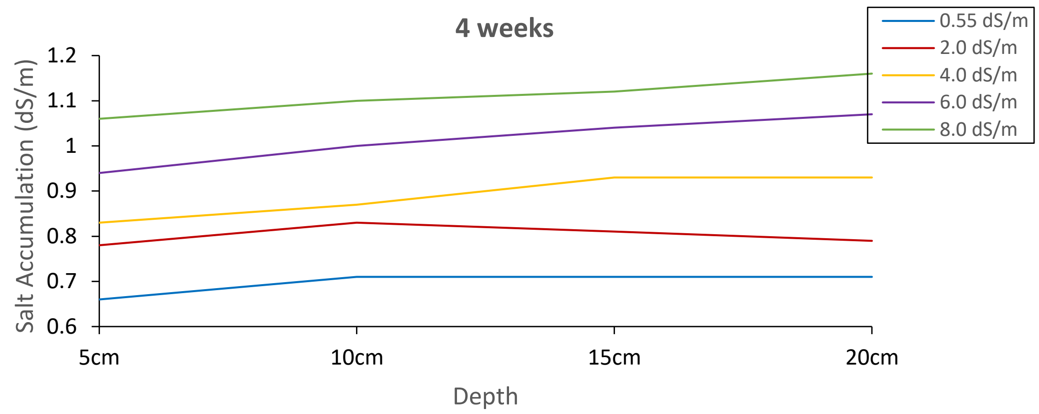

Figure 70: Measured salinity levels at different depths at 4 weeks

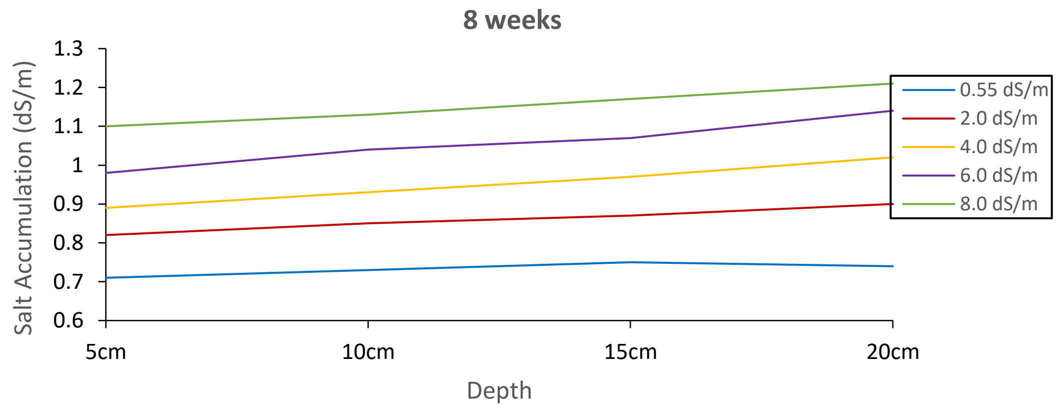

Figure 71: Measured salinity levels at different depths at 8 weeks

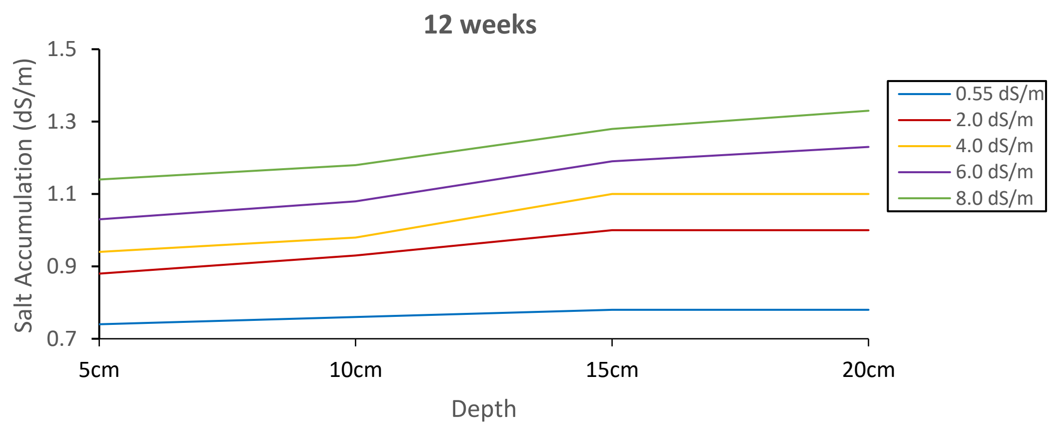

Figure 72: Measured salinity levels at different depths at 12 weeks

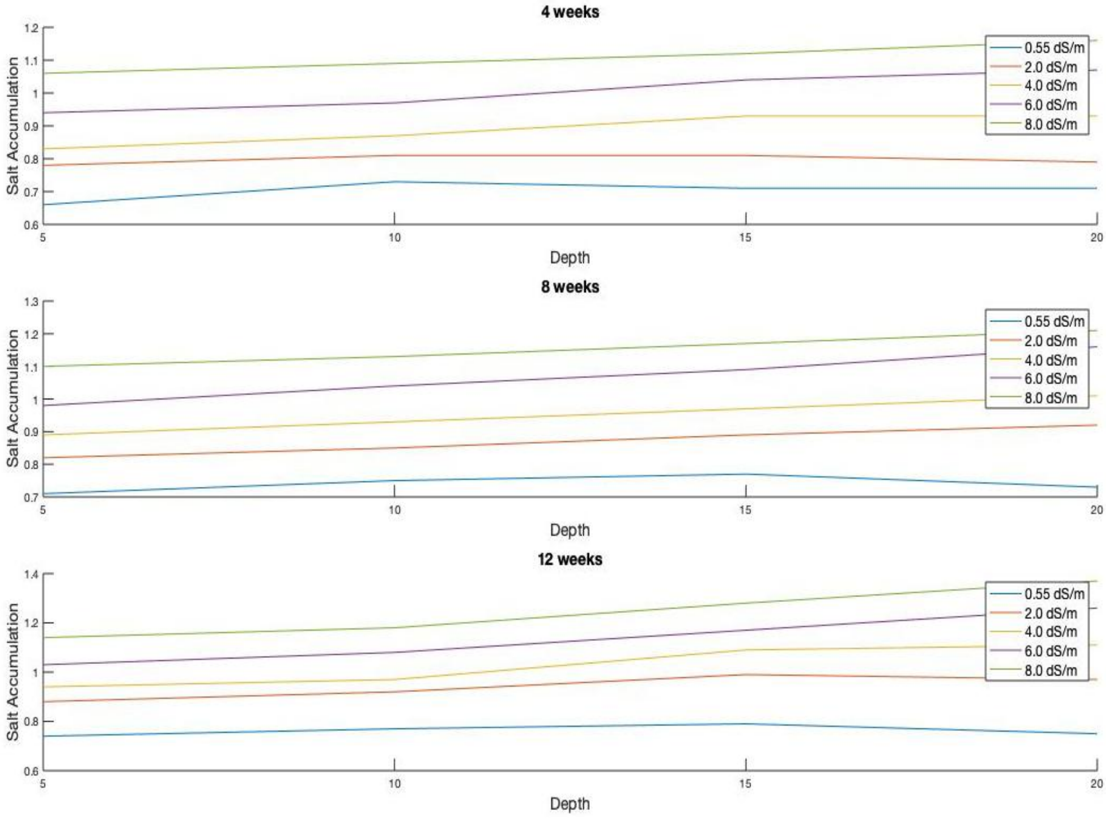

Figure 73: Simulated salinity levels at different depths 4, 8 and 12 weeks as influenced by irrigation water salinity level

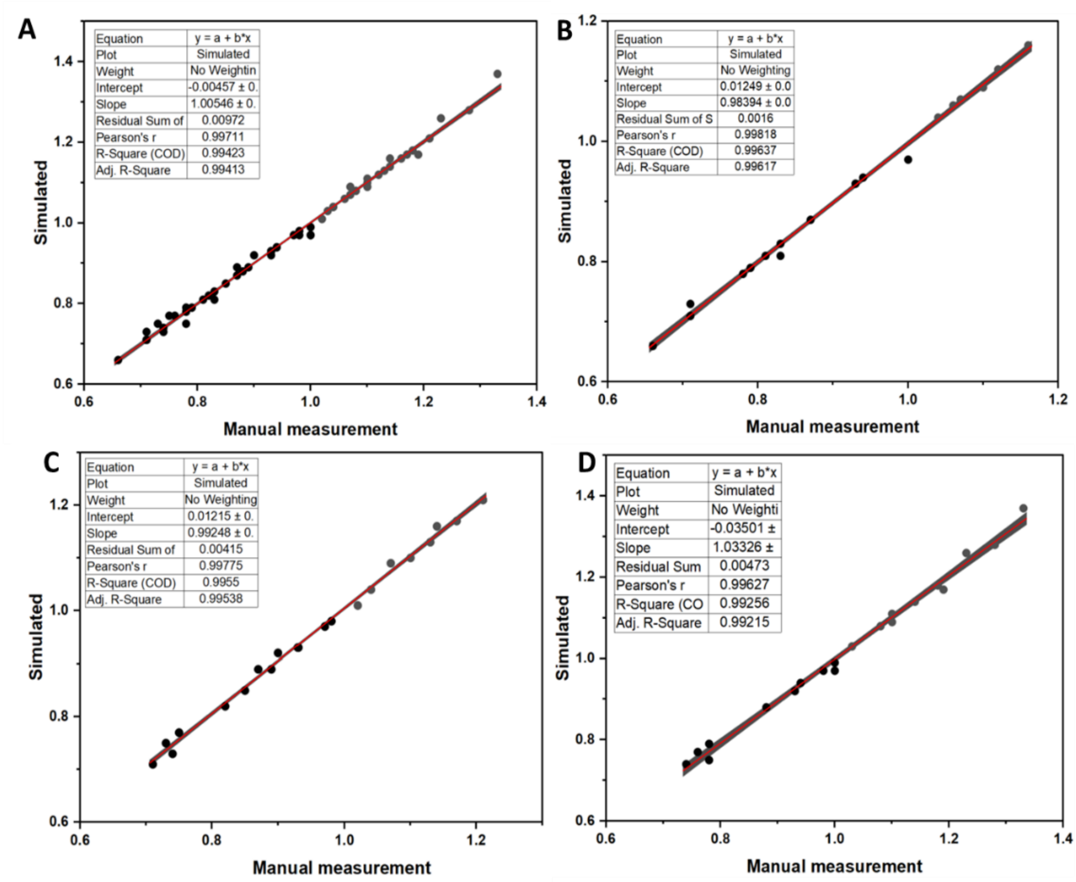

Figure 74: Regression analysis indicating degree of similarity between measured and simulated soil salinity at A: combined weeks, B: 4 weeks, C: 8 weeks and 12 weeks after irrigating with irrigation water of varying salinity levels.

Effect of irrigation water salinity level on water distribution in the soil

Figure 78 displays a set of three-line graphs, each showcasing the relationship between soil moisture and depth at different time intervals: 4 weeks, 8 weeks, and 12 weeks as influenced by irrigation water salinity levels. The horizontal axis represents depth, extending approximately from 5cm to 20cm. The vertical axis indicates soil moisture, with values stretching from about 5 to 10. There are several lines, each differentiated by colour, signifying different salinity levels measured in ds/m: 0.55 ds/m, 2.0 ds/m, 4.0 ds/m, 6.0 ds/m, and 8.0 ds/m. At 4 weeks, the lines in this graph depict a slight increase in soil moisture with increasing depth, and each line for a different salinity level seems to have a similar trend but at varying moisture levels. At 8 weeks, the representation of depth on its horizontal axis, while its vertical axis, labelled soil moisture, has values ranging from approximately 5.5 to 8. The lines in this graph follow a trajectory slightly more curved than the previous one, with the increase in soil moisture being more pronounced as the depth increases. Each line represents a distinct salinity level, and they are distinguishable by their unique colours. At 12 weeks, the horizontal axis depicts depth and its vertical axis, titled soil moisture, displays values from around 3 to 9. The trend in this graph appears similar to the 8-week graph, with lines showing a more prominent increase in soil moisture with depth. The lines representing different salinity levels remain consistent with those in the previous graphs, and their colours help distinguish them. At 4, 8 and 12 weeks, the lines consistently show that as depth increases, so does soil moisture. The exact difference in moisture levels for each salinity level and the precise nuances in line curvature can be inferred from the visual representation (Figure 78). Analysis of data (Figure **79**) revealed a R^2 value of 0.97304 at 4 weeks, 0.81200 at 8 weeks and 0.98914 at 12 weeks indicating the model was able to predict over 80% of the measured data. Findings are in tandem with earlier results from Siyal and Skaggs (2009) indicating that predictions of the soil water content from simulations were found to be in good agreement with the experimentally observed data. This was corroborated by the findings of Selim, Bouksila, Berndtsson and Persson (2012) who indicated that simulation results demonstrated that model prediction for soil moisture distribution within the flow domain was excellent. When irrigation water with high salinity is used, it can lead to a decrease in soil moisture content. This occurs because the high salt concentration in the water creates a gradient that prevents the soil from effectively absorbing moisture, ultimately affecting the plants' growth and health.

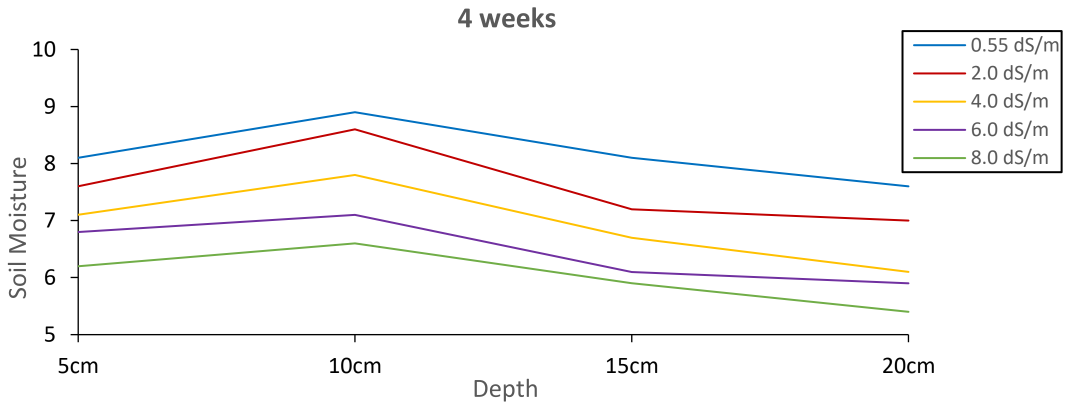

Figure 75: Measured soil moisture at different depths at 4 weeks

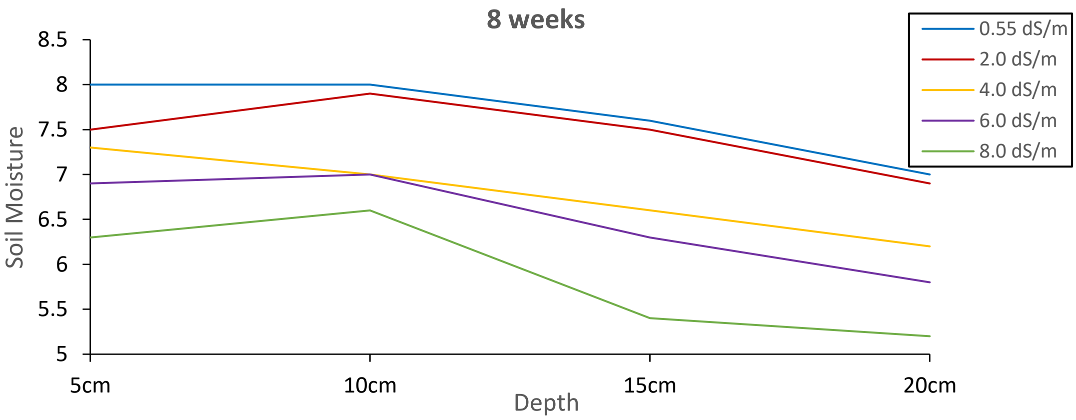

Figure 76: Measured salinity levels at different depths at 8 weeks

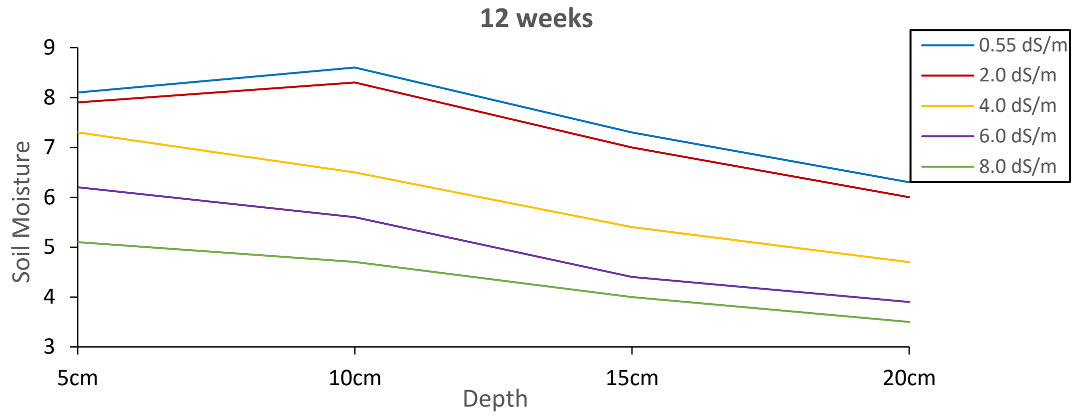

Figure 77: Measured salinity levels at different depths at 12 weeks

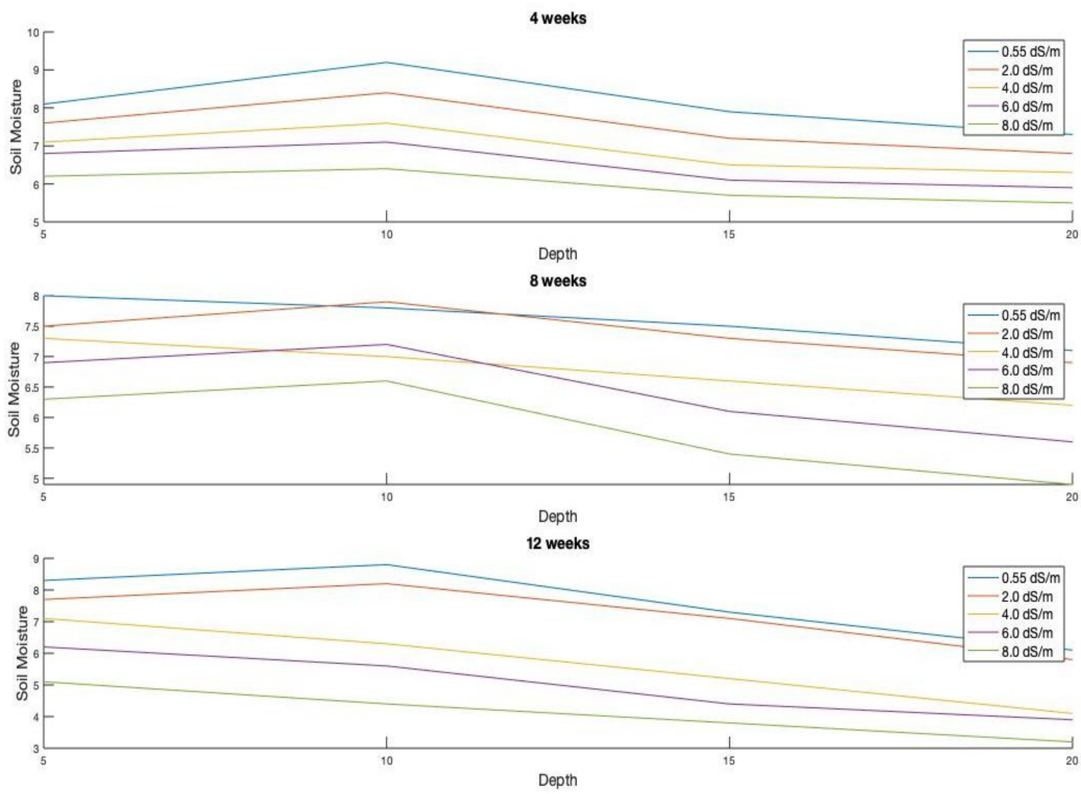

Figure 78: Simulated soil moisture levels at different depths 4, 8 and 12 weeks as influenced by irrigation water salinity level

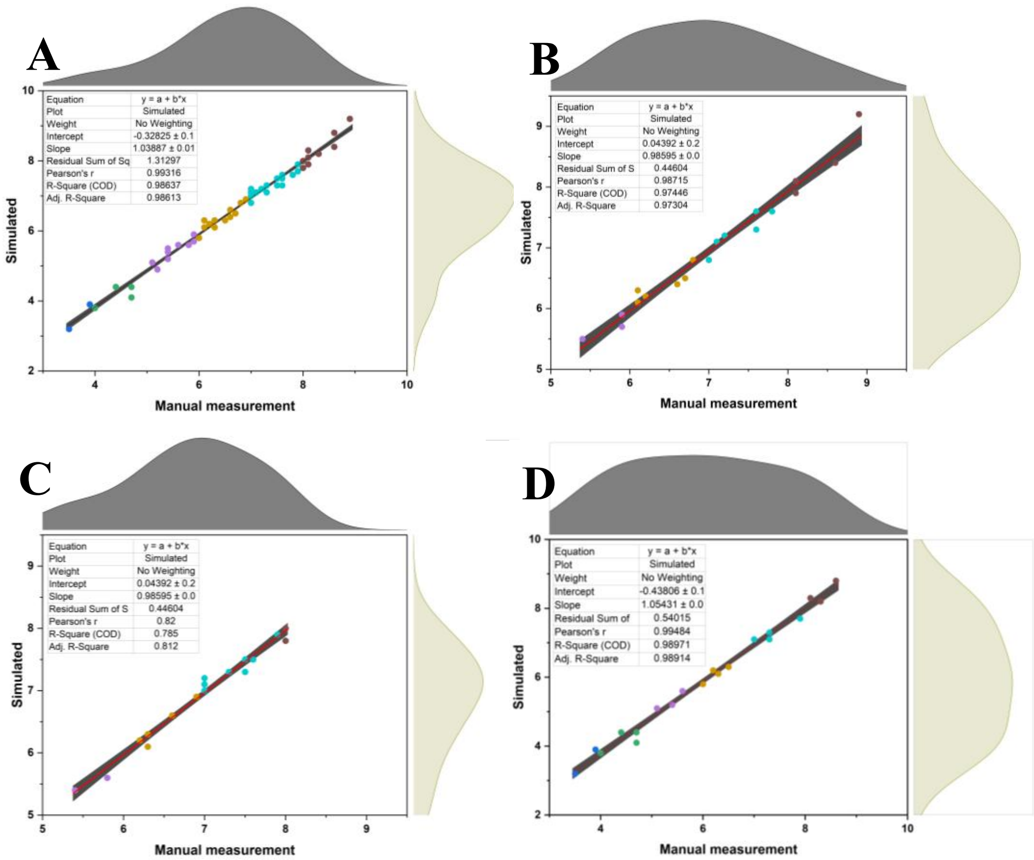

Figure 79: Regression analysis indicating degree of similarity between measured and simulated soil moisture at A: combined weeks, B: 4 weeks, C: 8 weeks and 12 weeks after irrigating with irrigation water of varying salinity levels.

Effect of soil type on water distribution in the soil

Figure 83 presents a series of three-line graphs that represent the relationship between water movement and depth over three different durations: 60 minutes, 120 minutes, and 180 minutes. In the 60-minute graph, the horizontal axis denotes depth, spanning from a starting point of around 5cm and extending to approximately 20cm. The vertical axis represents water levels, with values ranging from about 5 to 10. Three distinct lines in this graph correspond to different soil types: Clay (depicted in a blue colour), Sand (shown in a yellow colour), and Loam (portrayed in a brownish hue). The lines indicate that, with increasing depth, water movement decreases. Of the three soil types, Clay has the least decline in water movement with depth, Sand shows a steeper descent, and Loam sits between the two. At 120 minutes, the horizontal axis represents the depth and the vertical axis denotes the water level with values again stretching from approximately 5 to 10. The lines for Clay, Sand, and Loam in this graph also depict a decline in water movement with depth, although the variations between the soil types are more pronounced. Sand showcases the most rapid decline, followed by Loam, and then Clay, which remains relatively consistent. At 180 minutes all three soil types demonstrate a decline in water movement as depth increases. Sandy soil exhibited the most substantial decline, Loamy soil exhibited an intermediate rate, and Clayey soil had the most gradual decrease. Overall, data available in (Figure 83) suggest that over increasing durations, the water movement tends to decrease with depth across all soil types, with Sand being the most affected, followed by Loam, and Clay being the least impacted. Analysis of data Figure 84 revealed a R^2 value of 0.9674 after 60 minutes, 0.94407 after 120 minutes and 0.93355 after 180 minutes indicating the model was able to predict 90% of the measured data. Abu-Zreig and Atoum (2004) developed a model and validated it with measured data in which the predicted seepage rate correlated very well with experimental data. This was further substantiated by later findings of Provenzano (2007) who showed the suitability of a model to adequately simulate infiltration processes around an emitter in sandy-loam soil. The moisture levels in soils are significantly influenced by the type of soil, such as clay, sand, and loam. Each soil type has distinct characteristics that affect soil moisture. Clay soil has fine particles that tightly pack together, creating a dense structure that retains water. Consequently, clay soil tends to hold onto moisture for extended periods, making it more prone to waterlogging and less suitable for drainage. On the other hand, sand soil has larger particles with substantial spaces between them, resulting in rapid drainage and poor water retention. As a result, sandy soils often experience low soil moisture levels, making it challenging to sustain plant growth, especially during dry periods. Additionally, the fast-draining nature of sandy soils can lead to leaching of nutrients essential for plant health. Loam soil, a combination of sand, silt, and clay, offers a balanced soil structure that promotes optimal soil moisture levels. Its composition allows for adequate drainage while retaining sufficient moisture for plant growth. This makes loam soil highly desirable for agricultural purposes as it provides an ideal environment for root development and nutrient uptake. Saleh & Setiawan (2010) indicated that the infiltration rates decreased linearly rather than exponentially even though the soil may be dry initially.

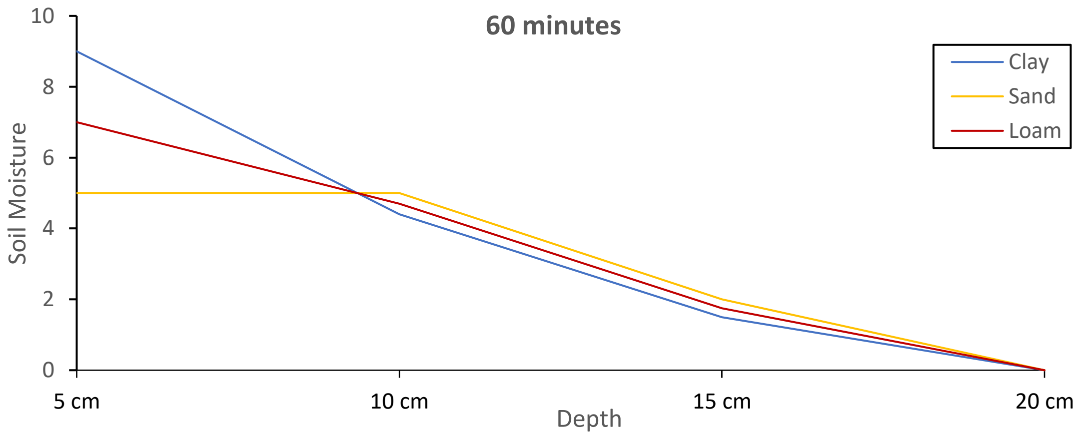

Figure 80: Measured soil moisture levels in different soil after 60 minutes

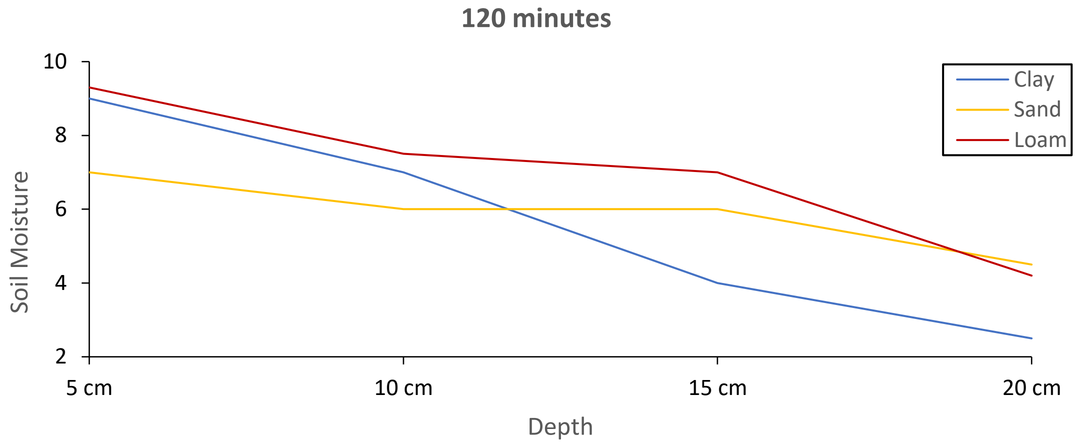

Figure 81: Measured soil moisture levels in different soil after 120 minutes

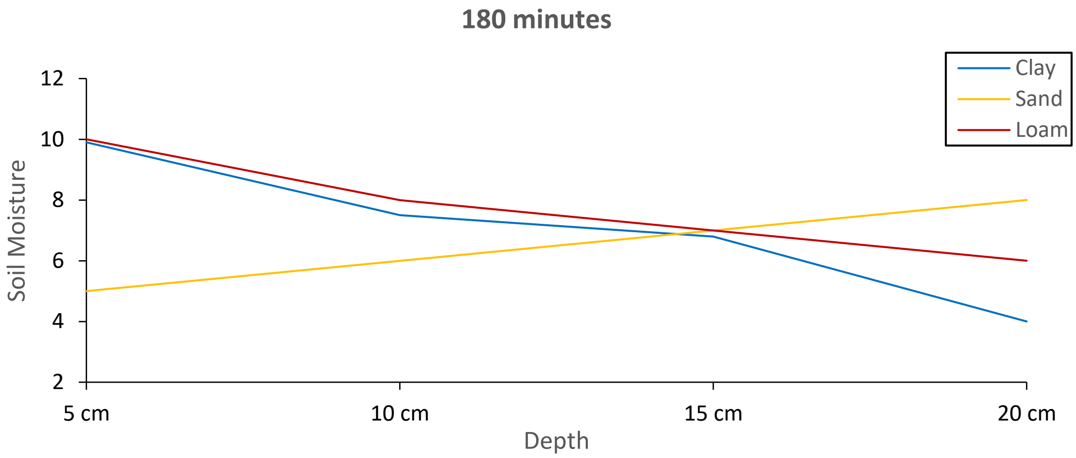

Figure 82: Measured soil moisture levels in different soil after 180 minutes

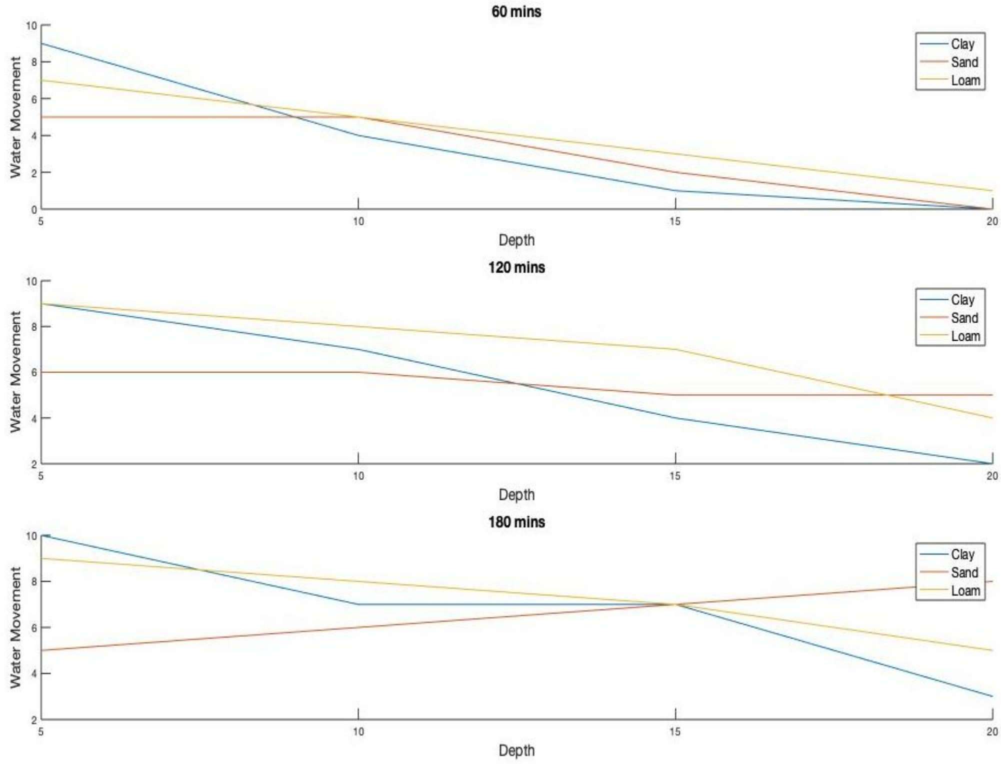

Figure 83: Simulated water moisture levels across different soil types at 60, 120 and 180 minutes

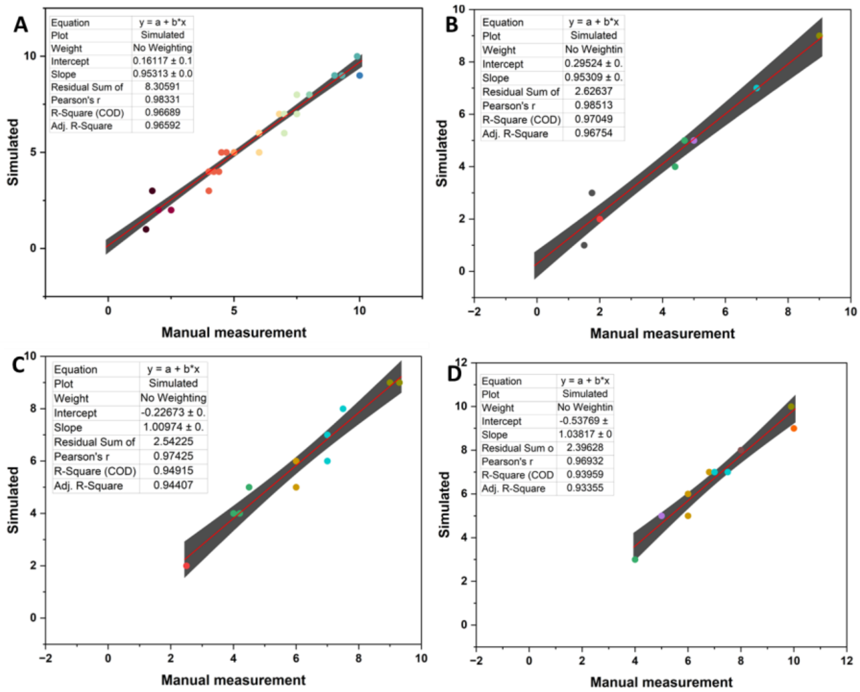

Figure 84: Regression analysis indicating degree of similarity between measured and simulated soil moisture at A: combined minutes, B: 60 minutes, C: 120 minutes and 180 minutes in different soil types

Conclusion

MATLAB was validated to evaluate the moisture and salinity levels as influenced by soil type and different irrigation water salinity levels. This validation was done by comparing the simulation results with experimental observations. Data analysis revealed a degree of similarity (R^2) of 0.99413, 0.98613 and 0.96689 between experimental and simulated results for the effect of irrigation salinity level on soil salinity level, irrigation salinity level on soil moisture level and the effect of soil type on soil moisture. A laboratory experiment was carried out to determine moisture levels in different soils at specific periods after irrigating whereas a field experiment was undertaken to assess moisture and salinity levels at different soil depths after irrigating bell pepper plants with different irrigation water of different salinity levels. Understanding the impact of different soil types on soil moisture levels is crucial for effective land management and agricultural practices. By recognizing the characteristics of clay, sand, and loam soils, farmers and land managers can implement appropriate irrigation and drainage strategies to optimize soil moisture levels for healthy plant growth and sustainable land use. Irrigation water salinity has a significant impact on both soil moisture and soil salinity levels. Salinity differences between depths of 5cm, 10cm, 15cm and 20cm increased with time and increasing level of irrigation water salinity level. Understanding the relationship between irrigation water salinity, soil moisture content, and soil salinity levels is crucial for effective agricultural practices. There is a continuous exploration of innovative techniques to mitigate the impact of high salinity levels in irrigation water, such as the adoption of SLECI systems.

CHAPTER EIGHT

CONCLUSION & RECOMMENDATIONS

The research aimed at evaluating a SLECI system using bell pepper (*Capsicum annuum*) as a test crop. To achieve this goal, the following objectives were set out: evaluating the performance of a SLECI system as influenced by water quality and soil properties, assessing the response of bell pepper to different irrigation systems and fertilizer applications, evaluating bell pepper growth and yield response to varying burying depth and fertigation levels, assessing the response of bell pepper to water salinity under a SLECI system and simulating the distribution of water and salt in a SLECI system.

Conclusions

Research objective one aimed at investigating the effect of irrigation water quality and soil properties on the performance indicators of the SLECI system. Pearson correlation tests revealed seepage rate positively correlated with Iron, (r = .805, P= .009) SAR (r = .918, P = .000) Sodium (r= .867 P = .002) and negatively correlated Zinc (r= -.905, P = .001), Copper (r = -.902, P = .001), Calcium (r = -.760, P = .017) and Magnisium (r = -.705, P = .034) (Figure 7). Hydraulic conductivity (ks) positively correlated with SAR (r = .774, P= .014) Potassium (r = .734, P = .024) sodium (r= .693, P = .039) and negatively correlated Zinc (r= -.890, P = .001), Copper (r = -.906, P = .001), Calcium (r = -.914, P = .001) and Magnisium (r = -.871, P = .002). Drainage porosity positively correlated with Iron (r= .838, P = .005), Molybdenum (r= .677, P= .045), Sodium (r= .892, P= .001), SAR (r = .938, P= .000) and negatively correlated Zinc (r= -.908, P =.001), Copper (r= -.880, P= .002), Calcium (r = -.709, P=.033) and Magnisium (r = -.674, P= .046). With respect to soil properties, seepage rate positively correlated with porosity (r= .986, P= .000) infiltration rate (r= .994, P= .000) negatively (bulk density r= -.991, P= .000) particle density (r=-.889, P= .001) soil salinity (r= -.789, P= .012) soil sodicity (r= -.878, P= .002). Hydraulic conductivity (ks) positively correlated with porosity (r= .960, P= .000) infiltration rate (r= .957, P= .000) negatively correlated bulk density (r= -.970, P= .000) particle density (r=-.855, P= .003) soil salinity (r= -.925, P= .000) soil sodicity (r= -.966, P= .002). Drainage porosity (ks) positively correlated with porosity (r= .982, P= .000) infiltration rate (r= .990, P= .000) negatively correlated bulk density (r= -.984, P= .000) particle density (r=-.887, P= .001) soil salinity (r= -.748, P= .020) soil sodicity (r= -.852, P= .004). Hydraulic conductivity in sandy soils was highest and was 37.4 % and 5.8% more compared to clay and loamy soils, seepage rate was highest in sandy soils 12.9% and 30.7% better compared to loamy and clay soils, wetting perimeter was 25% and 26.3% greater for clay tube in loamy soils compared clay tube in clay and sandy soil, while drainage perimeter was 29. 4% clay and 14% greater for clay tubes in sandy soils compared to clay and loamy soils.

Research objective two aimed at investigating the effects of different irrigation systems and fertilizer application methods on the growth, yield, productivity and quality of bell pepper fruits. The analysis of variance and subsequent Tukey pairwise test showed that different irrigation systems and fertilizer application methods resulted in significant differences in the growth parameters, yield attributes, productivity indicators and quality parameters. Compared to watering, SLECI systems and drip irrigation improved bell pepper plant height by 19.2 % and 20.9 %. SLECI system improved number of fruits and yield/hectare of bell pepper by 16.5% and 15% compared to the drip irrigation method. Compared to the watering, a 22 % and 20 % increase in leaf area was recorded for both the SLECI system and drip irrigation system. Fertigation improved bell pepper plant height increase by 17.8% compared to the basal fertilizer application. Bell pepper grown under fertigation exhibited a 33% increase in the number of fruits per bell pepper plant in comparison with the basal fertilizer application. The highest marketable yield of 99.2 % was recorded in bell pepper fruits under the SLECI system; fertigation. The lowest incidence of BER of 0.6 % was recorded in the interaction of SLECI system and fertigation. SLECI system improved marketable yield of bell pepper by 3.5 % and 6.5 % compared to drip irrigation systems and watering. Fertigation increased marketable yield of bell pepper by 2.7 % compared to the basal fertilizer application.

Research objective three aimed at investigating the effects of SLECI system burying depth and fertilizer application dosage on the growth, yield and productivity of bell pepper plants. A burying depth of 10cm increased plant height by 5% and 30.3% and leaf area by 1.7% and 16.5% compared to a burying depth of 5cm and 15cm. Bell pepper plants subjected to 80 % RAD recorded significantly ($p \leq 0.05$) higher plant height of 54.43 cm compared to plants subjected to 60 % RAD (48.24 cm) and 100 % RAD (53.08 cm). The highest leaf area of 61.48 cm2 was recorded in plants subjected to 80 % RAD, followed by 60.84 cm2 recorded in plants subjected to 100 % RAD whereas the least leaf area of 54.61 cm2 was observed in plants grown under 60 % RAD. The highest plant height of 62.51 cm and leaf area of 66.52 cm2 was observed in bell pepper plants grown under a burying depth of 10 cm and 80 % RAD. With respect to yield parameters, a burying depth of 10cm produced 27% and 42.6% more number of fruits per plant than a burying depth of 5 cm and 15 cm, with a significant increase in average fruit weight by 5.3% and 35.3% was attained under a burying depth of 10 cm compared to a burying depth of 10 cm and 15 cm. The highest yield of 0.7974 t/ha was recorded in plants grown under a burying depth of 10cm which was 8.6% and 63.9% better than plants grown under 5 cm and 15 cm respectively. Result indicates that even though the recommended fertilizer application dosage of bell pepper was reduced by 20% (80% RAD) it produced the highest fruits per plant (8.5), average fruit weight of 73.88 g and the highest yield of 0.8772t/ha which was an improvement of 29.5% and 63.7% when compared to bell plants that were subjected to 100% RAD and 60% RAD.

Research objective four aimed at assessing the growth, yield, water productivity and quality of bell pepper under varying water salinity levels using a SLECI system. Compared to the control (0.55 dS/m) increasing water salinity levels to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m decreased plant height, leaf area, stem girth of bell pepper plants with the highest decrease being 6% for plant height, 2.4% for leaf area, 8.8% for stem girth. For yield parameters, increasing water salinity level from 0.55 dS/m to 2.0 dS/m, 4.0 dS/m, 6.0 dS/m and 8.0 dS/m decreased the number of fruits, average fruit weight, yield per hectare of bell pepper plants with the maximum decrease being 13.1 % for the number of fruits, 3.1 % for average fruit weight and 18 t/h for yield per hectare. Even though bell pepper plants were subjected to irrigation water salinity stress the highest water use efficiency of 1.871 kg/l was recorded in plants irrigated with 2.0 dS/m, outperforming the control. An increase in water salinity level resulted in a higher incidence of blossom end rot of bell pepper fruits.

Research objective five aimed at stimulating the distribution of water and salt in an SLECI system. The MATLAB Simulink model was used to evaluate the moisture and salinity levels as influenced by soil type and different irrigation water salinity levels. The simulated results were similar to the observed experimental data. A degree of similarity (R^2) of 0.99413, 0.98613 and 0.96689 was observed between experimental and simulated results for the effect of irrigation salinity level on soil salinity level, irrigation salinity level on soil moisture level and the effect of soil type on soil moisture. Irrigation water salinity has a significant impact on both soil moisture and soil salinity levels. Salinity differences between depths of 5cm, 10cm, 15cm and 20cm increased with time and increasing level of irrigation water salinity level. Understanding the relationship between irrigation water salinity, soil moisture content, and soil salinity levels is crucial for effective agricultural practices.

Recommendations

The present study focused on evaluating the performance of a SLECI system using bell peppers in the coastal savannah agro-ecological zone of Ghana. More investigations need to be undertaken in the future using different crops as test crops, different agronomic conditions and different agroecological zones of Ghana.

Future research should be carried out by comparing the SLECI system to other subsurface irrigation systems such as wick irrigation and subsurface drip irrigation systems focusing on crop water consumption, weed control, distribution of moisture and salinity and fertigation.

Future research should be undertaken by evaluating the auto-regulative ability of SLECI systems by comparing it to different irrigation scheduling techniques such as thermal imaging, weather sensing and soil sensing under surface irrigation systems and subsurface irrigation systems.

Future research should be undertaken to compare the cost benefit analysis of using SLECI system and other irrigation systems for vegetable production

The adoption of a SLECI system and fertigation for crop production provides an opportunity to save water and fertilizer since it enables fertilizer to be directly applied to the effective root zone, where plant root rapidly absorbs the nutrients thereby taking better advantage of the fertilizer supplied. Additional benefits include little or no human intervention to irrigate and apply fertilizer due to the auto-regulative capability of the SLECI system.

Salt accumulation during irrigation is a specific concern in regions where the amount of water lost through evaporation and plant transpiration is significantly more than the amount of rainfall received. This issue is exacerbated by the ongoing use of fertiliser, which is essential to meet the demand for food. Therefore, implementing an SLECI system will enable the use of low-quality water in situations where there is a shortage of fresh water. This system can effectively minimize the build-up of salt and its negative impact on crop development and productivity.

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APPENDICES

Analysis of variance for data collected in Objective two (2)

Variate: Plant height 2 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	668.023	334.012	98.16	<.001
Fertigation	1	89.449	89.449	26.29	<.001
Irrigation_system. Fertigation	2	5.389	2.695	0.79	0.459
Residual	48	163.327	3.403		
Total	53	926.188			

Variate: Plant height 4 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	223.507	111.753	25.54	<.001
Fertigation	1	883.549	883.549	201.90	<.001
Irrigation_system. Fertigation	2	0.515	0.258	0.06	0.943
Residual	48	210.060	4.376		
Total	53	1317.631			

Variate: Plant height 6 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	1488.707	744.354	138.63	<.001
Fertigation	1	1791.130	1791.130	333.60	<.001
Irrigation_system. Fertigation	2	37.229	18.615	3.47	0.039
Residual	48	257.720	5.369		
Total	53	3574.786			

Variate: Plant height 8 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	3461.06	1730.53	140.64	<.001
Fertigation	1	1977.62	1977.62	160.72	<.001
Irrigation_system.Fertigation	2	6.05	3.02	0.25	0.783
Residual	48	590.64	12.30		
Total	53	6035.36			

Variate: Plant height 10 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	3909.914	1954.957	387.87	<.001
Fertigation	1	4097.707	4097.707	813.00	<.001
Irrigation_system.Fertigation	2	279.741	139.871	27.75	<.001
Residual	48	241.931	5.040		
Total	53	8529.293			

Variate: Plant height 12 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	2170.636	1085.318	156.36	<.001
Fertigation	1	2662.827	2662.827	383.62	<.001
Irrigation_system.Fertigation	2	130.368	65.184	9.39	<.001
Residual	48	333.182	6.941		
Total	53	5297.013			

Variate: Leaf area 2 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	390.5261	195.2630	214.58	<.001
Fertigation	1	7.0851	7.0851	7.79	0.008
Irrigation_system.Fertigation	2	0.6085	0.3043	0.33	0.717
Residual	48	43.6781	0.9100		
Total	53	441.8977			

Variate: Leaf area 4 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	1078.231	539.115	146.40	<.001
Fertigation	1	23.338	23.338	6.34	0.015
Irrigation_system.Fertigation	2	21.588	10.794	2.93	0.063
Residual	48	176.756	3.682		
Total	53	1299.913			

Variate: Leaf area 6 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	1377.017	688.508	144.84	<.001
Fertigation	1	705.973	705.973	148.52	<.001
Irrigation_system.Fertigation	2	138.596	69.298	14.58	<.001
Residual	48	228.165	4.753		
Total	53	2449.751			

Variate: Leaf area 8 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	1083.809	541.904	239.97	<.001
Fertigation	1	726.587	726.587	321.76	<.001
Irrigation_system.Fertigation	2	172.435	86.218	38.18	<.001
Residual	48	108.394	2.258		
Total	53	2091.224			

Variate: Leaf area 10 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	1162.234	581.117	282.03	<.001
Fertigation	1	1573.992	1573.992	763.90	<.001
Irrigation_system.Fertigation	2	6.373	3.187	1.55	0.223
Residual	48	98.903	2.060		
Total	53	2841.502			

Variate: Leaf area 12 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	464.130	232.065	63.86	<.001
Fertigation	1	3524.011	3524.011	969.81	<.001
Irrigation_system.Fertigation	2	397.449	198.725	54.69	<.001
Residual	48	174.419	3.634		
Total	53	4560.009			

Variate: Number of fruits per plants

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	179.5926	89.7963	124.33	<.001
Fertigation	1	257.8519	257.8519	357.03	<.001
Irrigation_system.Fertigation	2	13.5926	6.7963	9.41	<.001
Residual	48	34.6667	0.7222		
Total	53	485.7037			

Variate: Average fruit weight

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	7811.96	3905.98	331.69	<.001
Fertigation	1	2926.93	2926.93	248.55	<.001
Irrigation_system.Fertigation	2	1.39	0.69	0.06	0.943
Residual	48	565.24	11.78		
Total	53	11305.52			

Variate: Yield per hectare

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	6.077E+09	3.039E+09	240.07	<.001
Fertigation	1	6.116E+09	6.116E+09	483.23	<.001
Irrigation_system.Fertigation	2	4.979E+08	2.490E+08	19.67	<.001
Residual	48	6.075E+08	1.266E+07		
Total	53	1.330E+10			

Variate: Fertilizer Use Efficiency

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Irrigation_system	2	337.2788	168.6394	240.07	<.001
Fertigation	1	339.4524	339.4524	483.23	<.001
Irrigation_system.Fertigation	2	27.6359	13.8179	19.67	<.001
Residual	48	33.7186	0.7025		
Total	53	738.0857			

Variate: Water Use Efficiency

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Irrigation_system	2	0.4150693	0.2075347	899.38	<.001
Fertigation	1	0.1109178	0.1109178	480.68	<.001
Irrigation_system.Fertigation	2	0.0345251	0.0172625	74.81	<.001
Residual	48	0.0110761	0.0002308		
Total	53	0.5715883			

Variate: Blossom End Rot Incidence

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Irrigation_system	2	360.0627	180.0313	535.94	<.001
Fertigation	1	64.4193	64.4193	191.77	<.001
Irrigation_system.Fertigation	2	0.6412	0.3206	0.95	0.392
Residual	48	16.1239	0.3359		
Total	53	441.2471			

Variate: Marketable fruits

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Irrigation_system	2	368.9304	184.4652	420.61	<.001
Fertigation	1	91.5202	91.5202	208.68	<.001
Irrigation_system.Fertigation	2	6.8015	3.4007	7.75	0.001
Residual	48	21.0511	0.4386		
Total	53	488.3031			

Analysis of variance for data collected in Objective three (3)

Variate: Plant height 2 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.2891	0.1446	0.21	
Buried_depth_cm	2	399.9336	199.9668	288.27	<.001
Fertigation_levels	2	29.7995	14.8998	21.48	<.001
Buried_depth Fertigation_levels	4	9.7798	2.4449	3.52	0.011
Residual	70	48.5575	0.6937		
Total	80	488.3595			

Variate: Plant height 4 wat

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.7410	0.3705	0.49	
Buried_depth_cm	2	1677.9810	838.9905	1100.51	<.001
Fertigation_levels	2	125.7114	62.8557	82.45	<.001
Buried_depth Fertigation_levels	4	25.5960	6.3990	8.39	<.001
Residual	70	53.3657	0.7624		
Total	80	1883.3951			

Variate: Plant height 6 wat

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	42.17	21.08	1.75	
Buried_depth_cm	2	3421.74	1710.87	142.05	<.001
Fertigation_levels	2	363.27	181.63	15.08	<.001
Buried_depth Fertigation_levels	4	157.48	39.37	3.27	0.016
Residual	70	843.08	12.04		
Total	80	4827.74			

Variate: Plant height 8 wat

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	2.911	1.455	1.36	
Buried_depth_cm	2	5759.837	2879.919	2699.99	<.001
Fertigation_levels	2	675.088	337.544	316.46	<.001
Buried_depth Fertigation_levels	4	106.581	26.645	24.98	<.001
Residual	70	74.665	1.067		
Total	80	6619.082			

Variate: Plant height 10 wat

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	4.587	2.293	1.92	
Buried_depth_cm	2	4958.676	2479.338	2077.22	<.001
Fertigation_levels	2	572.476	286.238	239.81	<.001
Buried_depth Fertigation_levels	4	113.692	28.423	23.81	<.001
Residual	70	83.551	1.194		
Total	80	5732.982			

Variate: Leaf area %2_wat_cm2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.1601	0.0801	0.27	
Buried_depth	2	43.9410	21.9705	74.68	<.001
Fertigation_levels	2	10.8024	5.4012	18.36	<.001
Buried_depth.Fertigation_levels	4	5.0707	1.2677	4.31	0.004
Residual	70	20.5947	0.2942		
Total	80	80.5690			

Variate: %4_wat_cm2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.5513	0.7757	1.34	
Buried_depth	2	182.5077	91.2538	157.69	<.001
Fertigation_levels	2	35.2064	17.6032	30.42	<.001
Buried_depth.Fertigation_levels	4	23.6000	5.9000	10.20	<.001
Residual	70	40.5092	0.5787		
Total	80	283.3746			

Variate: %6_wat_cm2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.4390	0.7195	1.35	
Buried_depth	2	9.9503	4.9751	9.33	<.001
Fertigation_levels	2	135.5698	67.7849	127.07	<.001
Buried_depth.Fertigation_levels	4	228.9309	57.2327	107.29	<.001
Residual	70	37.3423	0.5335		
Total	80	413.2323			

Variate: %8_wat_cm2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	5.164	2.582	2.43	
Buried_depth	2	981.801	490.900	461.19	<.001
Fertigation_levels	2	893.832	446.916	419.87	<.001
Buried_depth.Fertigation_levels	4	783.742	195.936	184.08	<.001
Residual	70	74.510	1.064		
Total	80	2739.048			

Variate: %10_wat_cm2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.0207	0.5104	0.84	
Buried_depth	2	1363.4126	681.7063	1126.91	<.001
Fertigation_levels	2	778.5376	389.2688	643.49	<.001
Buried_depth.Fertigation_levels	4	558.3795	139.5949	230.76	<.001
Residual	70	42.3455	0.6049		
Total	80	2743.6960			

Variate: Number_of_fruits

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.1728	0.0864	0.21	
Buried_depth	2	223.8765	111.9383	266.68	<.001
Fertigation_levels	2	146.0988	73.0494	174.03	<.001
Buried_depth.Fertigation_levels	4	44.4938	11.1235	26.50	<.001
Residual	70	29.3827	0.4198		
Total	80	444.0247			

Variate: Average weight per plant

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	12.627	6.314	6.16	
Buried_depth	2	10534.914	5267.457	5135.69	<.001
Fertigation_levels	2	6569.121	3284.560	3202.40	<.001
Buried_depth.Fertigation_levels	4	2259.372	564.843	550.71	<.001
Residual	70	71.796	1.026		
Total	80	19447.830			

Variate: tonnes/hectare

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.002034	0.001017	0.31	
Buried_depth	2	4.139007	2.069504	637.49	<.001
Fertigation_levels	2	4.227870	2.113935	651.17	<.001
Buried_depth.Fertigation_levels	4	1.573984	0.393496	121.21	<.001
Residual	70	0.227245	0.003246		
Total	80	10.170140			

Variate: WUE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.0000659	0.0000329	0.31	
Buried_depth	2	0.1341041	0.0670520	637.49	<.001
Fertigation_levels	2	0.1369833	0.0684916	651.17	<.001
Buried_depth.Fertigation_levels	4	0.0509972	0.0127493	121.21	<.001
Residual	70	0.0073627	0.0001052		
Total	80	0.3295132			

Variate: FUE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.1144	0.0572	0.31	
Buried_depth	2	232.8196	116.4098	637.49	<.001
Fertigation_levels	2	237.8182	118.9091	651.17	<.001
Buried_depth.Fertigation_levels	4	88.5368	22.1342	121.21	<.001
Residual	70	12.7825	0.1826		
Total	80	572.0715			

Analysis of variance for data collected in Objective four (4)

Variate: Plant height 2 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	3.7818	1.8909	3.25	
Water_salinity	4	11.2942	2.8236	4.86	0.003
Residual	38	22.0871	0.5812		
Total	44	37.1631			

Variate: %4_wat_cm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	38.757	19.379	12.53	
Water_salinity	4	26.090	6.522	4.22	0.006
Residual	38	58.765	1.546		
Total	44	123.612			

Variate: %6_wat_cm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.376	0.188	0.18	
Water_salinity	4	51.259	12.815	12.57	<.001
Residual	38	38.744	1.020		
Total	44	90.379			

Variate: %8_wat_cm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	6.2084	3.1042	3.56	
Water_salinity	4	65.3476	16.3369	18.74	<.001
Residual	38	33.1338	0.8719		
Total	44	104.6898			

Variate: %10_wat_cm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	3.4631	1.7316	4.75	
Water_salinity	4	29.8880	7.4720	20.48	<.001
Residual	38	13.8613	0.3648		
Total	44	47.2124			

Variate: Leaf area 2 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.0602	0.0301	0.24	
Water_salinity	4	1.7174	0.4294	3.48	0.016
Residual	38	4.6881	0.1234		
Total	44	6.4656			

Variate: %4_wat_cm_2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	2.6655	1.3327	5.73	
Water_salinity	4	2.2553	0.5638	2.42	0.065
Residual	38	8.8432	0.2327		
Total	44	13.7639			

Variate: %6_wat_cm_2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.1373	0.0686	0.42	
Water salinity	4	0.3656	0.0914	0.55	0.698
Residual	38	6.2782	0.1652		
Total	44	6.7810			

Variate: %8_wat_cm_2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.0116	0.5058	2.17	
Water_salinity	4	3.1235	0.7809	3.35	0.019
Residual	38	8.8638	0.2333		
Total	44	12.9989			

Variate: %10_wat_cm_2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.0565	0.0282	0.27	
Water_salinity	4	2.1725	0.5431	5.17	0.002
Residual	38	3.9889	0.1050		
Total	44	6.2179			

Variate: Stem girth 2 weeks after transplanting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.22178	0.11089	1.69	
Water_salinity	4	5.23689	1.30922	19.95	<.001
Residual	38	2.49378	0.06563		
Total	44	7.95244			

Variate: %4_wat_mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.7000	0.3500	1.32	
Water_salinity	4	12.4653	3.1163	11.72	<.001
Residual	38	10.1067	0.2660		
Total	44	23.2720			

Variate: %6_wat_mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.7951	0.8976	2.35	
Water salinity	4	7.9044	1.9761	5.17	0.002
Residual	38	14.5182	0.3821		
Total	44	24.2178			

Variate: %8_wat_mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	4.0298	2.0149	6.44	
Water salinity	4	10.7320	2.6830	8.58	<.001
Residual	38	11.8813	0.3127		
Total	44	26.6431			

Variate: %10_wat_mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	4.0320	2.0160	11.11	
Water_salinity	4	6.9676	1.7419	9.60	<.001
Residual	38	6.8924	0.1814		
Total	44	17.8920			

Variate: Number of fruits

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.09244	0.04622	1.12	
Water_salinity	4	15.88578	3.97144	95.87	<.001
Residual	38	1.57422	0.04143		
Total	44	17.55244			

Variate: Average fruit weight

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.04844	0.02422	0.29	
Water salinity	4	36.59333	9.14833	109.00	<.001
Residual	38	3.18933	0.08393		
Total	44	39.83111			

Variate: Water Use Efficiency

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.21427	0.10714	4.45	
Water_salinity	4	1.20747	0.30187	12.54	<.001
Residual	38	0.91502	0.02408		
Total	44	2.33676			

Variate: Yield per hectare

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Block stratum	2	1.342E-06	6.709E-07	2.97	
Water_salinity	4	1.326E-04	3.315E-05	146.97	<.001
Residual	38	8.572E-06	2.256E-07		
Total	44	1.425E-04			

Variate: Blossom End Rot Incidence

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Block stratum	2	0.00400	0.00200	0.04	
Water_salinity	4	17.08578	4.27144	86.42	<.001
Residual	38	1.87822	0.04943		
Total	44	18.96800			

Composition of fertilizer used for field & greenhouse experiment

PLANTIFOL 10-50-10

Composition	Percentage (%)
Total nitrogen (N)	10%
Phosphorus pentoxide (P_2O_5) water soluble	50%
Potassium oxide (K_2O) soluble water	10%
Magnesium oxide (MgO) water soluble	2%
Boron (B) water soluble	0.010%
Copper (Cu) chelated by EDTA	0.005%
Iron (Fe) chelated by EDTA	0.054%
Manganese (Mn) chelated by EDTA	0.030%
Molybdenum (Mo) water soluble	0.003%
Zinc (Zn) chelated by EDTA	0.005%

PLANTIFOL 12-5-36

Composition	Percentage (%)
Total nitrogen	12%
Phosphorus pentoxide (P_2O_5) water soluble	6%
Potassium oxide (K_2O) soluble water	36%
Magnesium oxide (MgO) water soluble	3.7%
Boron (B) water soluble	0.020%
Copper (Cu) chelated by EDTA	0.0035
Iron (Fe) chelated by EDTA	0.040%
Manganese (Mn) chelated by EDTA	0.050%
Molybdenum (Mo) water soluble	0.003%
Zinc (Zn) chelated by EDTA	0.012%

PLANTIFOL 20-20-20

GUARANTEED RICHNESS	Percentage (%)
Total nitrogen (N)	20%
Ureic nitrogen (N)	10,2%
Ammoniacal Nitrogen (N)	4%
Nitric Nitrogen	5,8%
Phosphorus pentoxide (P_2O_5) water soluble	20%
Phosphorus pentoxide (P_2O_5) soluble in neutral ammonium citrate and in water	20%
Potassium oxide (K2O) soluble water	20%
Boron (B) water soluble	0.0020%
Copper (Cu) water soluble	0.003%
Copper (Cu) chelated by EDTA	0.003%
Iron (Fe) water soluble	0.060%
Iron (Fe) chelated by EDTA	0.060%
Manganese (Mn) soluble water	0.050%
Manganese (Mn) chelated by EDTA	0.050%
Molybdenum (Mo) water soluble	0.003%
Zinc (Zn) water soluble	0.012%
Zinc (Zn) chelated by EDTA	0.012%