

**PERFORMANCE OF CARROTS UNDER VARIOUS FERTILIZATION AND
WATER APPLICATION REGIMES**

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**DISSERTATION SUBMITTED IN PARTIAL FULFILMENT FOR THE DEGREE
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ABSTRACT

Carrot (*Daucus carota* L.) is a crop cultivated in Tanzania, but its productivity is still low, mainly due to poor agronomic practices and limited information on optimal levels of water along with type and level of fertilizer application that enhance crop production. Thus, the main objective of this study was to evaluate the effect of carbonate foliar application (lithovit), soil-based NPK fertilizer application and various levels of water application on the growth, yield and quality of carrots under the semi-arid conditions of Morogoro in Tanzania. Various water application levels in the first season (96.6 m³ for 100% (I₁₀₀), 77.28 m³ for 80% (I₈₀) and 57.96 m³ for 60% (I₆₀)) equivalent to 475.83 mm, 380.67 mm, and 285.498 mm and in the second season (47.34 m³ for 100% (I₁₀₀), 37.872 m³ for 80% (I₈₀) and 28.404 m³ for 60% (I₆₀)) equivalent to 233.64 mm, 186.92 mm, and 140.19 mm, respectively, with different rates of lithovit (1, 1.5 and 2 g/L/plant) and 150 kg NPK ha⁻¹ were applied. The experiment was set as a 3×6 factorial in a split plot design. ANOVA on the growth, yield, and quality parameters was done with the aid of Genstat statistical software. NPK soil-based fertilizer application level of 2 g/plant under full irrigation, represented by the replenishment of 100% of ET_c, appears to be optimal for carrot production. Full irrigation was found to be superior to other levels for carrot production. The interaction between full irrigation and the 2 g/plant fertilizer rate of soil-based NPK fertilizer enhanced carrot production compared to other interactions. Foliar fertilizer may not satisfy the complete nutrient requirement of the crop; further study on carrot productivity should be conducted using soil-based NPK fertilizer and foliar fertilizer in combination with organic fertilizers under various water application levels for comparative purposes.

DECLARATION

I, **CIZA ALEXANDRE**, do hereby declare to the Senate of the Sokoine University of Agriculture that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted in any other institution.

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DEDICATION

I dedicate this work to my parents CIZA Jean Berchmas and NTAKIRUTIMANA Agnes whose love and care has created the foundation for my education. This work solely, is the fruit of their hard work of raising me in good manners.

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Paper I: A. Ciza, F. R. Silungwe and N. I. Kihupi. Carrot Productivity under Various Levels of Irrigation and Fertilization: Published in Asian Research Journal of Agriculture 15(4): 56-68, 2022; <https://doi.org/10.9734/ARJA/2022/v15i430167>.

Paper II: A. Ciza, F. R. Silungwe and N. I. Kihupi. Effect of Foliar Fertilizer and Irrigation Levels on Carrot Productivity. Article Information
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LIST OF ABBREVIATIONS AND SYMBOLS

%

Percentage

AM	Ante-Meridiem
ANOVA	Analysis of Variance
CO ₃	Carbonate
Ca	Calcium
CaCO ₃	Calcium Carbonate
Cm	Centimeter
Cmol	Centimole
CO ₂	Carbon Dioxide
dS/m	Decisiemens per meter
D _z	Maximum Rooting Zone Depth
Ea	Application Efficiency
EC _e	Electrical Conductivity
ET _c	Crop Evapotranspiration
ET _o	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FAOSTAT	Statistics of Food and Agriculture Organization
FC	Field Capacity
G	Gram
H	Hour
Ha	Hectare
I	Irrigation Interval
I _g	Gross Irrigation Requirements
I _n	Net Irrigation Requirements
K	Potassium
K _c	Crop Coefficient
Kg	Kilogram

K_r	Reduction Factor
L	Liter
M	Meter
m^2	Square Meter
m^3	Cubic meter
Meq	Milliequivalent
Mg	Magnesium
Mg	Milligram
$MgCO_3$	Magnesium Carbonate
MJ	Megajoule
mL	Milliliter
Mm	Millimeter
MSc	Master of Science
N	Nitrogen
NP	Number of Emitters Per Plant
NSCA	National Sample Census of Agriculture
P	Phosphorus
P	Maximum Allowable Depletion
P_e	Effective rainfall
pH	Potential of Hydrogen
PNFS	Plant Nutrients for Food Security
P_w	Percentage Wetted Area
PWP	Permanent Wilting Point
Q	Emitter discharge
Q_{fc}	Volumetric Moisture Content at Field Capacity
Q_{PWP}	Volumetric Moisture Content at permanent

	wilting point
RAM	Readily Available Moisture
RH	Relative Humidity
SAR	Sodium Adsorption Ratio
SoET	School of Engineering Sciences and Technology
SUA	Sokoine University of Agriculture
T	Tonne
Ta	Duration of Irrigation per day
TDS	Total Dissolved Solids
TMA	Tanzania Meteorological Authority
TSS	Total Soluble Solids
UNESCO	United Nation Educational, Scientific and Cultural Organisation
USDA	United States Department of Agriculture
WHO	World Health Organisation

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

Carrots are root vegetable crops in the top ten most economically important in the world in terms of both area of production and market value (De Loach and Lewis, 2004; Arshad *et al.*, 2015). They are one of the essential and major root vegetables in the daily human diet. Carrots are rich in beta-carotene, which is necessary for the human body to form vitamin A, which is needed to prevent blindness caused by the low level of light (Saljoughian, 2012; Sharma *et al.*, 2012). They are also high in antioxidants that play an important role in blood pressure control and contribute to better bone health (Dagadkhair *et al.*, 2020). Carrots are a cool-season crop from the Apiaceae family. Other vegetables in this family include celery, celeriac and parsley (Alam *et al.*, 2015). Carrots have a crisp texture and they can be orange, white, red and white-blended in colour when fresh (Tushir, 2021). The taproot of a carrot is edible and the leaves are used in salads (Tushir, 2021). Due to their delicious taste and a certain number of health benefits, carrots are produced all over the world (Harling, 2017).

The world's annual production of carrots is 27 million tons, with China leading the way with 47.33%, followed by Uzbekistan with 5.25%, Russia with 4.21%, the United States with 3.6%, and the United Kingdom with 2.23% (FAOSTAT, 2021). In Africa, Morocco is the leading carrot producing country, with a total production area of 13 476 hectares and an average yield of 35.6 tons per hectare per year (Chedadi *et al.*, 2019). In the major carrot producing countries already mentioned (China, Uzbekistan, Russia, the United States, the United Kingdom and Morocco), the production of carrots is higher than the consumption. This indicates that they are self-sufficient in terms of carrot production and

the surplus is exported (Bash, 2015). Tanzania, one of Africa's top 20 countries in vegetable production (FAOSTAT, 2021), with an approximate area for carrot production of 810 hectares, has a total annual carrot production of 4 553 tons (NSCA, 2012b). This volume of production is low compared to daily carrot requirements. According to Lukmanji *et al.* (2008), the average per capita daily carrot consumption in Tanzania is approximately 50 g, while the recommended daily consumption is at least 80 g (WHO, 2003). This indicates that the consumption of carrots is still below the recommended level. In Tanzania, Morogoro Region ranks the highest in carrot production at 7.65 tons ha⁻¹, followed by Kilimanjaro at 5.9 tons ha⁻¹ and Arusha at 5.6 tons ha⁻¹ per year (NSCA, 2008). The area under carrot production in Morogoro is approximately 190 ha, with a total production of 1 453 tons per annum (NSCA, 2008).

Despite the high carrot production in Morogoro Region compared to other regions in Tanzania, it is found to be low when compared to the other producing regions in Africa, such as Tigray Region in Ethiopia, which produces 10.3 tons ha⁻¹ per year (Tabor, 2012); Gauteng Province in South Africa, which produces 30 tons ha⁻¹ per year (Bash, 2015) and Juja Region in Kenya, which produces 20 tons ha⁻¹ per year (Jeptoo *et al.*, 2013). The production of carrots is found to be primarily influenced by agronomic factors such as soil moisture (Joslanny *et al.*, 2020), method of fertilizer application (Sylvestre *et al.*, 2015), and rate of fertilizer application (Badr and Helmy, 2011). According to Ludong (2008), the 150 % of Crop Water Requirement (ET_c) was found to be optimum for carrot production. El-nasr and Ibrahim (2011) reported that the foliar fertilizer application of potassium at a rate of 3 ml/L/plant influenced the growth (plant height, number of leaves, and leaf length), yield and root quality of carrots. Also, Arshad *et al.* (2015) reported that the application of 1.4 g/plant of NPK enhanced the growth (carrot height and number of leaves) and yield of carrots. However, little information is found on whether these

approaches that increase carrot production can be integrated to form an optimum management practice that would result in improved carrot production.

In comparison to other root vegetables, carrots use comparatively little fertilizer (Allemann and Young, 2002). However, they have a high requirement for soil minerals, particularly potassium and phosphorus, owing to their remarkably fast absorption of nutrients. According to Thorup and Srensen (1999), carrots remove around 170 kg N ha⁻¹, 35 kg P ha⁻¹ and 300 kg K ha⁻¹ after harvesting 100 t ha⁻¹ of carrots. This has a negative impact on the soil, and the carrot crop does not receive the essential nutrients for optimum growth and quality production. To improve soil fertility and plant growth, inorganic fertilizers should be used to add nutrients to the soil. However, information on the correct amount is limited, resulting in over or under application rates that eventually lead to low production of crops (PNFS, 2002).

In Tanzania, farmers use inorganic fertilizers and irrigation water at a low level (Ariga and Heffernan, 2012). According to Everaarts *et al.* (2015), application of inorganic fertilizers for carrot production in the country ranges from 1 to 32 kg N ha⁻¹, 1 to 30 kg P ha⁻¹, and 11 to 64 kg K ha⁻¹, while the recommended fertilizer rate for carrot production per hectare is 80 kg N, 40 kg P and 120 kg K (DAFF, 2004). Rhoda *et al.* (2005) reported that, in Tanzania, most of the farmers use manual irrigation system for carrot production. This system resulting in over or under irrigation water application, while carrots require at least 25.4 mm of water every week (Rhoda *et al.*, 2005). Thus, the amount of fertilizer and irrigation water applied to carrots is quite low when compared to the NPK and irrigation water recommended levels. This low rate of fertilizer and irrigation water use is the main contributor to the low production of carrots. There is therefore a need to provide farmers with the information on the appropriate use of inorganic fertilizers and irrigation water

application to enhance carrot production (Ariga and Heffernan, 2012). Thus, this study aimed to generate standard recommendations for farmers on NPK soil-based fertilizer, foliar fertilizer and irrigation water application for carrot production.

1.2 Problem Statement and Justification

The increase in demand for carrots outweighs the current production in Tanzania. The yields of carrots have persistently been low due to constraints on production associated with inadequate agronomic practices (Sylvestre *et al.*, 2015). Already, the literature is rich in studies on plant nutrients and fertilizer application rates for common crops such as maize, wheat, beans and paddy (Mowo *et al.*, 2006) for Tanzania, while limited research work has been done on the carrot crop. Around the globe, the information on fertilizing methods, rates, and levels of irrigation required for carrots has been investigated. Despite the fact that such studies may not necessarily benefit Tanzanian carrot farmers directly, there is limited information on the benefits of combining the recommended irrigation levels, method of fertilizer application, and rates of fertilizer application for carrot production. Thus, farmers confront the challenge of determining which method of fertilizer application to use and how much to apply to a carrot crop (Djoufack *et al.*, 2020). As a result, the amount of fertilizer applied is either insufficient or toxic for carrot growth and yield of good quality (PNFS, 2002).

Furthermore, irrigation water plays an important role in the production of carrots. However, it remains unclear as to which level of irrigation water application gives the best quantity and quality of carrots (Kifle *et al.*, 2017). Both irrigation water and fertilizer may have positive or negative effects on plant growth and development. Quezada *et al.* (2006) reported that the growth, yield and quality parameters of carrots were significantly enhanced by foliar application of potassium at a 100% water application level, while

Gutezeit (2001) reported that carrot growth, quality and yield were significantly affected by nitrogen at a 75% water application level. These studies indicate the need for thorough investigation on the interactions between irrigation level, method of fertilizer application and the rates of fertilizer application.

In order to address the identified gaps, this study investigated the effects of the interaction of soil-based inorganic fertilizer application and foliar feeding at various water application levels using drip irrigation on the growth, quality and yield of carrots. The study is important as its results will help farmers to know which fertilizer type (soil-based inorganic fertilizer or foliar feeding) and at what rate of fertilizer application and irrigation level would the yield, quality, and growth of carrots be enhanced.

1.3 Objectives

1.3.1 Main objective

The main objective of this study was to evaluate the performance of carrots under various fertilization and water application regimes.

1.3.2 Specific objectives

The specific objectives were to:

- i. Assess the effect of different irrigation water levels on the growth, yield, and quality of carrots.
- ii. Assess the effect of different fertilizer types at various rates of application on the growth, yield and quality of carrots.
- iii. Assess the effects of the interaction between the rate of application of different fertilizers and irrigation water levels on the growth, yield, and quality of carrots.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Historical and Agronomic Aspects of Carrots

2.1.1 Origin and distribution

Carrots are an important root crop that comes in a variety of colours, including orange, white, red, and white-blend, with a crisp texture when fresh. Their shape can range from short stumps to tapering cones (Iorizzo *et al.*, 2020). The edible part of a carrot is the tap root, which is generally bright orange in colour (Alam *et al.*, 2015).

Carrots probably originated in Persia (regions of which are now Iran and Afghanistan in Asia) (Singh *et al.*, 2021). Carrots were known to the Greeks and the Romans, and their primary use was mainly for medicinal purposes, like curing stomachs, treating wounds, and treating kidney illnesses (Kjellenberg, 2007). Carrots were known as a food crop in India, China and Japan by the 13th century (Lib, 1977). The greatest development and improvement of the original wild carrot that had thin, long roots took place in France (Lib, 1977). Carrots are now a popular vegetable grown all over the world.

2.1.2 Botanical description of carrots

Carrots are cool-season biennial vegetables of the Apiaceae family (Umbeliferae), related to celery, celeriac, coriander, fennel, parsnip and parsley, as well as the less commonly grown cumin and coriander, which also include some highly toxic plants, such as hemlock (Zerga, 2019). With almost 3700 species, the Apiaceae is the 16th largest flowering plant family (Kumar *et al.*, 2020; Tavares *et al.*, 2014). The carrot grows a rosette of leaves while building up the enlarged taproot and can mature in 90 or 120 days depending on climatic conditions.

Fast-growing cultivars mature in three months (90 days) after seeding, while slower-maturing cultivars need 120 days to mature (Dagadkhair *et al.*, 2020).

Carrot seedlings have a sharp separation between the taproot and the stem after germination. About 10–15 days after germination, the first real leaf appears, and succeeding leaves are alternate and spirally arranged, with leaf bases enveloping the stem (Que *et al.*, 2019). The bases of the seed leaves near the taproot are pushed apart as the plant grows. The internodes are not distinguishable and the stem is compressed just above the ground. The stem narrows and turns pointed when the seed stalk elongates for flowering, and the stem grows upward to form a highly branching inflorescence up to 60–200 cm tall and the roots are of various shapes (Chandrakar, 2014).

Carrot roots are usually long and conical in shape, but cylindrical and nearly-spherical roots are also available. The diameter of the root can range from 1 to 10 cm, and the length of the root can range from 5 to 50 cm (Chandrakar, 2014). The flesh root comes in various colours, but orange-fleshed roots are the most popular with modern consumers because of their pigmentation, which is caused by high levels of alpha and beta-carotene, giving the greatest source of pro-vitamin A (Iorizzo *et al.*, 2020).

The botanical varieties of carrots are separated into two broad groups based on the shape of their leaves and roots: (i) Eastern and Western carrots. Domestication of eastern carrots, also known as Asian carrots, began in Persia in the 10th century. The roots of the eastern carrot are purple and yellow in colour. They have slightly dissected leaves and often branched roots (Iorizzo *et al.*, 2016). (ii) The western carrot first appeared in the Netherlands in the 17th century. Because of the build-up of carotenoids, the roots of the western carrot are orange, red, or white. The roots of the western carrots are unbranched

and their leaves are deeply dissected and they are divided into four categories (Que *et al.*, 2019). These are: (i) the Emperor, (ii) Nantes, (iii) Chantenay, and (iv) Danvers are the four primary types of western carrots. Emperor carrots have a deep orange cortex with a lighter orange core and are long and tapered. Nantes carrots are bright orange, cylindrical, and have a blunt, rounded base. Baby Nantes typically have a small core, a sweet flavour, a crisp texture, and are of high quality. Chantenay carrots are short, tapered and used mostly for storage or processing. They are tender, crisp, and range in colour from medium to light orange. Danvers carrots are longer than chantenay but are also short and tapered. Their flesh is often tinged with green and is a deep orange colour (Zandstra *et al.*, 1986; Delahaut and Newenhouse, 1998).

2.1.3 Soil and climate

Carrots are considered cool-season vegetables since they require the right climate and soil conditions to grow and develop good flavour. Hot temperatures can damage the carrots' growth and reduce the quality. The minimum temperature for growth is 5 °C and the optimum temperature to get the best carrot production is between 18° and 25 °C. Because carrots have a deep and dense root structure, they can endure warm temperatures during the growth season, but not during seed germination. Carrots benefit from increased carbon dioxide (CO₂) levels in the air because it promotes photosynthesis and growth, especially at high temperatures and in proper soil (Suojala, 2000).

Carrots are commonly grown in sandy soil because the soil is loose enough to allow the roots to grow properly, but the optimal soil for carrots is silt loam, which has the best combination of water-holding capacity and drainage. Carrots can be grown in both acidic and alkaline soils with pH ranges of 5.5 to 6.5 and 6.6 to 7.3, respectively (Nuñez *et al.*, 2008). Carrots grown on humus-rich soils tend to have an excessive number of leaves,

resulting in forked and hairy carrots. The roots also tend to be more rough and coarse on the outside. Carrots are susceptible to saline soils and excessive irrigation water should be avoided.

Like most vegetables, carrots require at least 25.4 mm of water every week under semi-arid climatic conditions. Supplemental irrigation is required if carrots do not receive enough water from rainfall. When irrigating carrots, care should be taken to ensure that the soil is well saturated. The roots won't develop as deeply if only the surface of the soil is wet (Rhoda and David, 2005). A consistent water supply is essential for optimum colour and root growth. The roots will split if there are frequent wet-dry cycles. Excessive watering inhibits good colour development and may promote diseases.

2.1.4 Planting

Proper soil preparation is very important for carrot growing. If the roots of carrots can't easily grow, it can lead to small and deformed crops. In carrot farming, row spacing can range from 200 to 400 mm. The breadth between sets of rows in double or triple rows ranges from 400 to 600 mm. The seeds are directly sown in the field on ridges or raised beds. Broadcast sowing is preferable to row planting. In loose, light sand soils, seeding depth should be 10 to 25 mm. On heavier soils and during the colder months, planting depth should be 5 to 15 mm and kept shallow. Slightly deeper planting is recommended in summer when the soil dries out quickly. The chance of a successful establishment of the crop will be increased if the seed is sown in moist soil and only if the soil is kept moist (Dekker, 2010).

2.1.5 Fertilization

2.1.5.1 Foliar application

A number of authors have described foliar feeding as a technique of feeding plants by applying liquid fertilizer directly to their leaves, from where plants are able to absorb essential elements through their stomata and also through their epidermis (Fageria *et al.*, 2009 and Patil and Chetan, 2018).

Foliar fertilization has been considered as an important tool for sustainable and productive management of crops. It is theoretically more environmentally friendly, immediate, and target-oriented than soil fertilization since nutrients can be directly delivered to plant tissues during critical stages of plant growth (Younus *et al.*, 2017). Timely foliar application increases the level of absorption by the leaf and it is an admirable way of supplying instant nutrients to the plants in case of deficiency. Thus, it is an effective method for correcting the soil deficiencies, overcoming the soils' inability to mobilize nutrients to the plants, and an economical way to supplement the plants' nutrients for more efficient fertilization (Younus *et al.*, 2017).

Fageria *et al.* (2009) reported that the deficiency of iron in calcareous soils can be corrected by foliar application of ferrous sulphate or iron chelate solutions more efficiently than by soil application of iron sources. Foliar fertilization has gained popularity because it reduces crop production costs, preserves soil quality and has the potential to boost agro-ecosystem productivity (Girma *et al.*, 2007).

(a) Appropriate time and weather conditions for foliar applications

Environmental influences such as time of day, temperature, humidity, and wind speed influence the physical and biological aspects of foliar applications. Warm, moist, and calm

conditions favour the highest tissue permeability (Kannan, 2010). Foliar fertilization provides rapid utilization of nutrients and permits the correction of observed deficiencies in less time. Within three to four days, the crop's response to foliar application of nutrients can be evident (Fageria *et al.*, 2009).

When plant roots are not well developed at the growth stage, foliar fertilization is more effective in terms of absorption and, when applied during flowering, can have advantages over soil treatment in terms of increasing protein content in the plant (Gooding and Davies, 1992). The time of foliar fertilizer application is an important aspect for effective absorption. When the stomata of the leaves are open and the temperature is not too high to cause leaf burning, the plant can absorb foliar nutrition effectively. When the air temperature is low, the optimal times for foliar application are in the morning and evening. However, Woolfolk *et al.* (2002) reported that foliar N applications are frequently associated with leaf burn when applied early in the morning while the crop is still wet.

Wind and rain can also disturb the foliar spraying by causing the spray solution to wander. Thus, rain and wind should be avoided for foliar spraying because it takes at least three to four hours for the given fertilizer to be absorbed by the plant (Fageria *et al.*, 2009). Gamble and Emimo (1987) reported that high rates of foliar absorption are also dependent on high relative humidity and optimum soil moisture, as rapid drying can lead to crystallization on the leaf surface. When soil moisture is limited, foliar spray is less effective. Foliar feeding should only be applied when the plant is not experiencing water stress, such as being overly wet or dry. When the plant is cool and full of water, it is the perfect time to apply nutrients (Denelan, 1988; Girma *et al.*, 2007). The most critical times to apply are when the crop is under a given nutrient stress. Stress periods occur during

periods of active growth activity. This is likely when the plant is changing from a vegetative to a reproductive stage (Cantisano, 2000).

(b) Foliar feeding limitations

According to Patil and Chetan (2018), nutrients applied in foliar application cannot meet the entire nutrient requirements of the crop. Applying higher concentrations than those recommended might result in leaf burn as water evaporates and salts remain on the leaves. Due to toxicity considerations, small amounts of nutrients should be applied at a higher frequency. However, frequent applications at lower concentrations are very costly. Foliar application efficiency is dependent on climatic conditions like temperature, humidity, and wind velocity. The method of foliar application is useful only for crops that are tolerant to aerial spray and is not recommended for some crop stages (Patil and Chetan, 2018).

It is not recommended to apply foliar fertilizer after the mid-season stage since it may cause the plant to become severely discoloured. In their study, Thorn *et al.* (1981) found that application of foliar fertilizer high in urea content after flowering results in severe discoloration of the carrot plants and has no prolonged effect on the soil. This means that foliar feeding gives quick results, but the benefits are also quick to disappear. Thus, liquid feeding must be done often, preferably on a regular schedule (Fageria *et al.*, 2009).

(c) Effect of foliar feeding on the growth, quality and yield of carrots.

Many studies have been conducted to evaluate the effects of foliar feeding on the growth, yield, and quality of carrots. For instance, Badr and Helmy (2011) conducted a study to evaluate the influence of foliar application of potassium on the yield and quality of carrot plants grown under sandy soil conditions in Egypt. This study revealed that 2 mL/L/plant of foliar potassium significantly enhanced the growth, yield, and quality parameters of

carrots. Alhariri and Boras (2020) evaluated the responses of seed germination and yield-related traits to seed pre-treatment and foliar spray of humic and amino acid compounds in carrots in Syria. This study revealed that foliar application of humic and amino acid organic solutions at a rate of 1.5 mL/plant significantly improved carrot growth and root yield by increasing plant height, plant fresh weight, leaf fresh weight and root fresh weight.

El-nasr and Ibrahim (2011) carried out research to determine the effect of foliar application with some sources of potassium on the growth, yield and quality of carrot plants in Egypt and found that spraying carrot plants with potassium at a rate of 3 mL/L increased vegetative growth, yield, and root quality in two seasons. In their study, Quezada *et al.* (2006) reported that the growth, yield and quality parameters of carrots are significantly enhanced by foliar application of potassium with full irrigation. Anub (2019) reported that applying ammonium phosphate and urea to carrots enhanced the length of leaves under a 75% water application level. The studies conducted by Evers (1989), Intrigliolo and Castel (2010) with the aim of evaluating the effects of different fertilization practices on the sugar content of carrots revealed that less fertilized treatments increased more sugar in carrots than the most fertilized treatments.

2.1.5.2 Inorganic fertilizer (NPK)

(a) Importance of NPK

Inorganic fertilizer refers to any number of synthetic compound substances created specifically to increase crop yield (Mozumder and Berrens, 2007). Zafar *et al.* (2013) reported that the most commonly deficient elements applied routinely as soil fertilizer to agriculture are nitrogen, phosphorus, and potassium. Among these commonly used nutrients, nitrogen (N) is of special importance because it has numerous functions in

plants and essentially all life processes depend on it. It occurs chiefly in amino acids, plant proteins, and enzymes that speed up biological processes and normal cell division and enable the plant to capture sunlight energy by photosynthesis and ensure that energy is available when and where the plant needs it to optimize plant growth and yield (Zekri and Obreza, 2003). Plants take nitrogen from the soil by absorption through their roots as amino acids, nitrate ions, or ammonium ions. Thus, the rate at which it is applied is based on soil testing and the requirements of the crop to be grown (Ndakidemi and Semoka, 2006).

Phosphorus (P) is necessary for life processes such as photosynthesis, synthesis and breakdown of carbohydrates, and the transfer of energy within the plant. It helps plants store and use energy from photosynthesis to form seeds, develop roots, speed maturity, and resist stresses. Phosphorus is also important for cell division and enlargement, so plant growth is reduced when the supply of P is too low (Patel and Kumar, 2021).

Potassium (K) is necessary for several basic physiological functions, like the formation of synthesis of proteins, normal cell division, growth, and neutralization of organic acids. It improves the efficiency of plant water and sugar use for maintenance and normal growth functions. Potassium works with P to stimulate and maintain rapid root growth and plant health in plants (Maathuis, 2009).

(b) Proper time favouring NPK applications

The time of fertilizer application is an important aspect of fertilizer management practices as it affects the efficiency of use. When fertilizer is applied in the morning, it takes advantage of cooler temperatures and lower winds, ensuring that essential elements reach the roots quickly, plants are not stressed by midday heat and there is no nutrient loss (Reddy, 2017).

The application of inorganic fertilizers at the wrong time may result in nutrient losses, a waste of fertilizer, and damage to the crop because plants require varying nutrient levels and ratios at different growth stages. When the plant needs the nutrients, fertilizers should be applied at the exact time to avoid fertilizer stress to the crop. The optimum timing for fertilizer application is, therefore, determined by the nutrient uptake pattern of the crop and soil moisture content (Powelson *et al.*, 2011; Sheriff, 2005).

Fertilizer application usually corresponds to the watering schedule at the specific time. To help the nutrients find their way into the plant root zone, it is better to apply the fertilizers when plants are irrigated to help nutrients dissolve and move from the surface to the zone where the most active roots are concentrated (Mattos, 2011). However, when irrigation water is at its optimum, liquid fertilizer application can result in excess water which can damage the plant.

Alstrom (1991) reported that liquid fertilizer should not be applied during the evening because if moisture remains on plants overnight, they will be vulnerable to fungal infections that enter through leaf wounds or stomata. An option is the application of fertilizer through fertigation in the early evening. Fertigation ensures that the foliage is not dampened overnight because it allows injecting the fertilizer into the flowing water from the laterals with strategically placed emitters to reach roots without wetting the foliage (Kumar *et al.*, 2012).

Fertilizer cannot be applied at the same time as transplantation. When plants are transplanted from the nursery to the field, some root hairs break. The fertilizer gets into the plant's roots through the broken points and burns or causes the plant to die (Lakey and Kinley, 2015).

Amali and Namo (2015) noted that the crop is affected by the timing and frequency of fertilizer application since some crops are greater feeders of specific nutrients than others. In this case, farmers have to be mindful of the time of applying inorganic fertilizers to supplement available soil nutrients. In their study on carrots, Szelag *et al.* (2019) suggested applying fertilizer to young carrots early to promote root development and growth parameters (number of leaves, length of leaves and plant height). In most root plants, growth and development proceed in two main phases, which are the vegetative and reproductive, respectively; the reproductive phase begins after the completion of the vegetative phase. Early application of N fertilizer enhances the growth of leaves, making enough assimilates available to be transferred to the roots at a later stage of the crop's growth (Amali and Namo, 2015).

The timing and management of N application is essential to ensure sustained nutrition at the end of vegetative growth, while too late application may lead to N starvation. According to Temeche *et al.* (2021), the primary measures to minimize the coincidence of drought periods with sensitive crop growth stages that contribute to considerable yield losses are to choose a better N rate and timing.

(c) NPK fertilizer limitations

Plants require soil nutrients like nitrogen, phosphorus and potassium for their growth. However, excessive use of fertilizers damages the plants and may lead to poor quality of crops in the long term because of the intricacies of soil health (Kracmarova *et al.*, 2020). Excess NPK results in a high salt content and, thus, a reduced absorption of beneficial minerals like magnesium. NPK harms plants indirectly by reducing the amount of trace elements available, causing plant tissue to soften and become less stable, thus increasing the likelihood of diseases and pests, which results in a decrease in yield when it is applied several times in the soil (Herrmann and Bucksch, 2014).

Long-term usage of inorganic fertilizer enables soils and plant tissues to regularly absorb and accumulate heavy metals, which therefore affects the microbial activity, nutritional quality and yield of the crop (Shimbo *et al.*, 2001; Maqbool *et al.*, 2020). It inhibits the uptake of micronutrients, increases pest populations, reduces the essential soil nutrients and minerals that are naturally found in fertile soil, and increases the salts in the soil (Abdiani *et al.*, 2019).

High inorganic fertilizer increases the salts in the soil; excessive nitrogen takes water away from the plant while leaving the salts behind. As a result, the plants are prone to dehydration-induced burns and yellowing (Taylor *et al.*, 2013).

An overabundance of nitrogen has a direct influence on the local environment. Plants are unable to absorb all the excess nitrogen in the soil. The plants use about half of the nitrogen fertilizer, while the other half is discharged into the atmosphere. After that, the microorganisms in the soil convert it to nitrous oxide, which is a gas that contributes to global warming (Silva and Uchida, 2000).

Also, for natural harmony, high nitrogen levels near plants must be regularly monitored and revised. The fundamental reason for this is that excess nitrogen slowly leaches into and out of the soil through runoff and infiltration water. When nitrogen leaches from the soil, it is known to be in the form of nitrates due to microbial conversion. As a result, groundwater and surface water become contaminated by nitrate levels and clay soils become compacted (Hofman and Cleemput, 2004).

In clay soils, inorganic fertilizer compounds leach into the subsoil and combine with clay, generating a thick, impermeable layer known as hardpan (Osman, 2013). The presence of the hardpan causes the soil compaction and tends to alter the soil pH.

Inorganic fertilizer tends to alter the pH of the soil and make it more acidic, thereby affecting the microorganisms that can live in it. Some plants can tolerate a wide range of soil pH levels, while others grow in acidic soils. However, plants will suffer if the soil gets overly acidic and the food produced on these soils will have fewer vitamins and minerals (Kakar *et al.*, 2020).

Inorganic fertilizers may also cause the loss of biodiversity and the deterioration of soil physical properties, as well as the accumulation of toxic chemicals in water bodies (Agbede, 2010). Thus, agrochemicals are one of the major sources of pollution in developing countries, posing a threat to human and livestock health (Sharma and Singhvi, 2017). Banerjee *et al.* (2010) confirmed that high chemical inputs increase the influence of the agriculture sector on the ecosystem and decrease the maintenance and sustainability of agricultural practices. Nutrient management and fertilizer application are the most important critical factors affecting plant growth, yield, and quality performance in modern agriculture (Kakar *et al.*, 2020).

(d) The effect of NPK fertilizer on carrot growth, quality and yield

Many studies on the effect of NPK fertilizer on carrots have been conducted worldwide. A study by Arshad *et al.* (2015) reported that 1.4 g NPK /plant is suitable for optimum growth and yield of carrots in Pakistan. Carrot yield and quality are affected by nitrogen fertilizer. In a study conducted in Florida by Hochmuth *et al.* (1999) on nitrogen fertilization to maximize carrot yield and quality on a sandy soil, it was observed that 150 kg N ha⁻¹ fertilizer increased the yield of carrots.

Normally, the rates of nitrogen fertilizer that produce carrot root yield should also produce carrot quality. In a study carried out in Bangladesh with the aim of studying the effect of

nitrogen and potassium on the quality and yield of carrots, Ali *et al.* (2003) reported that the root yield increased progressively and significantly with the increased application of nitrogen and potassium. Application of nitrogen at a rate of 200 kg h⁻¹ and potassium at a rate of 250 kg h⁻¹ increased the yield by 324% over the control. The highest carotene content was recorded in the carrot plants that received 200 kg N ha⁻¹.

Potassium is a major nutrient that plants require in large quantities to improve plant growth and quality parameters. The rate of potassium may increase yield, shoot growth, and quality parameters. Shikha *et al.* (2016) conducted a study in Bangladesh with the objective of finding an appropriate rate of potassium for higher yield and quality of carrots. This study revealed that 70 kg K ha⁻¹ promoted the growth parameters (plant height, number of leaves per plant, and shoot fresh weight), total yield, and root parameters (root length, root diameter and root weight) of carrot plants.

Also, El-nasr and Ibrahim (2011) conducted research to study the effects of different rates of potassium fertilization (0, 60, 120 and 179 kg ha⁻¹) on the growth, yield, and quality of carrot plants. This study indicated that 179 kg K ha⁻¹ produced the tallest plant height, the highest number of leaves per plant, and the freshest weight of shoots, as well as the highest total yield per hectare in two seasons. Also, the obtained results showed that the quality parameters (root length, root diameter, root weight and TSS) were increased with increasing potassium fertilizer rate in two seasons.

Phosphorus is taken as the main plant nutrient that is essential for plant growth, respiration, photosynthesis, cell division, energy storage, and speed of maturity (Patel and Kumar, 2021). According to Lobna (2014), the rates of phosphorus enhanced the growth of carrots. This was shown in a study conducted on potassium and phosphorus as plant

nutrients for carrot growth. This study revealed that application of phosphorus up to 95 kg ha⁻¹ is suitable for yield and growth parameters of carrot.

Sylvestre *et al.* (2015) carried out a study in Rwanda to assess the effect of NPK on the growth and yield of carrots. This study showed that 300 kg NPK ha⁻¹ enhanced the height of carrots, the number of leaves, root shoulder diameter and yield more than the control treatment. In their study, Noella *et al.* (2014) found that fertilizer had no effect on total soluble sugar content in carrots; the highest TSS was obtained in plots without fertilizer.

2.1.6 Fertilization and water application regimes

Irrigation water affects crop growth as well as crop yield and quality. Irrigation should be managed to avoid yield and quality decrease caused by either a deficit or an excess of water (Malakar *et al.*, 2019). It is important to adopt efficient irrigation management strategies to enhance carrot production (Lopes *et al.*, 2018). The aim of efficient irrigation is to maximize the return in terms of yield and value on the use of water requirements while ensuring good nutrient utilization (Abdel-aziz, 2017).

Water requirements related to evapotranspiration and the timing of maximum demand vary with different crops. The amount of evapotranspiration depends on crop factors which in turn are affected by growth stages, atmospheric conditions such as radiation, temperature, wind and humidity; management including ground covers and soil moisture content (Muniandy *et al.*, 2016) and other environmental aspects such as soil salinity, level of soil fertility, hardness of the soil surface and disease and pests. Crop water requirements can be used as a reference to find the right balance between the quantity of extractable soil moisture available for the crop and the amount of water required at a certain growth stage. Therefore, it is necessary to determine the crop water requirements

for proper irrigation system design, water resource planning, and irrigation scheduling (Chartzoulakis and Bertaki, 2015).

Irrigation scheduling is the use of water management practices to maximize production by avoiding the over-application of water, water scarcity and drought stress. Over irrigation decreases yields by reducing soil aeration and causing fertilizer leaching, as well as increasing water and energy costs (Pereira *et al.*, 2009). In addition, over irrigation has the ability to elevate water tables and pollute the water supply (Hussain *et al.*, 2020). Conversely, proper irrigation scheduling saves costs and fertilizer use by maximizing irrigation water efficiency (Ouda and Zohry, 2020).

In addition to managing the quantity of water applied, suitable management of fertilizer positively influences the production of roots, especially inorganic fertilizers to confirm the availability of NPK to attain adequate yields (Heffer *et al.*, 2015). Fertilizer, particularly NPK, should not be ignored when considering irrigation of crops. If adequate water is applied, the crop growth rate will be determined by nutrient supply (Heffer *et al.*, 2015). However, improper NPK fertilization and irrigation management are key contributors to water quality and scarcity problems in agricultural production (Zia *et al.*, 2013). Excessive irrigation water application can result in high amounts of NPK leaching (Li *et al.*, 2018). Irrigation and fertilizer management can enable adequate NPK absorption while reducing off-site impacts and irrigation return flows, which can be contaminated by salts and nitrates (Wang and Li, 2019; Wang and Xing, 2016).

In addition, to promote optimal growth, plants' needs for nitrogen can be met by a combination of soil and fertilizer N. Soil nitrogen changes are closely associated with soil moisture levels (Wang and Xing, 2016). All biological activities, such as plant nitrogen

intake and growth, residue decomposition and nitrification, progress at their maximum rate when soil moisture is optimal. When moisture is inadequate, these biological activities proceed very slowly (Abera *et al.*, 2012). However, if the moisture is excessive, nitrogen (NO₃-N) leaching and oxygen deficiency in the soil can occur, leading to a reduction in root respiration. Carrot growth may be limited by this condition (Abera *et al.*, 2012). The most significant component in achieving optimum carrot yields is determining the frequency of irrigation to keep enough water in the soil based on water availability and crop needs (Zinkernagel *et al.*, 2020).

Carrot cultivation requires careful preparation, including the application of the proper amount of fertilizer and irrigation water (Anub, 2019). Rose (2008) noted the need for crop management, particularly carrot soil fertility, in order to encourage good plant growth. Aside from soil fertility, water management effectiveness is a significant consideration in carrot growing. According to Adiles *et al.* (2011), management practices will have an impact on carrot sustainable agriculture. Rose (2008) reported that carrots require consistent watering at the appropriate times.

2.1.6.1 Effect of water application regimes on the growth, yield, and quality of carrots

A study conducted by Ludong (2008) to evaluate the effects of irrigation rate on the growth, yield, nutritive value and water use efficiency of carrots in Australia reported that the growth and yield of carrots were more positively affected by NPK at 150% water application than at a 100% water application regime. A study by Gutezeit (2001) revealed that the highest total yields were obtained at 75% water application level and 150 kg N ha⁻¹ for both soil types (sandy and loamy soils). Friedlander *et al.* (2013) in Senegal reported that among the different irrigation systems, drip irrigation increased carrot yields and

saved fertilizer quantity, thus making this more farmer-friendly. In a study conducted in Chile, Quezada *et al.* (2006) found that a 100% water application level produced the highest carrot yield. Anub (2019) conducted a study in the Philippines to evaluate the effect of different irrigation intervals on the growth and yield of carrots and reported that the root length and root weight were significantly affected by irrigation, with a two-day interval giving the highest yield, while irrigation at a four-day interval resulted in the lowest yield.

A study by De Carvalho *et al.* (2018) in Brazil revealed that the application of irrigation depths corresponding to 97% of ET_c promoted the highest carrot yields. Abdel-Aziz (2017) in Egypt conducted a study with the objective of evaluating the effect of deficit irrigation during the growth stages compared to full irrigation. This study revealed that the quality parameters (root length, root diameter and total soluble solids) decreased with increasing deficit irrigation during the growth stages. A study by Joslanny *et al.* (2020) in Brazil revealed that full irrigation produced more positive results in carrot production than the 80 and 60% water application levels.

In their study, Nagaz *et al.* (2012) found that a 100% water application level produced higher carrot yields over three years than an 80 or 60% water application level in Tunisia. Abdel-Mawly *et al.* (2004) studied the effects of irrigation levels and N fertilization rates on the growth and yield of carrots at Al-Azhar University. The results indicated that frequent irrigation with a 100% water application level resulted in the highest root yield. Also, the results showed that increasing nitrogen rate by up to 286 kg N ha⁻¹ significantly increased the root yields. The highest root yields were obtained when 100% of the evaporation replenishment was interacted with 286 kg N ha⁻¹.

A study by Afrin *et al.* (2019) with the aim of investigating the influence of organic and inorganic fertilizers with various irrigation intervals on the growth and yield of carrots in Bangladesh revealed that among different irrigation intervals (7, 15 and 30 day irrigation intervals), the highest carrot height and the highest yield were obtained from the 7 days irrigation interval. Considering the treatment combinations, irrigation at 7 days interval with mixed fertilizer produced the highest plant height, number of leaves, diameter of root, length of root, and fresh weight of individual roots. Zeipi *et al.* (2014) conducted a study to compare the yield and quality of carrots with sprinkler and drip irrigation systems in Latvia. They reported that the highest carrot yield was obtained by using sprinkler irrigation and observed that better water supply decreased sugar content in the roots. A study by Abdel-aziz (2017) in Egypt reported that the values of quality parameters for carrot roots (root length, root diameter and total soluble solids) decreased with increasing deficit irrigation.

2.2 Carrot Production, Marketing, and Consumption in Tanzania

Carrots are one of a lucrative horticultural business that has not been fully utilized in Tanzania. The area of carrot production is 810 ha, with a total production of 4 553 tonnes (NSCA, 2012b). Morogoro Region ranks the highest in carrot productivity at 7.65 tons ha⁻¹, followed by Kilimanjaro at 5.9 tons ha⁻¹ and Arusha at 5.6 tons ha⁻¹ per year (NSCA, 2008). The area under carrot production in Morogoro is approximately 190 ha, with a total production of 1 453 tons per annum (NSCA, 2008). At 10 cm spacing, each hectare is predicted to have a population of 2 471 050 plants (Everaarts *et al.*, 2015).

Farmers grow carrots using farmyard manure and mulch. They also avoid using chemical pesticides in favour of natural pest control methods like intercropping (Selina, 2021). In Tanzania, carrots are harvested in two stages: first, baby carrots are uprooted on the 75th

day after planting. The mature roots are harvested at 90 days after planting (Everaarts *et al.*, 2015).

Carrots are sold through five main distribution systems: (i) local village markets, (ii) regional markets, (iii) national markets, (iv) export markets, and (v) supermarket (Eskola, 2005; Weatherspoon and Reardon, 2003). A bag of 100 kg of carrots costs between TZS 150 000 and 200 000 in some parts of Tanzania (Everaarts *et al.*, 2015). The average daily vegetable intake in Tanzania is approximately 158 g, while the recommended daily intake is at least 400 g (WHO, 2003). This indicates that consumption of micronutrient-dense foods like vegetables is still below the recommended level.

2.3 Syntheses of the Literature Review

Carrot (*Daucus carota L.*) is normally grown under irrigation system. In Tanzania, carrot productivity is still low, mainly due to poor agronomic practices as a result of limited information on optimal levels of irrigation water and fertilizer type along with its rate that enhance crop production. It was found that the growth, yield and sugar content of carrots were affected differently at various irrigation water (IW) application levels and fertilizer rates. NPK soil-based fertilizer application level of 2 g/plant under full irrigation appears to be optimal for carrot production. Full irrigation was found to be superior to other levels for carrot production. The interaction between full irrigation and the 2 g/plant fertilizer rate of soil-based NPK fertilizer enhanced carrot production compared to other interactions. Foliar fertilizer may not satisfy the complete nutrient requirement of the crop. Carrots grown at a deficit irrigation water level of 80% were found to have the highest content of sugar.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location

The field experiment was conducted at the School of Engineering and Technology (SoET) research field (grid zone 350 213.19 E, 9 243 788.94 N, 37M; 512 m above sea level). The SoET is part of the Sokoine University of Agriculture (SUA) and is situated 3 km from Morogoro Municipality, Tanzania (Figure 1).

3.1.2 Topography

Morogoro urban district is bounded on the south-eastern side by the Uluguru Mountains and on the western side by the Mindu and Nguru ya Ndege hills. The district is dominated by plains of various shapes and sizes.

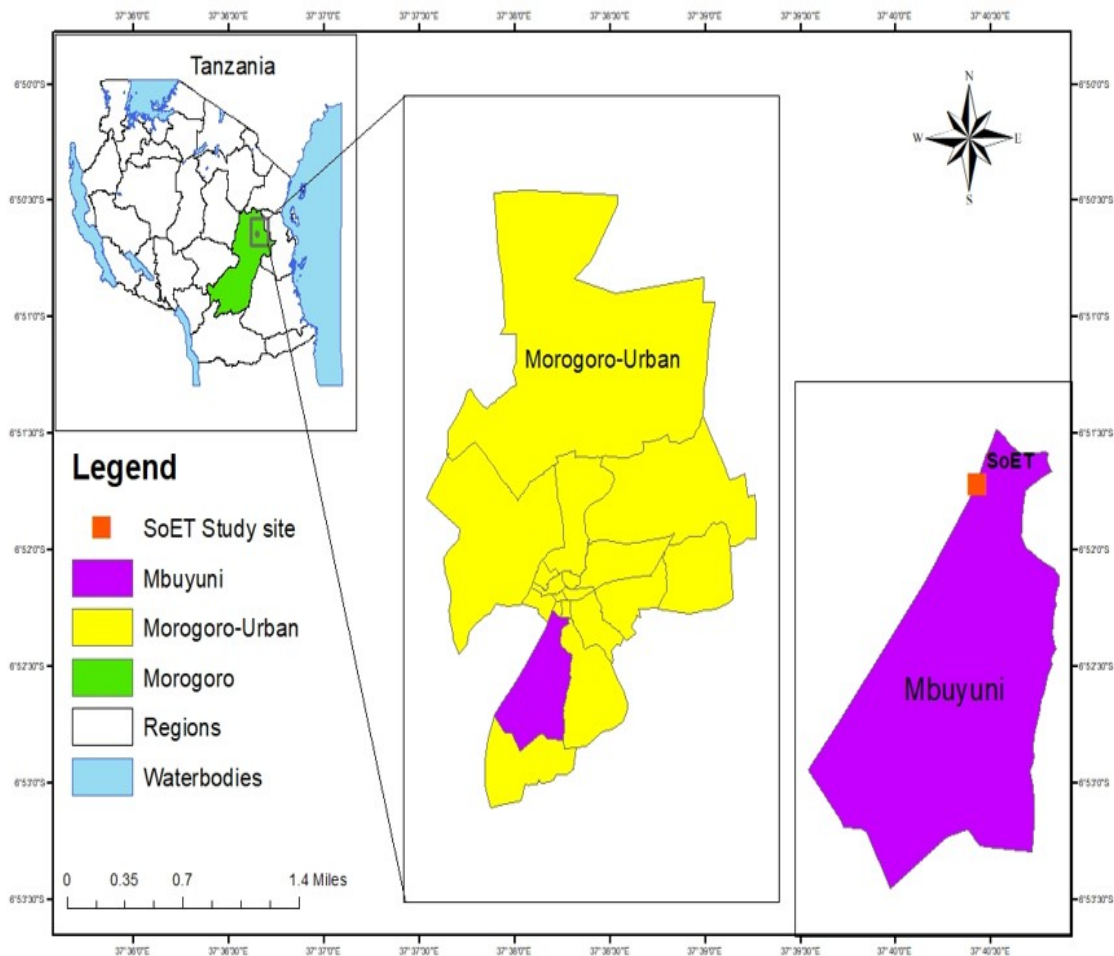


Figure 1: Map showing the location of the study site

3.1.3 Climate

Within the Morogoro urban area, rainfall is bimodal, with long rains between March and May and short rains between October and December. The long rains (Masika) average 411.1 mm per year, whereas the short rains (Vuli) average 149.8 mm per year (Figure 2). Table 1 shows the average monthly weather data for Morogoro Urban District in Tanzania over a five-year period with the highest mean relative humidity (84.2 %) in April and the lowest mean relative humidity (66.1%) in September. The highest wind speed (181.2 km/day) was in December, while the lowest wind speed (39.9 km/day) was in May.

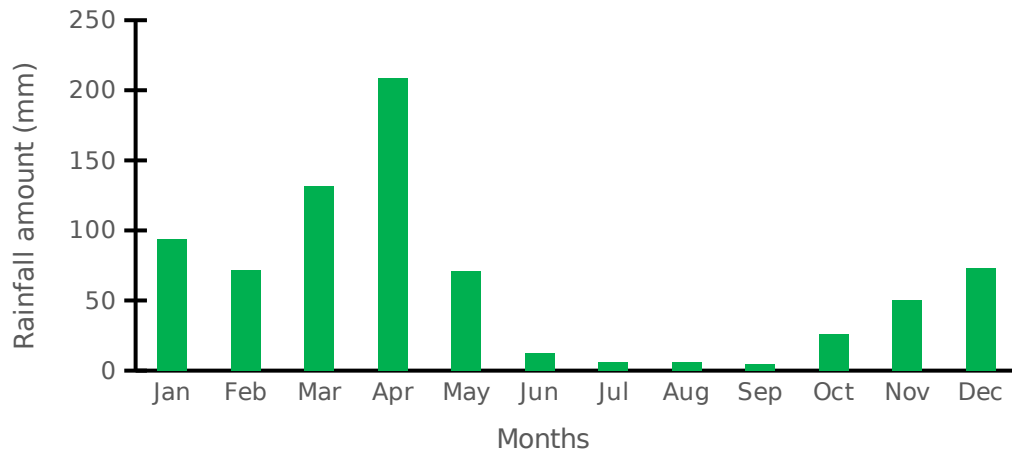


Figure 2: Mean monthly rainfall (mm) at Morogoro (1961-2020)

Source: (SUA TMA meteorological station, 2021)

Table 1: Mean monthly weather data within Morogoro urban (2015-2020)

TH	MON	MEAN RH (%)	WIND (Km/day)	TEMPERATURE (°C)		RADIATIO N (MJ/m ²)
				MAXIMUM	MINIMUM	
JAN		72.6	181.2	32.1	22.1	19.8
FEB		71.4	159.0	32.7	22.2	21.0
MAR		77.1	85.4	32.3	22.0	18.5
APR		84.2	49.4	29.6	21.5	15.2
MAY		82.7	39.9	28.2	19.9	13.9
JUN		76.6	48.2	28.2	16.9	15.4
JUL		71.5	61.7	27.9	16.1	15.2
AUG		68.7	83.7	28.8	17.2	16.4
SEP		66.1	109.7	30.6	17.7	18.2
OCT		66.6	118.7	31.5	19.5	18.2
NOV		68.4	144.9	31.7	21.2	19.7
DEC		70.9	173.5	32.6	22.2	20.0

Source: (SUA TMA meteorological station, 2021).

3.1.4 Soils

Soils in Morogoro Region vary according to topology and agro-ecological zones. The soil in the experimental area is classed as Ultisol in the USDA soil taxonomy and as Acrisol in the FAO-UNESCO classification (Msanya *et al.*, 2003). Details of the physical and chemical properties of the soil for the experimental site in the top 300 mm layer are given in the Results and Discussion section.

3.2 Experimental Design and Layout

The experiment was conducted over two seasons, beginning December 4, 2020 for the first season and May 20, 2021 for the second season, ending March 4, 2021 and August 20, 2021, respectively. A factorial arrangement of treatments was laid out in a split-plot design. Two factors; factor 1 being water application regime, which was at 3 levels (100%, 80% and 60% of readily available water), and factor 2 being fertilizer application regime, which was at 6 levels (NPK1, NPK2, NPK3, Foliar1, Foliar 2 and Foliar 3), were investigated in a 3 x 6 factorial with three replications (El-Helaly, 2018). There were, therefore, a total of 18 treatment combinations (plots) for each replication (Figure 3).

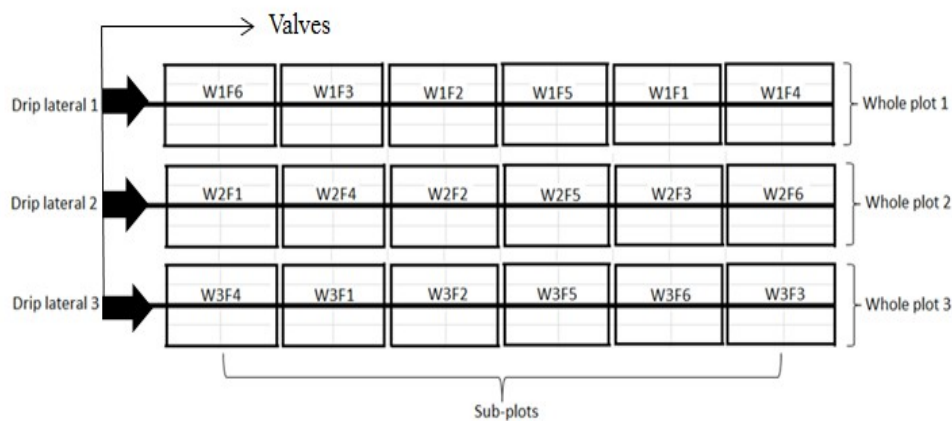


Figure 3: Experimental layout for one block (replication)

In the Figure 3, whole plots comprised the treatment combinations for individual levels of the water application regime factor (i.e., those served by the same drip lateral), while sub-plots represent the respective treatment combinations, e.g., W3F1. The factor "fertilizer application regime" is denoted by "F", while the respective levels of the factor are denoted by Arabic numerals "1-6". In this case, F1 = NPK1; F2 = NPK2; F3 = NPK3; F4 = Foliar1; F5 = Foliar 2; and F6 = Foliar3. The factor "irrigation water application regime"

is denoted by “W”, while the respective levels of the factor are denoted by Arabic numerals “1-3”. In this case, W1 = 100% ET_c, W2 = 80% ET_c, and W3 = 60% ET_c. Each subplot measured 1.5 m × 2 m in size and was separated from the next by a 0.5 m buffer zone. The total experimental area was 216 m².

3.3 Agricultural Practices

3.3.1 Preparation of the land and planting

The land preparation was done manually using hand hoes. Flatbeds were then constructed and planting rows were prepared along which drip lines were laid out. Carrot seeds (Nantes variety) were mixed with sand before planting to avoid over-seeding and thus reduce the need for thinning. Carrots were directly sown at a depth of 1 cm with a spacing of 10 cm.

3.3.2 Water application

Valves were installed at the head of each lateral feeding the whole plot (Figure 3). The discharge of one emitter corresponding to full irrigation, i.e., 100% of readily available water (I₁₀₀) application level, was 2 L/h. The discharges of the other emitters corresponding to water application levels of 80% and 60% of readily available water (I₈₀ and I₆₀, respectively) were attained based on the 2 L/h discharge by adjusting the valve and taking several measurements from an emitter using graduated cylinders. The measurements were taken at three positions (at the beginning, middle and end) of the lateral.

3.3.3 Weeding

Weeding was done 4 times for each season to give the test plants ideal conditions for growth. This was mainly achieved by inter-cultivation followed by hand-weeding.

Thinning was done two weeks after the emergence of the crop to attain the required spacing of 10 cm between plants, which gave 45 plants per sub-plot with a row spacing of 20 cm.

3.3.4 Fertilizer application

Two types of fertilizer were used. These were NPK fertilizer applied to the soil and Lithovit (foliar feeding) sprayed on the leaves. The recommended dosage of Lithovit for carrots is 1 kg ha⁻¹ (0.3-0.5 kg per 100 L of water) applied twice during the growing season: the first at bedding out and the second 28 days later (Rauniyar, 2012). NPK was also applied twice: once at planting and again at the mid-season stage. Lithovit was applied at three rates (1, 1.5 and 2 grams/L/plant) and NPK was also applied at three rates (1, 1.5 and 2 grams/plant), which together make up the six levels of the fertilizer application regime factor. Both fertilizers were applied early in the morning, before 9:00 AM, as recommended by Reddy (2017). NPK was applied to the soil manually, while a knapsack sprayer was used for foliar feeding application.

3.3.5 Disease and pest management

Dudu-acelamectin 5% EC was applied at the rate of 15 mL per 20 L of water to control insect pests, while Linkmil 72 WP was applied at the rate of 60 g per 20 L of water to control fungal diseases such as leaf spot, soft rot and sclerotinia rot.

3.4 Data Collection

3.4.1 Physical and chemical properties of the soil and irrigation water

3.4.1.1 Soil sample collection

Soil samples were collected from the experimental site before planting for two seasons. Simple random sampling techniques were used for collecting soil samples (Petersen and

Calvin, 1986). The soil samples were collected using an auger and kept in containers, then transported to the laboratory for drying in an oven at 70 °C for 3 days to a constant weight, then ground and sieved to pass through a 0.05 mm sieve for further analysis.

3.4.1.2 Water sample collection

Irrigation water samples were collected from an existing rainwater harvesting (RWH) reservoir at the botanical garden close to the experimental site and taken to the laboratory for analysis.

3.4.1.3 Laboratory analyses

Table 2 shows the methods used to analyse the physicochemical properties of the soil and water at the experimental site.

Table 2: Methods used to analyse the physical and chemical properties of the soil and water

Soil properties	Method used	Reference
Bulk density	Core sampler method	Blake and Hartge (1986)
FC and PWP	Pressure membrane method	Obi (1974)
Particle size distribution	hydrometer method	Bouyoucos (1962)
Soil pH	glass-and-calomel electrode pH meter	Dewis and Freitas (1970)
Total nitrogen (N)	Kjeldahl method	Bremner (1960)
Phosphorus (P)	Olsen method	Hesse (1971)
Electrical conductivity	Electric conductivity meter	Rhoades (1996)
Magnesium and Calcium	Ammonium acetate extraction	Hesse (1971)
Potassium (K)	Flame photometer	Hesse (1971)
Sodium (Na)	Spectrophotometer	Hesse (1971)
HCO ₃ and CO ₃	potentiometric titration method	(FAO, 1980)

Table 3: Methods used to analyse the chemical properties of the irrigation water

Irrigation water properties	Method used	Reference
Water pH	Glass electrode pH meter	Ayers and Westcot (1985)
Electrical conductivity	Conductometry (1: 2.5 H ₂ O,V/V)	Ayers and Westcot (1985)
Potassium	Flame photometric	Ayers and Westcot (1985)
Nitrogen	Nitrate test strips	Ayers and Westcot (1985)
Bicarbonate (HCO ₃)	Titration (with 0.01 NH ₂ SO ₄)	Ayers and Westcot (1985)

Carbonate (CO ₃)	Titration (with 0.01 NH ₂ SO ₄)	Ayers and Westcot (1985)
Sodium	Flame photometric	Ayers and Westcot (1985)
Total dissolved solids	TDS = 640 × E _C (for E _C < 5 dS/m) TDS = 800 × E _C (for E _C > 5 dS/m)	Ayers and Westcot (1985)
Calcium	EDTA (0.05N) titrimetric	Mezgebe <i>et al.</i> (2015)
Magnesium	EDTA (0.05N) titrimetric	Mezgebe <i>et al.</i> (2015)
SAR	$SAR = Na + \frac{Ca}{\sqrt{0.5 Ca Ca}}$	Park <i>et al.</i> (2015)
Phosphorus	orthophosphate test	Park <i>et al.</i> (2015)

Porosity was determined indirectly from bulk density measurements while soil texture was determined using the USDA textural triangle (Bouyoucos, 1962).

3.4.2 Calculation of crop and irrigation water requirements

3.4.2.1 Estimation of reference evapotranspiration

The reference crop evapotranspiration (ET_o) was determined using the Penman-Monteith equation (Allen *et al.*, 1998) with the aid of INSTAT plus (v3.6) software (Stern *et al.*, 2006).

3.4.2.2 Determination of crop coefficients

The crop coefficient (K_c) values given in FAO-56 (Allen *et al.*, 1998) for carrots were used in the determination of ET_c for the single crop coefficient approach. The K_c values given are 0.7 for the initial stage, 1.05 for the mid-season stage and 0.95 for the late season stage. The corresponding lengths of growth stages are 18, 27, 27 and 18 days for the initial, crop development, mid-season and late season stages, respectively.

3.4.2.3 Determination of crop water requirements

Crop water requirement (ET_c) was calculated using ET_o and appropriate crop coefficients (Doorenbos and Pruitt, 1977).

$$ET_c = ET_o \times K_c \quad (1)$$

Where,

ET_c = Crop evapotranspiration (mm day^{-1})

ET_o = Reference evapotranspiration (mm day^{-1})

K_c = Crop coefficient

For drip irrigation design, a reduction factor (k_r) should be applied to the conventional ET_c calculations. Such an application is made due to the nature of the system of irrigation where only a portion of the soil is wet and the crop water requirement can thus be reduced accordingly (Goldberg *et al.*, 1976; Karmeli and Keller, 1975). Thus, the crop water requirement was adjusted using the method developed by Savva and Frenken (2002).

Rainfall is a major climatic factor that influences crop growth. In this study, rainfall was measured using the manual rain gauge method during the experiment throughout the growing season and it was used to determine the dependable effective rainfall. This was computed using CROPWAT version 8.0 software (Smith, 1992).

3.4.2.4 Irrigation requirements

The net irrigation requirement was calculated using the following equation:

$$I_n = ET_c - P_e \quad (2)$$

Source: (Smajstrla and Zazueta, 2011)

Where: I_n = Net irrigation requirement (mm)

ET_c = Crop water requirement (mm)

P_e = Dependable effective rainfall (mm)

The gross irrigation was calculated using the following equation:

$$I_g = \frac{I_n}{Ea} \quad (3)$$

Source: Savva and Frenken (2002)

Where: I_g = Gross irrigation requirement (mm)

E_a = Field application efficiency (%)

In this study, an E_a of 90% was used (Savva and Frenken, 2002).

3.4.2.5 Irrigation scheduling

Important soil parameters required for determination of the readily available moisture (RAM) are namely: field capacity (FC) and permanent wilting point (PWP). These were determined from laboratory measurements using Pressure membrane method (Obi, 1974). Available soil moisture (mm/m) was determined from FC and PWP, while data for maximum rooting depth (cm) and maximum allowable depletion were obtained from the literature for carrots (Allen *et al.*, 1998; Savva and Frenken, 2001).

The readily available moisture (RAM) was calculated using the following equation:

$$RAM = (\theta_{fc} - \theta_{pwp}) \times P \times D_z \times P_w \quad (4)$$

Source: (Vermeiren and Jobling, 1984)

Where: RAM = readily available soil moisture (mm)

θ_{fc} = Volumetric moisture content at the field capacity (mm/m)

θ_{pwp} = Volumetric moisture content at the permanent wilting point (mm/m)

P = Maximum allowable depletion (%)

D_z = Maximum rooting zone depth (m)

P_w = Percentage wetted area (%)

The irrigation interval was calculated using the following equation:

$$I = \frac{RAM}{ET_C} \quad (5)$$

Where: I = irrigation interval (days)

The duration of irrigation at peak demand was established using the following equation:

$$T_a = \frac{A I_g}{q \times N_p} \quad (6)$$

Where,

T_a = the duration of irrigation per day (hours)

A = Area to be irrigated

I_g = gross irrigation requirement (mm)

q = emitter discharge (l/h)

N_p = number of emitters per plant

3.4.3 Crop growth parameters

The growth parameters that were collected include plant height, the number of leaves per plant and the length of leaves. From each treatment, the height of 5 tagged carrot plants was measured using a ruler from the ground level to the top of the root shoot. The obtained measurements were recorded in cm. On the same plants, the length of leaves was measured from the bulb neck to the tip of the leaf using a ruler. The number of fully expanded leaves was counted and recorded as the number of leaves per plant.

3.4.4 Yield parameter

Yield data was obtained after harvesting. The same carrots that were used to take data for the growth parameters were also used for the determination of fresh root weight by using a weighing scale balance. The obtained weights were recorded in kilograms.

3.4.5 Quality parameters

The same carrots that were used to take data for the growth parameters were also used for the determination of the quality of carrots. The root length was determined using a vernier caliper starting from the shoulder to the end of the tap root. The shoulder and core

diameter of roots were measured at 0.5 cm from the top of the shoulder using a vernier caliper, and measurements were recorded in mm. Total soluble solids, i.e., sugar level in carrots were measured using a hand-held refractometer (0–30% Brix) and recorded in percentage.

3.5 Statistical Analysis

Analysis of variance (ANOVA) on the data collected was done using Genstat statistical software, and mean separation was carried out using Duncan's multiple range test at the 0.05 probability level (David, 2013).

4.0 RESULTS AND DISCUSSION

4.1 Physical and Chemical Properties of the Soil in the Study Area

Table 4 shows the physical properties of the soil under the study. According to the classification system suggested by FAO (1977), the soil texture is sandy clay. According to Landon (1991), sandy clay soil is suitable for vegetable production but needs frequent irrigation and fertilization to maintain healthy growth. The bulk density is 1.12 g cm^{-3} and is classified as low to medium according to Landon (1991). The USDA (2012) reported that low to medium soil bulk density enhances healthy roots. Accordingly, the bulk density of the soil in the study area is good for carrot production.

From the bulk density test, the porosity was determined as 57.7 %. Soil porosity is important for plant production, and soil with a porosity range of 50 to 60% is regarded as being appropriate for carrot plant growth (Johansen *et al.*, 2015). This further indicates that the soil in the study area is suitable for carrot production.

Table 4: Mean physical properties of the soil in the study area

Physical properties	Values
Bulk density (g cm^{-3})	1.12
Porosity (% by vol.)	57.7
Particle size distribution (%)	
Clay	39.76
Sand	54.56
Silt	5.68

Soil chemical properties are presented in Table 5. According to Landon (1991), the pH of the soil under study was medium. The preferred pH range for carrots is 5.5 to 7. According to Heckman (2006), the amount of extractable phosphorus (P) in the experimental field can be categorized as being very low. In tropical soils, low availability

of P is a major constraint on agricultural productivity (Nziguheba and Bünemann, 2005). The low level of P in these soils is attributed to the continuous cultivation of farms that leads to a decline in soil fertility due to the constant removal of nutrients by plants without being returned back to the soil (Oberson and Joner, 2005). Therefore, tropical soils require supplemental P from sources such as inorganic fertilizers, manure and rock phosphate for adequate vegetable production (Oberson and Joner, 2005).

Table 5: Mean chemical properties of the soil under study

Chemical characteristics	Value	Description
pH 1:2.5 in H ₂ O	6.12	Medium acidic soil
Total Nitrogen (%)	0.11	Low
Extractable Phosphorus (P) (mg kg ⁻¹)	0.28	Low
EC _e (dS/m)	0.16	Normal
Magnesium (M _g) (Cmol kg ⁻¹)	2.12	High
Potassium (K) (Cmol kg ⁻¹)	0.208	Medium
Sodium (N _a) (Cmol kg ⁻¹)	0.256	Normal
Calcium (C _a) (Cmol kg ⁻¹)	3.02	Low

According to the classification by Metson (1961), the nitrogen (N) in the study area was low. For practical purposes, however, the soil in the study area requires the application of adequate N sourced from organic materials (Heather, 2021). In most cases, carrot growers use inorganic fertilizers as the major source of nutrients in order to attain higher yields and growth parameters (Djoufack *et al.*, 2020). Inorganic fertilizers give a big and fast boost of N to the soil, but they fade quickly (Meliyo *et al.*, 2004). Correcting the N deficiency using organic methods requires time, but will result in a more even distribution of the added nitrogen over time (Heather, 2021). At the same time, organic fertilizers provide the necessary nutrients, improve soil structure, increase the microbial population and maintain crop quality (Shaji *et al.*, 2021).

Exchangeable magnesium (Mg) and potassium (K) values were considered to have been high and medium, respectively (Longe, 1967; Landon, 1991). The magnitudes of

exchangeable Mg and K could be attributed to the contents of the parent materials from which the soil was formed. Most nutrients, like Mg and K, dominate soils with medium to high pH (Fageria, 2002). Soils with a medium K may or may not respond to K fertilizer (Heckman, 2006).

The exchangeable sodium (Na) of the soil under study was rated as being low (Metson, 1961). Exchangeable Na is not an essential plant nutrient. Its absence or presence in very small quantities is not usually harmful to plant nutrition. However, high exchangeable Na may destroy the soil structure and negatively impact on hydraulic properties of the soil.

The levels of calcium (Ca) in the soil under study were rated as being low (Landon, 1991). Ca is an essential nutrient required by plants in relatively large amounts for healthy growth and cell elongation in both shoots and root development (Yaghoub, 2013). It contributes to the soil fertility by helping maintain a flocculated clay and, therefore, good aeration. Also, Ca has a role in maintaining soil physical properties and in preventing soil acidity (Knip *et al.*, 2002). K and Mg both compete with Ca for uptake into the soil, so high concentrations of K and Mg nutrients may reduce the amount of Ca available in the soil (Fake, 2010). Accordingly, the low Ca in the soil under study could be attributed to the high levels of Mg and K available in the soil. Therefore, the soil under study requires supplemental Ca from sources such as agricultural lime or inorganic fertilizer like eggshells in compost (Knip *et al.*, 2002; Aditya *et al.*, 2021). The electrical conductivity (EC_e) of the soil under study falls under normal range of EC according to Scherer (1996).

4.2 Irrigation Water Quality

Table 6 shows the chemical properties of the water used to irrigate the test crop under this study. The pH (7.8) of the water was within the recommended values for irrigation water (Ayers and Westcot, 1985). The electrical conductivity (EC_w) (1.013 dSm^{-1}) of the water

used to irrigate the crop falls in the range of slight to moderate (permissible or medium) according to Ayers and Westcot (1985). Moderate salinity water types are good and have no restrictions for irrigation, except for the requirement of moderate leaching to reduce buildup of the soil salinity and its attendant problems (Ayers, 1977).

Table 6: Irrigation water quality

Parameters	Results	Description
pH (in H ₂ O)	7.8	Normal
C _a (mg L ⁻¹)	37.52	Permissible
N _a (me L ⁻¹)	9.95	Slight to moderate
K (mg L ⁻¹)	2.4	High
EC _w (dSm ⁻¹)	1.013	Medium
M _g (mg L ⁻¹)	47.8	Permissible
P (mg L ⁻¹)	0.04	Non-problem
SAR (meq L ⁻¹)	1.33	Low
Bicarbonate (HCO ₃) (meq L ⁻¹)	0.38	Good
Carbonate (CO ₃) (meq L ⁻¹)	1.38	Medium
Nitrogen (mg L ⁻¹)	0.03	Normal
TDS (mg L ⁻¹)	648.32	Medium

The sodium (Na) (9.95 me L⁻¹) content of the irrigation water was found to be slight to moderate based on Ayers and Westcot (1985) classification. Crop growers face numerous challenges as a result of the Na in irrigation water. It reduces the osmotic potential of water and increases the energy that the plants use to extract moisture from the soil. Na can accumulate in plant stem and leaf tissues and reach toxic levels (Cahn, 2019). Na in the irrigation water with ranges of slight to moderate can be used for irrigation purposes, but chemical means like addition of gypsum are required and the plant has to work harder to absorb water from the soil. When water availability is restricted, the plant soon begins to wilt and grow slowly with reduced yields (Zaman *et al.*, 2018).

Nitrogen (N) (0.03 mg L^{-1}) content of the irrigation water was rated as normal according to Ayers and Westcot (1985). N in the irrigation water is an essential plant nutrient and stimulates the crop growth as soil-applied fertilizer would, but in excess amounts, it can cause significant water quality problems and generate over-stimulation of growth, delayed maturity, or poor quality (Hopkins *et al.*, 2007). Accounting for the nitrogen in the irrigation water allows for substantial decreases in fertilizer costs because it is effectively used by the crop as fertilizer nitrogen. A study by Hidaka (1995) reported that the nitrogen content in irrigation water increased yields in the absence of fertilizer application. Therefore, farmers are advised to reduce the standard nitrogen fertilizer rate if the irrigation water is high in nitrogen (Cahn *et al.*, 2017).

The sodium adsorption ratio (SAR) (1.33 meq L^{-1}) was low according to the classification by Park *et al.* (2015). The sodium hazard of irrigation water is determined by the SAR. A high SAR indicates that there is potential for sodium to accumulate in the soil because, as the SAR increases, the sodium hazard increases and hence, the suitability of water for irrigation decreases. This leads to a decrease in the infiltration and permeability of the soil to water (Hopkins *et al.*, 2007).

The SAR measures the relative concentration of sodium to calcium and magnesium. If irrigation water with a high SAR is applied to a soil, the sodium in the water can displace the calcium and magnesium in the soil, which causes a decrease in the ability of the soil to form stable aggregates, a loss of soil structure and the soil cannot be easily cultivated (Zaman *et al.*, 2018). When the SAR of irrigation water is from 3 to 6, care should be taken with sensitive crops; from 6 to 8, gypsum should be used and soils should be sampled and tested every 1 or 2 years to determine whether the irrigation water is causing a sodium increase (Hopkins *et al.*, 2007).

The total dissolved solids (TDS) (648.32 mg L^{-1}) of the irrigation water were classified as medium (Ayers and Westcot, 1985). It allows the water to be used directly for irrigation purposes. The TDS is useful for evaluating the osmotic effects of salts on crop growth. The high levels of TDS are very likely to cause plant growth problems, loss of soil consistency and thus be harmful to soil fertility (Arshad and Shakoor, 2017; Jadaun *et al.*, 2020). The TDS and conductivity levels in the irrigation water are typically closely correlated. The higher the TDS, the higher the salt hazard, which results in higher electrical conductivity (Hopkins *et al.*, 2007). The density of the irrigation water can be harmful due to an increase in TDS concentrations. High TDS may reduce the clarity of the water by absorbing more heat from solar radiation than water molecules will, which leads to an increase in water temperature (Chhabra, 2018). Also, it may contribute to a decrease in photosynthesis by blocking sunlight and causing less dissolved oxygen to be released into the water by plants, which leads to plant death (Chhabra, 2018).

The phosphorus (P) of the water that was used for irrigation had a value of 0.04 mg L^{-1} . Based on the classification by Park *et al.* (2015), the irrigation water under the study was rated as non-problematic for irrigation. High P levels in the irrigation water have a negative impact on root growth, soil fertility, and infiltration (Oster *et al.*, 2016). It may significantly increase the P in the soil, which causes antagonism and deficiencies in other nutrients (Buelow *et al.*, 2015). Therefore, P levels in irrigation water need to be considered in the overall fertilization program. Based on the rather low soil P content in most soils, it would be an advantage if the irrigation water had a higher concentration of P as it is successfully used by the crop as fertilizer. Ingram (2014) reported that when irrigation water has a P level of greater than 5 mg L^{-1} , additional P in the fertilization program is not necessary.

The K concentration (2.4 mg L^{-1}) of the irrigation water under study was classified as high. According to Ayers and Westcot (1985), this is beyond the permissible limit. High K in irrigation water may reduce plant processes like photosynthesis, respiration, root growth and deteriorate soil fertility, resulting in a reduction in crop yield (Ingram, 2014). Based on that, the K in the irrigation water has the same effect as the K in soil-based fertilizer and an excess of K in irrigation water can cause problems, just as too much fertilizer would, this soil may need no additional K additions through fertilization (Ingram, 2014).

Ca (37.52 mg L^{-1}), Mg (47.8 mg L^{-1}), HCO_3 (0.38 meq L^{-1}), and CO_3 (1.38 meq L^{-1}) concentrations are within the acceptable range for irrigation water (Mezgebe *et al.*, 2015). Ca concentrations in irrigation water are most often a reflection of the type of rock where the water originates (Rengasamy and Marchuk, 2011). High levels of Ca in irrigation water may lead to antagonism, resulting in a deficiency in phosphorus and leading to clogged irrigation equipment due to scale formation (Chhabra, 2018). Likewise, magnesium in water tends to originate from the rock. The high concentrations of Mg in irrigation water build up on contact surfaces, plug pipes and irrigation lines, and damage water heaters (Chhabra, 2018). At high concentrations, Mg can also cause foliar deposits of scale and scale formation, which may require softening (Oster *et al.*, 2016). HCO_3 and CO_3 are common constituents of irrigation water and can influence soil property performance. Irrigation water high in CO_3 and HCO_3 can react with calcium and magnesium in the soil to form insoluble calcium carbonate (CaCO_3) and magnesium carbonate (MgCO_3) (Hopkins *et al.*, 2007). This reaction reduces the amount of free calcium and magnesium in the soil, allowing sodium to compete for and occupy negatively-charged exchange sites on clay particles. Excess sodium in clay results in the

destruction of soil structure and reduced water percolation through the soil profile. This effect is referred to as the sodium permeability hazard (Zaman *et al.*, 2018).

4.3 Crop Water Requirement

It was found that carrots with a growth period of 90 days would require 475.8 mm for the first season (December, January, February, and March) and 233.64 mm for the second season (May, June, July, and August) to grow until maturity in Morogoro, Tanzania. The applied water volume was 96.6 m³ for 100% (I₁₀₀), 77.28 m³ for 80% (I₈₀) and 57.96 m³ for 60% (I₆₀) in the first season, while in the second season it was 47.34 m³ for 100% (I₁₀₀), 37.872 m³ for 80% (I₈₀) and 28.404 m³ for 60% (I₆₀) respectively. In the first season, crop water requirement enhanced carrot growth, yield, and quality parameters more than in the second season.

4.4 Effect of different Irrigation Water Levels on the Growth, Yield, and Quality

Parameters of Carrots under Foliar Feeding

4.4.1 Growth parameters

4.4.1.1 Plant height

Table 7 shows values of plant height for different water application levels in the first and the second seasons. In the first season, the plant heights for 80% and 100% water application levels were not significantly different at the 5% level, and both were significantly different from the 60% water application level. However, in the second season, plant height differed significantly among the three water application levels. Carrots irrigated at 100% water application level produced the highest plant height in season one (43.27 cm) and season two (40.92 cm) compared to 60% and 80% water application levels. On the other hand, the water application level of 60% of ET_c resulted in

the shortest plant height in the first season (37.4 cm) and the second season (37.42 cm).

The results showed that the maximum plant height was produced under the full irrigation. An important factor to consider is the proper irrigation schedule in order to maximize the height of carrots. Similar results were obtained by Seljåsen *et al.* (2013) who reported that the height of carrot plants was positively influenced by the availability of water at the proper timing and amount.

Table 7: Effect of different water application levels on the growth, yield, and quality parameters of carrots under foliar fertilizer

Water application level	Plant height (cm)	Number of leaves	Leaf Length (cm)	Root length (cm)	Root fresh weight (t ha ⁻¹)	Root core diameter (mm)	Root shoulder diameter (mm)	TSS (%)
First season								
60%	37.4 a	9.61 a	10.66 a	14.25 a	16.7 a	13.19 a	23.77 a	8.15 a
80%	41.54 b	9.92 a	10.76 a	16.07 b	21.9 b	16.53 b	26.82 b	8.5 a
100%	43.27 b	10.6 b	11.34 a	17.07 b	30.9 c	18.83 c	29.08 c	8.11 a
LSD (5%)	2.185	0.366	0.716	1.008	1.3	1.728	1.816	0.4995
Second season								
60%	37.4 a	8.79 a	9.53 a	13.82 a	15.1 a	12.8 a	23.39 a	6.38 a
80%	38.83 b	9.78 b	10.06 b	15.36 b	21.2 b	14.03 b	25.90 b	7.67 b
100%	40.92 c	10.43 c	10.54 c	16.94 c	28.4 c	15.98 c	27.13 b	6.34 a
LSD (5%)	0.606	0.378	0.325	1.02	1.19	1.025	2.073	1.107

Means followed by the same letter(s) within a column are not significantly different according to Duncan's multiple range Test

4.4.1.2 Number of leaves

Table 7 shows that the number of leaves per plant was not significantly different ($p>0.05$) between 60% and 80% water application levels, and both were significantly different from the 100% water application level in the first season. However, in the second season, the number of leaves per plant differed significantly among the three water application levels. Irrigating carrots at 100% water application level produced the highest number of leaves in the first season (10.6) as well as in the second season (10.43) compared with the other treatments. The lowest number of leaves per plant was obtained from the 60% water application level in both seasons.

The increase in the number of leaves as water application increased up to 100% of ET_c could be attributed to the better utilization of nutrients using adequate soil moisture. These results are in agreement with those found by Nagaz *et al.* (2012), who reported an increase in the number of leaves of carrots as irrigation water application level increased up to full irrigation.

4.4.1.3 Length of leaves

Leaf lengths were not significantly different ($p>0.05$) among the three water application levels in the first season. However, in the second season, the three water application levels differed significantly ($p<0.05$). Results in Table 7 show that irrigating carrots at 100% water application level resulted in the maximum length of leaves in season one (11.34 cm) as well as in season two (10.54 cm). Likewise, the 60% water application level recorded the minimum length of leaves in the first season (10.66 cm) as well as in the second season (9.53 cm). These results might be due to better water application during the vegetative stage, which helped the crop to better utilize the nutrients and made the plant more efficient in expressing its potential in photosynthesis activity and enhancement of

the length of leaves. In connection with this, Zeipi *et al.* (2014) reported that the length of leaves can be increased if optimal soil moisture and nutrition have been provided during the vegetative stages.

4.4.2 Yield parameter

4.4.2.1 Fresh root weight

Fresh root weight was significantly different ($p < 0.05$) among the three water application levels in both seasons. The highest fresh root weight in the first season (30.9 t ha^{-1}) as well as in the second season (28.4 t ha^{-1}) was recorded under the 100% water application level, while the lowest fresh root weight in the first season (16.7 t ha^{-1}) as well as in the second season (15.1 t ha^{-1}) was obtained under the 60% water application level. The results in Table 7 show that the fresh root weight increased significantly under the highest water application levels. This is in agreement with the findings by Gutezeit (2001), who obtained the highest yields at the highest water application level (75%) compared to 25 and 50% water application levels.

4.4.3 Root growth parameters

4.4.3.1 Root length

Results in Table 7 show that the root length was significantly different ($p < 0.05$) among the three water application levels in both seasons. Full irrigation resulted in the maximum length of root in season one (17.07 cm) as well as in season two (16.94 cm), while the minimum root length in season one (14.25 cm) as well as in season two (13.82 cm) was recorded under the 60% water application level.

The increased root length due to different water application levels was possibly due to availability of sufficient moisture which helped in rapid cell elongation leading to longer

root formation. This observation was also made by Ahmad *et al.* (2005); Afrin *et al.* (2019), who reported that root length of carrot was higher with higher amount of water level.

4.4.3.2 Root core and shoulder diameters

Results in Table 7 indicate that root core diameter differed significantly ($p < 0.05$) among the three water application levels in the first season as well as in the second season. On the other hand, the root shoulder diameter followed the same trend as that of the root core diameter in the first season in terms of statistical significance, but during the second season the root shoulder diameter under the 80 and 100% water application levels did not differ significantly. The maximum root core diameter of 18.83 mm for season one and 15.98 mm for season two was obtained under full irrigation, while the minimum root core diameter of 13.19 mm in the first season and 12.8 mm in the second season was obtained under the 60% water application level. Likewise, the maximum root shoulder diameter in the first season (29.08 mm) and in the second season (27.13 mm) was obtained under the 100% water application level, and the minimum root shoulder diameter in the first season (23.77 mm) and the second season (23.39 mm) was obtained under the 60% water application level.

The findings of this study showed that deficit irrigation (60 and 80% water application levels) produced the minimum values for root core and shoulder diameters of carrots. These results could be attributed to the effect of prolonged water stress, which led to the formation of small roots in carrots. In confirmation of this, Reid and Gillespie (2017) reported that water deficits cause water stress in plants, prevent plant and root growth, and reduce the absorbing areas and capacities of plant roots.

4.4.4 Quality parameter

4.4.4.1 Total soluble solids (TSS)

Results in Table 7 indicate that the total soluble solids were not significantly influenced by water application levels in the first season. However, TSS under the 60 and 100% water application levels differed significantly ($p < 0.05$) from that under the 80% water application level during the second season. The maximum TSS in the first season (8.5%) and in the second season (7.67%) was obtained under the medium water application level (80% of ET_c), while the lowest TSS in the first season (8.11%) and in the second season (6.34%) was obtained under full irrigation.

The fact that the less watered carrots had higher TSS content in their roots could be interpreted that the redistribution of plant photosynthate toward the roots due to the water deficit led to decreased water content as well as increased sugar content. A similar notification has also been made by Fikselová *et al.* (2010), who reported that increased moisture has a negative influence on TSS content on carrot roots.

4.5 Effect of different Water Application Levels on the Growth, Yield and Quality

Parameters of Carrots under Soil based NPK Fertilization

4.5.1 Growth parameters

4.5.1.1 Plant height

Results in Table 8 show that in the first season, the plant heights did not differ significantly ($p > 0.05$) among the 80 and 100% water application levels and both were significantly different from the 60% water application level. However, in the second season, plant heights differed significantly among the three water application levels. Irrigating carrots at a 100% water application level resulted in the highest plant height in season one (44.59 cm) and season two (42.14 cm) compared to 60 and 80% water

application levels. On the other hand, the water application level of 60% of ET_c resulted in the shortest plant height in the first season (37.82 cm) and in the second season (38.1 cm).

Among the growth and yield-contributing characters, plant height is an important factor for the yield of carrots. It is evident that the plant height increased gradually as irrigation water levels increased up to the full irrigation. The findings of this study are similar to those found by Ludong (2008), who reported that the height of carrots was greater from the NPK at a 150% water application level than at a 100% water application level.

Table 8: Effect of different water application levels on the growth, yield and quality parameters of carrots under soil-based NPK fertilization

Water level	Plant height (cm)	Number of leaves	Leaf length (cm)	Root length (cm)	Root fresh weight ($t\ ha^{-1}$)	Root core diameter (mm)	Root shoulder diameter (mm)	TSS %
First season								
60%	37.82 a	10.37 a	10.86 a	15.15 a	20.5 a	15.3 a	24.27 a	8.994 a
80%	42.39 b	10.91 b	11.62 b	16.6 ab	25.2 a	17.39 a	29.28 b	9.978 b
100%	44.59 b	11.69 c	12.57 c	17.17 b	33 b	21.76 b	33.48 c	8.441 a
LSD (5%)	2.553	0.268	0.588	1.616	1.94	2.115	3.755	0.696
Second season								
60%	38.1 a	9.63 a	9.81 a	14.36 a	18.4 a	14.96 a	24.07 a	8.5 a
80%	40.16 b	10.26 b	10.64 ab	15.8 ab	23.4 a	16.72 b	28.51 b	8.8 b
100%	42.14 c	10.83 c	11.08 b	17.02 b	29.1 b	18.21 c	30 c	8.1 c
LSD (5%)	1.409	0.558	1.152	1.761	1.656	0.962	0.934	0.275

Means followed by the same letter (s) in the same column are not significantly different according to Duncan's Multiple Range Test.

4.5.1.2 Number of leaves

As shown in Table 8, the number of leaves differed significantly ($p < 0.05$) among the three water application levels in the first as well as the second season. Full irrigation produced the highest number of leaves per plant in the first season (11.69) as well as in the second season (10.83). The lowest number of leaves per plant in the first season (10.37) as well as in the second season (9.63) was obtained from the 60% water application level.

Full irrigation enhanced the number of leaves compared to deficit irrigation. A similar observation was also made by Joslanny *et al.* (2020), who found that full irrigation produced the highest number of leaves per plant than 80, 60, 40, and 20% water application levels.

4.5.1.3 Leaf length

Leaf lengths were significantly different ($p < 0.05$) among the three water application levels in the first season. In the second season, the leaf lengths under the 60 and 80%; 80 and 100% water application levels were not significantly different ($p > 0.05$); however, leaf lengths differed significantly ($p < 0.05$) between the 60 and 100% water application levels. Results in Table 8 show that full irrigation produced the maximum length of leaves in season one (12.57 cm) as well as in season two (11.08 cm). Likewise, the 60% water application level recorded the minimum length of leaves in the first season (10.86 cm) as well as in the second season (9.81 cm).

The longest leaves were obtained from the higher water application levels than from the lower water application levels. The results of leaf lengths obtained in this study are consistent with the findings by Jahan *et al.* (2020), who obtained a range of 10.37 to 13.65 cm under different water application levels.

4.5.2 Yield parameter

4.5.2.1 Fresh root weight

Results in Table 8 show that fresh root weight was not significantly different ($p > 0.05$) between the 60 and 80% water application levels, and both were significantly different from the full irrigation in both seasons. The highest fresh root weight in the first season (33 t ha^{-1}) as well as in the second season (29.1 t ha^{-1}) was recorded under full irrigation,

while the lowest fresh root weight in the first season (20.5 t ha^{-1}) as well as in the second season (18.4 t ha^{-1}) was obtained under the 60% water application level. Fresh root weight was higher under full irrigation during both seasons. This could be due to the availability of optimal water level, which increased root size and provided more photosynthetic surface, resulting in a higher root fresh yield. In agreement with this, in their study, Quezada *et al.* (2006) found that full irrigation produced the highest fresh root weight of carrots compared to deficit irrigation.

4.5.3 Root growth parameters

4.5.3.1 Root length

Results shown in Table 8 indicate that the root lengths under the 60 and 80%; 80 and 100% water application levels were not significantly different ($p > 0.05$), however, root length differed significantly ($p < 0.05$) between the 60 and 100% water application levels in both seasons. Full irrigation resulted in the maximum length of roots in the first season (17.17 cm) as well as in the second season (17.02 cm). Likewise, the minimum root length in the first season (15.15 cm) as well as in the second season (14.36 cm) was recorded under the 60% water application level. It's possible that the maximum root lengths under full irrigation were due to the intake of appropriate nutrients from the irrigation water for improved root growth, resulting in an increase in root length. These results are similar to those found by Ludong (2008), who found that the root lengths of carrots under the 150% water application level were not significantly different from those under the 100% water application level, but differed from those under the 95% water application level.

4.5.3.2 Root core and shoulder diameter

Results in Table 8 show that the root core diameter did not differ significantly ($p > 0.05$) between the 60 and 80% water application levels, and both were significantly different

from that under full irrigation in the first season. However, in the second season, the root core diameter differed significantly among the three water application levels. On the other hand, the root shoulder diameter differed significantly ($p < 0.05$) among the three water application levels in both seasons.

The maximum root core diameter of 21.76 mm for season one and 18.21 mm for season two was obtained under full irrigation, while the minimum root core diameter of 15.3 mm for season one and 14.96 mm for season two was obtained under the 60% water application level. Likewise, the maximum root shoulder diameter in the first season (33.48 mm) and in the second season (30 mm) was obtained under full irrigation, while the minimum root shoulder diameter in the first season (24.27 mm) and in the second season (24.07 mm) was obtained under the 60% water application level. The production of the maximum root core and shoulder diameters of carrots under full irrigation could be due to the absorption of sufficient moisture during the growing period that facilitated lower soil strength, nutrient absorption and a proper physical environment for better root growth, which increased the volume of roots as stated by Baba and Simon (2015).

4.5.4 Quality parameter

4.5.4.1 Total soluble solids

Total soluble solids were not significantly different ($p > 0.05$) between 60 and 100% water application levels and both were significantly different from those under the 80% water application level in the first season. However, in the second season, the total soluble solids significantly differed ($p < 0.05$) among the three water application levels. As shown in Table 8, the highest TSS in the first season (9.978%) and in the second season (8.8%) were obtained under the 80 water application level, while the lowest TSS in the first season (8.441%) and in the second season (8.1%) were obtained under full irrigation.

The maximum TSS for carrot roots was found at the medium water application level (80 % of ET_c). A similar observation was also made by Abdel-aziz (2017), who found an increase in TSS under the lower water application level.

4.6 Effects of Foliar Fertilizer on the Growth, Yield, and Quality Parameters of Carrots

4.6.1 Growth parameters

4.6.1.1 Plant height

Table 9 shows values of plant height for different Lithovit levels in the first and second seasons. In the first season, the plant heights for 1.5 and 2 g/L/plant fertilizer levels were not significantly different at the 5% level, and both were significantly different from the 1 g/L/plant fertilizer level. However, in the second season, plant height differed significantly among the three fertilizer levels. Spraying foliar fertilizer at a rate of 2 g/L/plant resulted in the highest plant height in season one (43.27 cm) and season two (41.14 cm) compared to 1 and 1.5 g/L/plant fertilizer rates. On the other hand, foliar fertilizer application rate of 1 g/L/plant resulted in the shortest plant height in the first season (37.55 cm) and the second season (36.18 cm). The results showed that carrot height increased under the highest fertilizer rate (2 g/L/plant). This is in agreement with a study by Badr *et al.* (2010), who reported that a higher level of foliar feeding produced the highest carrot height compared to the lower fertilizer levels.

In their study, Alhariri and Boras (2020) reported that foliar application of up to 1.5 g/L/plant fertilizer rate significantly enhanced carrot growth by increasing carrot height.

A study by El-nasr and Ibrahim (2011) reported that spraying carrot plants with foliar fertilizer at a rate of 3 ml/L/plant produced the highest values of plant height compared to control treatment (without foliar application) in two seasons.

Table 9: Effect of different rates of foliar fertilizer on the growth, yield, and quality parameters of carrots

Fertilizer level (g)	Plant height (cm)	Number of Leaves	Leaf length (cm)	Root length (cm)	Root fresh weight (t ha ⁻¹)	Root core diameter (mm)	Root shoulder diameter (mm)	TSS (%)
First season								
1	37.55 a	9.48 a	10.47 a	15.53 a	19.8 a	13.09 a	22.6 a	8.27 b
1.5	41.39 b	10.2 b	10.92 ab	15.71 a	23.6 ab	17.28 b	28.15 b	8.88 c
2	43.27 b	10.46 b	11.37 b	16.16 a	26.1 b	18.18 b	28.92 b	7.6 a
LSD (5%)	2.185	0.366	0.716	1.008	1.3	1.728	1.816	0.4995
Second season								
1	36.18 a	9.23 a	9.45 a	15 a	17.9 a	11.49 a	20.38 a	6.36a
1.5	39.85 b	9.7 b	10.29 b	15.42 a	22.9 b	15.11 b	27.53 b	8.25 b
2	41.14 c	10.08 c	10.39 b	15.7 a	24.03 b	16.21 c	28.51 b	5.78 a
LSD (5%)	0.606	0.378	0.325	1.02	1.19	1.025	2.073	1.107

Means followed by the same letter(s) within a column are not significantly different according to Duncan's Multiple Range Test.

4.6.1.2 Number of leaves

As shown in Table 9, the number of leaves per plant followed the same trend as that of plant height in the two seasons in terms of statistical significance. Spraying foliar fertilizer at a rate of 2g/L/plant produced the highest number of leaves per plant in the first season (10.46) as well as in the second season (10.08) compared with the other treatments. The lowest number of leaves per plant was obtained from the 1 g/L/plant fertilizer rate in both seasons.

The highest number of leaves was recorded at the highest fertilizer rate (2 g/L/plant). In agreement with this, El-Helaly (2018) stated that the use of high foliar feeding rates improved the number of leaves on carrots compared to low fertilizer rates. Badr *et al.* (2010) reported that among the different fertilizer rates (0.5, 1, 1.5 and 2 ml/L/plant), 2 ml/L/plant produced the highest number of leaves.

4.6.1.3 Leaf length

Leaf length was not significantly different ($p > 0.05$) between the 1 and 1.5 g/L/plant fertilizer rates in the first season and both were significantly different from the 2 g/L/plant fertilizer level. However, in the second season, the leaf lengths under the 1.5 and 2 g/L/plant fertilizer rates were not significantly different ($p > 0.05$) and both were significantly different from the 1 g/L/plant fertilizer rate. Results in Table 9 show that spraying foliar fertilizer at a rate of 2 g/L/plant resulted in the maximum length of leaves in season one (11.37 cm) as well as in season two (10.39 cm). Likewise, the 1 g/L/plant fertilizer rate recorded the minimum length of leaves in the first season (10.47 cm) as well as in the second season (9.45 cm).

Foliar application at a rate of 2 g/L/plant resulted in an increase in the length of leaves compared to other fertilizer rates in both seasons. Foliar nutrition using a high fertilizer rate can eliminate problems like fixation and immobilization of nutrients by penetrating the stomata of the leaf, entering the cells rapidly and fulfilling the nutrient demand of the growing plant, resulting in enhanced length of the leaf (Devi, 2016). This is in agreement with the findings of Anub (2019), who reported that an increased application rate of foliar feeding to carrots enhanced the length of the leaves.

4.6.2 Yield parameter

4.6.2.1 Fresh root weight

Fresh root weight was not significantly different ($p > 0.05$) between the 1.5 and 2 g/L/plant fertilizer levels in both seasons. However, whereas fresh root weight under the 1.5 g/L/plant fertilizer level differed significantly from that under the 1 g/L/plant fertilizer level in the second season, there was no significant difference between the two in the first season. Results in Table 9 show that the highest fresh root weight in the first season (26.1 t

ha⁻¹) as well as in the second season (24.03 t ha⁻¹) was recorded under the 2 g/L/plant fertilizer level, while the lowest fresh root weight in the first season (19.8 t ha⁻¹) as well as in the second season (17.9 t ha⁻¹) was obtained under the 1 g/L/plant fertilizer level. The root fresh weight increased under the 2 g/L/plant fertilizer rates. In their study, Shibairo *et al.* (2016) reported that higher fertilizer rates directly increased the root fresh weight by producing heavier roots than the lower rates.

4.6.3 Root growth parameters

4.6.3.1 Root length

Results in Table 9 indicate that the root length was not significantly influenced by the rate of fertilizer application. Nevertheless, the highest rate of 2 g/L/plant resulted in the maximum length of root in both seasons, while the minimum root length was recorded under the 1 g/L/plant fertilizer rate in both seasons. The root length was not significantly different in terms of effect, but the higher fertilizer level (2 g/L/plant) produced the maximum root length. A similar observation was also made by Badr and Helmy (2011), who reported that higher fertilizer rates produced longer roots than the lower fertilizer rates.

4.6.3.2 Root shoulder and core diameters

Results in Table 9 indicate that the root shoulder diameter did not differ significantly ($p > 0.05$) between the 1.5 and 2 g/L/plant fertilizer levels in the first as well as the second seasons and both were significantly different from that under the 1 g/L/plant fertilizer level. On the other hand, the root core diameter did not differ significantly ($p > 0.05$) between the 1.5 and 2 g/L/plant fertilizer levels in the first season, but during the second season, the root core diameter differed significantly ($p < 0.05$) among the three fertilizer levels. The maximum root core diameter of 18.18 cm for season one and 16.21 mm for

season two was obtained under the 2 g/L/plant fertilizer level, while the minimum root core diameter of 13.09 mm in the first season and 11.49 mm in the second season was obtained under the 1 g/L/plant fertilizer level. Likewise, the maximum root shoulder diameter in the first season (28.92 mm) and the second season (28.51 mm) was obtained under the 2 g/L/plant fertilizer level. The minimum root shoulder diameter in the first season (22.6 mm) and the second season (20.23 mm) was obtained under the 1 g/L/plant fertilizer level. These results are in agreement with those of Badr *et al.* (2010). Other studies (El-nasr and Ibrahim, 2011; Sharangi and Paria, 1995; and Arshad *et al.*, 2015) reported that higher fertilizer rates directly increased the root core and shoulder diameters than the lower fertilizer rates.

4.6.4 Quality parameter

4.6.4.1 Total soluble solids (TSS)

As shown in Table 9, the total soluble solids (TSS) were significantly influenced by fertilizer levels in season one. However, TSS under the 1 g/L/plant fertilizer level did not differ significantly ($p > 0.05$) from that under the 2 g/L/plant fertilizer level during the second season. The highest TSS in the first season (8.88%) and the second season (8.25%) was obtained under the medium fertilizer level (1.5 g/L/plant), while the lowest TSS in the first season (7.6%) and the second season (5.78%) was obtained under the high fertilizer level (2 g/L/plant). The results showed that a high fertilizer rate (2 g/L/plant) resulted in decreased sugar levels in the carrots. This is an intriguing result as it tends to suggest that there is an optimal level of fertilization for TSS accumulation. In confirmation of this, Evers (1989), Noella *et al.* (2014) and Mbatha (2008) reported that less fertilized treatments had a greater tendency to increase sugar content in carrots than the most fertilized treatments.

4.7 Effect of soil-based NPK Fertilizer on the Growth, Yield and Quality

Parameters of Carrots

4.7.1 Growth parameters

4.7.1.1 Plant height

Results in Table 10 show values of plant height for different soil-based NPK fertilizer levels in the first and second seasons. In the first season, the plant heights for 1.5 and 2 g/plant fertilizer levels were not significantly different at the 5% level, and both were significantly different from the 1 g/plant fertilizer level. However, in the second season, plant height differed significantly among the three fertilizer levels. Applying soil-based NPK fertilizer at 2 g/plant fertilizer level resulted in the highest plant height in season one (44.16 cm) and in season two (42.21 cm) compared to 1 and 1.5 g/plant fertilizer rates. The shortest plant height in the first season (38.43 cm) and the second season (37.57 cm) was obtained under the 1 g/plant fertilizer level.

Table 10: Effect of different rates of soil-based NPK fertilizer on the growth, yield, and quality parameters of carrots

Fertilizer level	Plant height (cm)	Number of leaves	Leaf length (cm)	Root length (cm)	Fresh root weight (t ha ⁻¹)	Root core diameter (mm)	Root shoulder diameter (mm)	TSS (%)
First season								
1	38.43 a	10.19 a	11.07 a	15.59 a	22.3 a	16.33 a	27.06 a	8.702 a
1.5	42.2 b	11.01 b	11.72 b	16.22 a	24.2 a	18.01 ab	28.21 ab	8.956 a
2	44.16 b	11.77 c	12.26 b	17.11 a	32.1 b	20.11 b	31.76 b	9.756 b
LSD(0.05)	2.48	0.268	0.588	1.616	1.94	2.115	3.755	0.696
Second season								
1	37.57 a	9.8 a	9.57 a	15.47 a	18.5 a	15.05 a	26.24 a	6.922 a
1.5	40.63 b	10.27 ab	10.87 b	15.74 a	23 a	16.47 b	27.79 b	8.811b
2	42.21 c	10.66 b	11.08 b	16.07 a	29.5 b	18.38 c	28.55 b	9.656 c
LSD(0.05)	1.409	0.558	1.152	1.761	1.656	0.962	0.934	0.275

Means followed by the same letter(s) within a column are not significantly different according to Duncan's Multiple Range Test.

These results could be due to the role of potassium and nitrogen as elements in metabolism and a variety of other processes necessary for plant growth (plant height) and

its development. The obtained results are in agreement with those found by Arshad *et al.* (2015). Another study by Ali *et al.* (2003) found that increasing NPK fertilization rate resulted in increased carrot plant height.

4.7.1.2 Number of leaves

As indicated in Table 10, the number of leaves was significantly different ($p < 0.05$) among the three fertilizer levels in the first season. In the second season, the number of leaves under the 1 and 1.5 g/plant and 1.5 and 2 g/plant fertilizer levels was not significantly different ($p > 0.05$). However, there was a significant difference ($p < 0.05$) between the 1 and 2 g/plant fertilizer levels. Applying soil-based NPK at 2 g/plant fertilizer level produced the highest number of leaves per plant in the first season (11.77) as well as in the second season (10.66) compared to the other treatments. The lowest number of leaves per plant was obtained from the 1 g/plant fertilizer rate in the first season (10.19) as well as in the second season (9.8).

These results are in agreement with those found by Shikha *et al.* (2016) and Lobna (2014). The study clearly implied that the increment in fertilization rate directly increased the number of leaves. A study by El-nasr and Ibrahim (2011) reported that the highest fertilization rate produced the highest number of leaves per plant in two seasons.

4.7.1.3 Leaf length

Table 10 shows that the leaf length was not significantly different ($p > 0.05$) between the 1.5 and 2 g/plat fertilizer rates and both were significantly different from the 1 g/plant fertilizer rate in both seasons. Results show that applying soil-based NPK at 2 g/plant resulted in the maximum length of leaves in season one (12.26 cm) as well as in season two (11.08 cm). Likewise, the 1 g/plant fertilizer rate recorded the minimum length of

leaves in the first season (11.07 cm) as well as in the second season (9.57 cm). The length of leaves was not significantly influenced by the application of different levels of NPK fertilizer in both seasons, but the higher fertilizer level (2 g/plant) produced the maximum leaf length. Similar observations were also made by Ludong (2008) and Sylvestre *et al.* (2015).

4.7.2 Yield parameter

4.7.2.1 Fresh root weight

Fresh root weight was not significantly different ($p > 0.05$) between the 1 and 1.5 g/plant fertilizer levels in both seasons. However, fresh root weight under the 2 g/plant fertilizer level differed significantly ($p < 0.05$) from that under the 1 and 1.5 g/plant fertilizer levels in both seasons. The highest fresh root weight in the first season (32.1 t ha⁻¹) as well as in the second season (29.5 t ha⁻¹) was recorded under the 2 g/plant fertilizer level, while the lowest fresh root weight in the first season (22.3 t ha⁻¹) as well as in the second season (18.5 t ha⁻¹) was obtained under the 1 g/plant fertilizer level. The results in Table 10 show that the values of root fresh weight increased under the highest fertilizer rate (2 g/plant) compared to the lowest fertilizer rates. This is in agreement with the findings of Ali *et al.* (2003), who reported that the root yield increased progressively and significantly with the increased application of nitrogen and potassium fertilizer.

4.7.3 Root growth parameters

4.7.3.1 Root length

Results in Table 10 show that the root length was not significantly influenced by the rate of fertilizer application. Nevertheless, the highest rate of 2 g/plant resulted in the maximum length of root in season one (17.11 cm) as well as in season two (16.07 cm). The minimum root length in season one (15.59 cm) as well as in season two (15.47cm)

was recorded under the 1 g/plant fertilizer rate. The results by Lobna (2014) agree with the present findings. The increase in root length could however be attributed to the increased nutrient use efficiency of both macro and micro nutrients from the NPK high level. This is logical as the macro and micro nutrients contribute to cell division and elongation, which in turn increase the root length of the carrots. This is in agreement with the findings of Habimana *et al.* (2014) and Murwira *et al.* (2002).

4.7.3.2 Root core and shoulder diameter

Table 10 shows that root shoulder and core diameters under the 1.5 g/plant fertilizer level did not differ significantly ($p > 0.05$) from those under the 1 and 2 g/plant fertilizer levels, but those under the 1 g/plant fertilizer level were significantly different from those under the 2 g/plant fertilizer level in the first season. However, in the second season, the root core diameter differed significantly ($p < 0.05$) among the three fertilizer levels, but the root shoulder diameter did not significantly differ ($p > 0.05$) between the 1.5 and 2 g/plant fertilizer rates, but both were significantly different from the 1 g/plant fertilizer rate. The maximum root core diameter in the first season (20.11 mm) as well as in the second season (18.38 mm) was obtained under the 2 g/plant, while the minimum root core diameter in the first season (16.33 mm) as well as in the second season (15.05 mm) was obtained under the 1 g/plant fertilizer level. Likewise, the maximum root shoulder diameter in the first season (31.76 mm) as well as in the second season (28.55 mm) was obtained under the 2 g/plant fertilizer level, while the minimum root shoulder diameter in the first season (27.06mm) as well as in the second season (26.24 mm) was obtained under the 1 g/plant fertilizer level. These results are in agreement with the findings by Sylvestre *et al.* (2015) and Arshad *et al.* (2015) who reported that inorganic fertilizers improve the soil structure and apart from this, they allow the root shoulder and core of carrot roots to easily expand.

4.7.4 Quality parameter

4.7.4.1 Total soluble solids (TSS)

Results in Table 10 show that the total soluble solids (TSS) were not significantly different ($p>0.05$) between the 1 and 1.5 g/plant fertilizer rates, but both were significantly different from those under the 2 g/plant fertilizer level in season one. However, TSS differed significantly ($p<0.05$) among the three fertilizer levels in the second season. The highest TSS in the first season (9.756 %) and in the second season (9.656%) was obtained under the 2 g/plant fertilizer rate, while the lowest TSS in the first season (8.702%) and in the second season (6.922%) was obtained under the 1 g/plant fertilizer rate. The improvement in the TSS in roots as a result of NPK could be attributed to the mode of action of macro nutrients in enhancing the photosynthetic activity and enzymes of carbohydrate transformation. This is in agreement with the findings by Lyngdoh (2001) and Noella *et al.* (2014) who reported that TSS increased with increasing levels of potassium, nitrogen and phosphorus.

In both seasons, NPK soil-based fertilizer produced the highest plant growth, yield, and quality parameters than foliar feeding. This shows that the percentage contribution of nutrients from NPK is much higher than the nutrients supplied through foliar feeding for obtaining crop growth, yield, and quality parameters. Although the application of nutrients through foliar feeding has higher utilization efficiency, it may not satisfy the complete nutrient requirement of the crop. This observation was also made by Albadawy and El-gioushy (2019), who reported that foliar application was not superior to soil or basal application for plant enhancement. Ling and Silberbush (2002) reported that foliar feeding alone does not have the potential to fulfil the requirements of the plant for nutrients, but may be used just as a supplemental method.

4.8 Effect of the Interaction between Irrigation Water and Foliar Fertilizer Levels on the Growth, Yield and Quality Parameters of Carrots

4.8.1 Growth parameters

4.8.1.1 Plant height

Results in Table 11 show that the plant height was not significantly different ($p > 0.05$) among the full irrigation \times 1 g/L/plant, 60% of $ET_c \times$ 2 g/L/plant, 80% of $ET_c \times$ 1.5 g/L/plant, 60% of $ET_c \times$ 1.5 g/L/plant and 80% of $ET_c \times$ 1 g/L/plant fertilizer levels, but they all were significantly different from the 60% of $ET_c \times$ 1 g/L/plant and the full irrigation \times 2 g/L/plant fertilizer levels in the first season. However, in the second season, results in Table 12 show that the plant height differed significantly ($p < 0.05$) between 60% of $ET_c \times$ 1 g/L/plant, 80% of $ET_c \times$ 1 g/L/plant, full irrigation \times 1 g/L/plant, and full irrigation \times 2 g/L/plant fertilizer levels. The interaction between full irrigation \times 2 g/L/plant fertilizer level produced the highest plant height in the first season (46.43 cm) as well as in the second season (43.08 cm) compared to other interactions, while 60% of $ET_c \times$ 1 g/L/plant resulted in the shortest plant height in the first season (33.83 cm) and in the second season (34.49 cm). The height of carrots increased with every increment of fertilizer and irrigation water, up to 2 g/L/plant in combination with full irrigation. The findings are in harmony with those by Prabhakar *et al.* (1991) and Batra (1990), who reported that the increase in irrigation water and fertilizer levels resulted in increased carrot height.

Table 11: Effect of the interaction between water application and foliar fertilizer levels on the growth parameters of carrots for first season

First season			
Fertilizer levels	1 g	1.5 g	2 g
Water levels	Plant height		
60%	33.83 a	38.49 b	39.87 bc
80%	39.11 b	42 bc	43.50 cd
100%	39.7 bc	43.69 cd	46.43 d
LSD (5%)	3.784		
	Number of leaves		
60%	8.93 a	9.93 bc	9.97 bc
80%	9.47 ab	10.17 bc	10.14 bc
100%	10.03 bc	10.5 c	11.27 d
LSD (5%)	0.635		
	Length of leaves		
60%	9.72 a	10.85 ab	11.41 b
80%	10.48ab	10.66 ab	11.14 b
100%	11.22ab	11.24 ab	11.56 b
LSD (5%)	1.241		

Means followed by the same letter (s) in the same column are not significantly different according to Duncan's Multiple Range Test

4.8.1.2 Number of leaves

Table 11 shows that the number of leaves per plant did not differ significantly ($p > 0.05$) among the full irrigation \times 1 g/L/plant, 60% of $ET_c \times$ 1.5 g/L/plant, 80% of $ET_c \times$ 1.5 g/L/plant, 60% of $ET_c \times$ 2 g/L/plant and 80% of $ET_c \times$ 2 g/L/plant fertilizer levels, but they all significantly differed from the full irrigation \times 2 g/L/plant fertilizer level in the first season. Table 12 shows that the number of leaves was not significantly different ($p > 0.05$) among the various interactions but significantly differed from the 60% of $ET_c \times$ 1 g/L/plant fertilizer rate in the second season. Application of full irrigation in combination with 2 g/L/plant fertilizer level produced the highest number of leaves in season one (11.27) as well as in season two (10.51), while the lowest number of leaves in season one (8.93) as well as in season two (8.16) was obtained under the 60% of $ET_c \times$ 1 g/L/plant fertilizer level. This could mean that the nutrients from irrigation water (full irrigation) in combination with the nutrients from foliar feeding enhanced photosynthesis which resulted in better plant growth (number of leaves). These results are in agreement with those found by Alam *et al.* (1970), who reported that the number of leaves per plant did

not differ significantly from different water application levels in combination with different fertilizer rates.

Table 12: Effects of the interaction between water application and foliar fertilizer levels on the growth parameters of carrots for second season

Second season			
Fertilizer levels	1		
	1 g	1.5 g	2 g
Water levels	Plant height		
60%	34.49 a	38.29 c	39.5 d
80%	35.74 b	39.91 de	40.85 ef
100%	38.31 c	41.37 f	43.08 g
LSD (5%)	1.105		
	Number of leaves		
60%	8.16 a	8.88 b	9.31 bc
80%	9.16 bc	9.75 cd	10.43 de
100%	10.36 de	10.43 de	10.51 e
LSD (5%)	0.65		
	Length of leaves		
60%	9 a	10.09 cde	9.5 abc
80%	9.47 ab	10.28 de	10.42 de
100%	9.87 bcd	10.51 e	11.25 f
LSD (5%)	0.563		

Means followed by the same letter (s) in the same column are not significantly different according to Duncan's Multiple Range Test.

4.8.1.3 Length of leaves

Results in Table 11 show that the leaf length under the 60% of $ET_c \times 1$ g/L/plant fertilizer level was significantly different ($p < 0.05$) from that under the 60% of $ET_c \times 1$ g/L/plant, 60% of $ET_c \times 2$ g/L/plant, 80% of $ET_c \times 2$ g/L/plant, and full irrigation $\times 2$ g/L/plant fertilizer levels in the first season. However, in the second season, 60% of $ET_c \times 1$ g/L/plant and 80% of $ET_c \times 1$ g/L/plant, 80% of $ET_c \times 1$ g/L/plant and full irrigation $\times 1$ g/L/plant, 80% of $ET_c \times 1.5$ g/L/plant and 80% of $ET_c \times 2$ g/L/plant fertilizer levels did not differ significantly ($p > 0.05$), and they all differed significantly from the full irrigation $\times 2$ g/L/plant fertilizer level. Results in Table 11 and Table 12 show that the maximum leaf length in season one (11.56 cm) as well as in season two (11.25 cm) was obtained under

full irrigation in combination with the 2 g/L/plant fertilizer level. Likewise, the minimum leaf length in season one (9.72 cm) as well as in season two (9 cm) was obtained under the 60% of $ET_c \times 1$ g/L/plant fertilizer level. The results reveal that irrigation water and fertilizer levels had a substantial impact on leaf length which consistently increased from lower water application and fertilizer levels to higher water application and fertilizer levels. This positive effect on the length of leaves due to increased irrigation and fertilizer levels could be attributed to the favourable soil moisture for proper plant growth associated with rapid increase and expansion of plant cells in combination with fertilizer components ($CaCO_3$, $MgCO_3$) that can penetrate rapidly into plant tissues through the stomata and play vital roles in the biological and physiological processes of carrot plants, resulting in an increase of the length of leaves (IFAS, 2015).

4.8.2 Yield parameter

4.8.2.1 Fresh root weight

Results in Table 13 and Table 14 show that fresh root weight was not significantly different ($p > 0.05$) between the 60% of $ET_c \times 1$ g/L/plant, 60% of $ET_c \times 1.5$ g/L/plant, 60% of $ET_c \times 2$ g/L/plant, 80% of $ET_c \times 1$ g/L/plant, and 80% of $ET_c \times 1.5$ g/L/plant fertilizer rates, but they all differed significantly from the full irrigation $\times 2$ g/L/plant fertilizer rate combination in both seasons. The highest fresh root weight in the first season (33.3 t ha^{-1}) as well as in the second season (32.8 t ha^{-1}) was recorded under the full irrigation in combination with the 2 g/L/plant fertilizer rate, while the lowest root fresh weight in the first season (15 t ha^{-1}) as well as in the second season (13.2 t ha^{-1}) was obtained under the 60% of $ET_c \times 1$ g/L/plant fertilizer rate. The results show that the highest values of fresh root weight of carrots were recorded at higher water application in combination with higher fertilizer levels in both seasons (full irrigation $\times 2$ g/L/plant fertilizer rate). This is

in agreement with the findings by Abdel-Mawly *et al.* (2004), who found that increasing irrigation water level and fertilizer rate significantly increased the root yield of carrots.

Table 13: Effects of interaction between water application and foliar fertilizer levels on the root growth parameters of carrots for first season

Fertilizer levels	First season		
	1 g	1.5 g	2 g
Water levels	Root length		
60%	14.3 ab	14.55 abc	13.9 a
80%	15.84 bcd	15.7 abcd	16.67 de
100%	16.43 cde	16.86 de	17.9 e
LSD (5%)	1.746		
	Root fresh weight		
60%	15 a	16.6 a	18.3 a
80%	17.6 a	21.3 ab	26.6 bc
100%	26.6 bc	32.6 c	33.3 c
LSD (5%)	2.26		
	Root core diameter		
60%	9.66 a	14.05 b	15.86 bc
80%	14.18 b	17.87 cd	17.54 cd
100%	15.44 bc	19.91 de	21.12 e
LSD (5%)	2.994		

Means followed by the same letter (s) in the same column are not significantly different according to Duncan's Multiple Range Test.

4.8.3 Root growth parameters

4.8.3.1 Root length

Table 13 and Table 14 show that the root length was not significantly different ($p > 0.05$) among the 60% of $ET_c \times 1$ g/L/plant, 60% of $ET_c \times 2$ g/L/plant, 80% of $ET_c \times 1$ g/L/plant, and 80% of $ET_c \times 1.5$ g/L/plant fertilizer levels, but they all differed significantly from the full irrigation in combination with the 2 g/L/plant fertilizer rate in both seasons. The maximum root length in season one (17.9 cm) as well as in season two (17.83 cm) was obtained under full irrigation in combination with the 2 g/L/plant fertilizer levels, while the minimum root length in season one (14.3 cm) as well as in season two (12.96 cm) was obtained under the 60% of $ET_c \times 1$ g/L/plant fertilizer level. The lowest water application level, in combination with lower fertilizer rate (60% of $ET_c \times 1$ g/L/plant fertilizer level), produced the minimum root lengths. This could be due to the prolonged water and

fertilizer stress that caused the carrot plants to absorb inadequate nutrients essential for root growth. A study by Sorensen *et al.* (1997) revealed that drought stress throughout the entire growth period of carrots caused a more severe reduction in root production.

Table 14: Effects of interaction between water application and foliar fertilizer levels on the root growth parameters of carrots for second season

Second season			
Fertilizer levels	1		
	1 g	1.5 g	2 g
Water levels	Root length		
60%	14.95 bc	12.96 a	13.55 ab
80%	14.37 abc	16 cde	15.71 cd
100%	15.69 cd	17.3 de	17.83 e
LSD (5%)	1.774		
	Root fresh weight		
60%	13.2 a	15.5 ab	16.6 ab
80%	17.7 ab	20.4 abc	25.6 cde
100%	22.7cd	29.7 de	32.8e
LSD (5%)	0.207		
	Root core diameter		
60%	9.51 a	13.69 c	15.19 cd
80%	11.5 b	15.24 cd	15.37 cd
100%	13.46 c	16.41 de	18.06 e
LSD (5%)	1.755		

Means followed by the same letter (s) in the same column are not significantly different according to Duncan's Multiple Range Test.

4.8.3.2 Root core diameter

Table 13 and Table 14 show that the root core diameter was not significantly different ($p > 0.05$) among the 80% of $ET_c \times 1$ g/L/plant, 60% of $ET_c \times 1.5$ g/L/plant and full irrigation $\times 1$ g/L/plant fertilizer rates, and they all differed significantly from the 60% of $ET_c \times 1$ g/L/plant and full irrigation $\times 2$ g/L/plant fertilizer rates in both seasons. The maximum root core diameter of 21.12 mm for season one and 18.06 mm for season two was obtained under full irrigation in combination with the 2 g/L/plant fertilizer level, while the minimum root core diameter of 9.66 mm for season one and 9.51 mm for season two was obtained under the 60% of $ET_c \times 1$ g/L/plant fertilizer rate. The results show that lower water application levels as well as lower fertilizer levels resulted in thinner roots. In

agreement with this, Afrin *et al.* (2019) reported that high water application level in combination with a high fertilizer rate produced the highest diameter of roots.

4.8.3.3 Root shoulder diameter

Table 15 shows that the root shoulder diameter was significantly different ($p < 0.05$) among the 60% of $ET_c \times 1$ g/L/plant, 100% of $ET_c \times 1$ g/L/plant, 80% of $ET_c \times 1.5$ g/L/plant, and full irrigation $\times 2$ g/L/plant fertilizer rates in the first season. However, in the second season, Table 16 shows that the root shoulder diameter was not significantly different ($p > 0.05$) among the 60% of $ET_c \times 1.5$ g/L/plant, 60% of $ET_c \times 2$ g/L/plant, 80% of $ET_c \times 1.5$ g/L/plant, 80% of $ET_c \times 2$ g/L/plant, full irrigation $\times 1.5$ g/L/plant, and full irrigation $\times 2$ g/L/plant fertilizer rates. The maximum root shoulder diameter of 31.7 mm for season one and 29.71 mm for season two was recorded under full irrigation in combination with the 2 g/L/plant fertilizer rate, while the minimum root shoulder diameter of 20.88 mm for season one and 16.3 mm for season two was recorded under the 60% of $ET_c \times 1$ g/L/plant fertilizer rate. A similar explanation as that advanced for the root core diameter could apply to the root shoulder diameter as these are very much related.

Table 15: Effects of the interaction between water application and foliar fertilizer levels on the root growth and quality parameters of carrots for first season

First season			
Fertilizer levels	1		
	1 g	1.5 g	2 g
Water levels	Root shoulder diameter		
60%	20.88 a	25.22 bc	25.2 bc
80%	22.46 ab	28.14 cd	29.86 de
100%	24.45 b	31.1 de	31.7 e
LSD (5%)	3.146		
	TSS		
60%	8.1 abc	8.933 cd	7.433 a
80%	8.9 cd	8.667 bcd	7.933 ab
100%	7.833 ab	9.067 d	7.433 a
LSD (5%)	0.865		

4.8.4 Quality parameter

4.8.4.1 Total soluble solids (TSS)

Results in Table 15 and Table 16 show that the TSS was not significantly different ($p>0.05$) among the 60% of $ET_c \times 1$ g/L/plant, 60% of $ET_c \times 2$ g/L/plant, 80% of $ET_c \times 2$ g/L/plant, full irrigation $\times 1$ g/L/plant, and full irrigation $\times 2$ g/L/plant fertilizer rates in both seasons. The highest TSS in the first season (9.067%) and in the second season (9.17%) was obtained under the 80% of $ET_c \times 1.5$ g/L/plant fertilizer level, while the lowest TSS in the first season (7.433%) and the second season (5.54) were obtained under the full irrigation $\times 2$ g/L/plant fertilizer rate. This effect suggests that in the case of soil moisture and fertilizer stress, the plant decreases the osmotic potential by increasing the levels of sugar content. This is supported by the findings of Intrigliolo and Castel (2010) and Evers (1989), who reported that the lower fertilizer level combined with decreased irrigation water level has a tendency to increase more sugar content in the roots than the most fertilized and irrigated treatments.

Table 16: Effects of interaction between water application and foliar fertilizer levels on the root growth and quality parameters of carrots for second season

Second season			
Fertilizer levels	1		
	1 g	1.5 g	2 g
Water levels	Root shoulder diameter		
60%	16.3 a	26.62 cd	27.24 d
80%	21.73 b	27.4 d	28.58 d
100%	23.12 bc	28.56 d	29.71 d
LSD (5%)	3.59		
	TSS		
60%	5.57 a	7.84 bde	5.74 ab
80%	7.97 e	9.17 e	5.87 abcd
100%	5.54 a	7.74 bcde	5.74 abc
LSD (5%)	1.918		

Means followed by the same letter (s) in the same column are not significantly different according to Duncan's Multiple Range Test

4.9 Effects of the Interaction between water Application and Soil-Based NPK

Fertilizer Levels on the Growth, Yield and Quality Parameters of Carrots

4.9.1 Growth parameters

4.9.1.1 Plant height

Results in Table 17 show that the plant height was significantly different ($p < 0.05$) between the full irrigation \times 2 g/plant fertilizer rate and the rest of the interactions in the first season. However, in the second season, Table 18 shows that the plant height did not differ significantly ($p > 0.05$) among the full irrigation \times 1.5 g/plant, full irrigation \times 2 g/plant, and 80% \times 1.5 g/plant fertilizer levels. The maximum plant height in the first season (49.22 cm) as well as in the second season (44.19 cm) was obtained under the full irrigation in combination with the 2 g/plant fertilizer level, while the minimum plant height in the first season (35.5 cm) as well as in the second season (34.74 cm) was obtained under the 60% of ET_c \times 1 g/plant fertilizer level. The highest water application level combined with the highest fertilizer rate resulted in higher plant height than the lower combinations. This could be attributed to better soil moisture levels to transport nutrients distributed by NPK in the soil to promote photosynthesis, regulate temperature, and keep cells turgid, resulting in better plant growth. In agreement with this, Brito *et al.* (2008) reported that the higher water application level favored by the transformation of organic matter derived from inorganic fertilizer due to the optimal level of soil moisture resulted in better development of the plant height.

Table 17: Effects of the interaction between water application and soil-based NPK fertilizer levels on the growth parameters of carrots for first season

First season			
Fertilizer levels	1		
	1 g	1.5 g	2 g
Water levels			
	Plant height		
60%	35.5 a	37.84 ab	40.11 abcd
80%	37.97 abc	46.04 ef	43.15 de
100%	41.83 bcde	42.71 cde	49.22 f
LSD (5%)	4.296		
	Number of leaves		
60%	9.83 a	10.5 bc	10.77 c
80%	10.23 ab	10.93 c	11.57 d
100%	10.5 bc	11.6 d	12.97 e
LSD (5%)	0.585		
	Length of leaves		
60%	10.38 a	10.91 ab	11.27 ab
80%	11.25 ab	11.65 bc	11.95 bc
100%	11.57 bc	12.59 cd	13.55d
LSD (5%)	1.019		

Means followed by the same letter (s) in the same column are not significantly different according to Duncan's Multiple Range Test

4.9.1.2 Number of leaves

As shown in Table 17 and Table 18, the number of leaves followed the same trend as that of the plant height in both seasons in terms of statistical significance. The maximum number of leaves in the first season (12.97) and the second season (11.37) was produced under the full irrigation in combination with the 2 g/plant fertilizer rate, while the minimum number of leaves in the first season (9.83) and the second season (9.47) was produced under the 60% of $ET_c \times 1$ g/plant fertilizer level. The increased number of leaves under a 100% water application level in combination with the 2 g/plant fertilizer rate could be attributed to the availability of more nutrients from irrigation water and NPK soil-based fertilizer that possibly increased the rate of cell division and elongation, leading to the production of more plant leaves as stated by Afrin *et al.* (2019).

4.9.1.3 Length of leaves

Table 17 shows that the length of leaves was not significantly different ($p>0.05$) among the 60% of $ET_c \times 1.5$ g/plant, 60% of $ET_c \times 2$ g/plant, and 80% of $ET_c \times 1$ g/plant fertilizer levels in the first season. However, in the second season, results in Table 18 show that the length of leaves differed significantly between the 60% of $ET_c \times 1$ g/plant and full irrigation $\times 2$ g/plant fertilizer rates. The maximum length of leaves in season one (13.55 cm) and in season two (11.85 cm) was obtained under the full irrigation in combination with the 2 g/plant fertilizer rate. The minimum length of leaves in season one (10.38 cm) and in season two (8.79 cm) was obtained under the 60% of $ET_c \times 1$ g/plant fertilizer rate. The leaf length increased when the full irrigation is combined with 1 g/plant fertilizer rate. The results of this study could be attributed to the physiochemical and biological improvements that occurred in the soil, including favourable temperature and moisture regimes, nutrient availability, and microbial activity that occurred in the carrot plant. For this reason, photosynthesis and stomatal conductance increased and the leaves became longer, as also observed by Jahan *et al.* (2020).

Table 18: Effects of the interaction between water application and soil-based NPK fertilizer levels on the growth parameters of carrots for second season

Fertilizer levels	Second season		
	1 g	1.5 g	2 g
Water levels	Plant height		
60%	34.74 a	39.15 bc	40.43 bcd
80%	37.88 b	40.6 cd	42.01 de
100%	40.11 bcd	42.13 de	44.19 e
LSD (5%)	2.44		
	Number of leaves		
60%	9.47 a	9.47 a	9.96 ab
80%	9.8 ab	10.3 abc	10.67 bcd
100%	10.1 abc	11.03 cd	11.37 d
LSD (5%)	0.967		
	Length of leaves		
60%	8.79 a	10.25 ab	10.37 ab
80%	10.03 ab	10.85 ab	11.03 ab
100%	9.88 ab	11.52 b	11.85 b
LSD (5%)	1.996		

Means followed by the same letter (s) are not significantly different according to Duncan's Multiple Range Test

4.9.2 Yield parameter

4.9.2.1 Fresh root weight

Results in Table 19 and Table 20 show that the fresh root weight was not significantly different ($p > 0.05$) among the 60% of $ET_c \times 1.5$ g/plant, 60% of $ET_c \times 2$ g/plant, 80% of $ET_c \times 1$ g/plant, 80% of $ET_c \times 1.5$ g/plant, 80% of $ET_c \times 2$ g/plant, full irrigation $\times 1$ g/plant, and full irrigation $\times 1.5$ g/plant fertilizer levels in both seasons, but they all differed significantly ($p < 0.05$) from the full irrigation $\times 2$ g/plant fertilizer level in both seasons. The highest fresh root weight of 44.4 t ha⁻¹ for season one and 38.8 t ha⁻¹ for season two was obtained under full irrigation in combination with the 2 g/plant fertilizer level. Likewise, the lowest fresh root weight of 16.3 t ha⁻¹ for season one and 12.6 t ha⁻¹ for season two was obtained under the 60% of $ET_c \times 1$ g/plant fertilizer rate.

Table 19: Effects of the interaction between water application and soil-based NPK fertilizer levels on the root growth parameters of carrots for first season

First season			
Fertilizer levels	1		
	1 g	1.5 g	2 g
Water levels			
Root length			
60%	14.53 a	15.23 ab	15.68 ab
80%	16 ab	16.39 ab	17.4 ab
100%	16.24 ab	17.02 ab	18.25 b
LSD (5%)	2.8		
Root fresh weight			
60%	16.3 a	22.5 ab	22.7 ab
80%	21.6 ab	24.6 ab	29.3 b
100%	29.1 b	25.4 ab	44.4 c
LSD (5%)	0.336		
Root core diameter			
60%	14.84 a	15.07 a	15.99 a
80%	16.3 a	17.83 ab	18.04 ab
100%	17.86 ab	21.14 b	26.3 c
LSD (5%)	3.663		

Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test

The present study shows that the combination between full irrigation and 2 g/plant fertilizer level increased the root fresh weight. This is in agreement with a study by Gutezeit (2001), which revealed that the interaction between higher water application level and fertilizer rate (75% of ET_c in combination with 150 kg N ha⁻¹) produced the highest fresh root weight compared to other combinations.

4.9.3 Root growth parameters

4.9.3.1 Root length

Results in Table 19 and Table 20 show that the root length was not influenced by the combination of irrigation water and fertilizer levels in both seasons. Full irrigation in combination with the 2 g/plant fertilizer rate resulted in the maximum root length in the first season (18.25 cm) as well as in the second season (17.49 cm). The minimum root lengths in the first season (14.53 cm) as well as in the second season (13.87 cm) were recorded under the 60% of $ET_c \times 1$ g/plant fertilizer level. The combination of high water application and fertilizer levels increased the root length in both seasons compared to other combinations. The increased root length due to high levels of irrigation water and fertilizer was possibly due to the availability of sufficient moisture and nutrients in the soil, which helped in rapid cell division and elongation, resulting in longer root formation. Ahmad *et al.* (2005) reported that the root length of carrots was higher with higher amount of water and fertilizer levels. Another study by Rima *et al.* (2021) reported that the root length was increased due to high levels of NPK and irrigation water application.

4.9.3.2 Root core diameter

Results in Table 19 and Table 20 show that the root core diameter was significantly different ($p < 0.05$) between the full irrigation \times 2 g/plant fertilizer rate and the rest of combinations in both seasons. The maximum root core diameter in season one (26.3 mm)

as well as in season two (20.24 mm) was obtained under the full irrigation in combination with the 2 g/plant fertilizer level. The minimum root core diameter in season one (14.84 mm) as well as in season two (13.54 mm) was obtained under the 60% of $ET_c \times 1$ g/plant fertilizer rate. The highest root core diameter obtained under higher water application and fertilizer levels could be due to the absorption of sufficient moisture and nutrients from NPK soil-based fertilizer throughout the growing period that facilitated lower soil strength, greater nutrient uptake and a proper physical environment for better root growth. As stated by Jahan *et al.* (2020), this increased the volume of root by both length and diameter and ultimately increased the yield. Ahmad *et al.* (2005) stated that treatments that produced the longest roots might have contributed to the maximum diameter of roots.

Table 20: Effects of the interaction between water application and soil-based NPK fertilizer levels on the root growth parameters of carrots for second season

Second season			
Fertilizer levels	1		
	1 g	1.5 g	2 g
Water level	Root length		
60%	13.87 a	14.33 ab	14.89 ab
80%	15.72 ab	16.13 ab	15.82 ab
100%	16.82 ab	16.75 ab	17.49 b
LSD (5%)	3.05		
	Root fresh weight		
60%	12.6 a	20.6 ab	22.1 ab
80%	19.2 ab	23.4 b	27.6 b
100%	23.6 b	24.8 b	38.8 c
LSD (5%)	0.286		
	Root core diameter		
60%	13.54 a	14.97 ab	16.39 bc
80%	15.15 ab	16.51 bc	18.51 d
100%	16.46 bc	17.94 cd	20.24 e
LSD (5%)	1.666		

4.9.3.3 Root shoulder diameter

Table 21 shows that the root shoulder diameter was not significantly different ($p>0.05$) among the 60% of $ET_c \times 1$ g/plant, 60% of $ET_c \times 2$ g/plant, 80% of $ET_c \times 1$ g/plant and 80% of $ET_c \times 1.5$ g/plant fertilizer levels in the first season. However, in the second season, results in Table 22 show that the root shoulder diameter differed significantly ($p<0.05$) between the 60% of $ET_c \times 1$ g/plant and the rest of combinations. The maximum root shoulder diameter in the first season (37.21 mm) and in the second season (30.47 mm) was obtained under the full irrigation in combination with 2 g/plant fertilizer rate, while the minimum root shoulder diameter in the first season (23.2 mm) and in the second season (22.41 mm) was obtained under the 60% of $ET_c \times 1$ g/plant fertilizer level. A similar explanation as that advanced for the root core diameter could apply to the root shoulder diameter as these are very much related.

4.9.4 Quality parameter

4.9.4.1 Total soluble solids (TSS)

Table 21 and Table 22 show that the total soluble solids were not significantly different ($p>0.05$) among the 60% of $ET_c \times 1$ g/plant, 80% of $ET_c \times 1.5$ g/plant, 60% of $ET_c \times 1.5$ g/plant and 80% of $ET_c \times 1$ g/plant fertilizer levels in both seasons, but they all differed significantly from the full irrigation \times 2 g/plant fertilizer level in both seasons. The highest TSS in the first season (10.36%) and in the second season (10%) was obtained under the full irrigation in combination with the 2 g/plant fertilizer level. Likewise, the lowest TSS in the first season (9.33%) and in the second season (9.23%) was obtained under the 60% of $ET_c \times 1$ g/plant fertilizer rate. The interaction between soil-based NPK fertilizer rates with irrigation water levels significantly influenced the growth, yield and quality parameters for carrots in both seasons. This could be due to the role of nitrogen, phosphorus, and potassium elements and soil moisture in allowing photosynthesis to

provide essential nutrients for the growth, yield, and quality parameters of carrots. As stated by Ardiles *et al.* (2011), proper water and fertilizer management is key to successful and sustainable agriculture development, not only for carrot farming but for other root crops as well.

Table 21: Effects of the interaction between water application and soil-based NPK fertilizer levels on the root growth and quality parameters of carrots for first season

First season			
Fertilizer levels			1
	1 g	1.5 g	2 g
Water levels	Root shoulder diameter		
60%	25.36 ab	23.2 a	24.26 ab
80%	26.42 ab	27.63 ab	33.79 cd
100%	29.41 bc	33.81 cd	37.21 d
LSD (5%)	6.504		
	TSS		
60%	7.857 a	8.133 ab	9.333 bcde
80%	8.85 abcd	8.567 abc	9.567 cde
100%	9.4 bcde	10.167 de	10.367 e
LSD (5%)	1.205		

Table 22: Effects of the interaction between water application and soil-based NPK fertilizer levels on the root growth and quality parameters of carrots for second season

Second season			
Fertilizer levels			1
	1 g	1.5 g	2 g
Water levels	Root shoulder diameter		
60%	22.41 a	24.18 b	25.62 bc
80%	27.09 c	28.88 d	29.56 d
100%	29.22 d	30.31 d	30.47 d
LSD (5%)	1.618		
	TSS		
60%	6.6 a	8.467c	9.233d
80%	6.867ab	8.867cd	9.733e
100%	7.3b	9.1d	10e
LSD (5%)	0.477		

Means followed by the same letter (s) in the same column are not significantly different according to Duncan's Multiple Range Test

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- i. The effects of foliar fertilizer were unsatisfactory under the 1 g/L/plant and 1.5 g/L/plant fertilizer levels, but foliar application of 2 g/L/plant gave higher positive effects and showed the highest values on average in both seasons.
- ii. The application of NPK soil-based fertilizer had a more significant influence on the growth, quality and yield of carrots than foliar fertilizer application. This clearly shows that foliar fertilizer alone cannot accomplish the requirements of the plant nutrients.
- iii. Full irrigation with respect to NPK soil-based fertilizer appears to be the best for carrot production in both seasons compared to other water application levels.
- iv. The interaction between full irrigation in combination with 2 g/plant of NPK soil-based fertilizer enhanced the growth, yield, and quality parameters of carrots compared to other combinations.

5.2 Recommendations

- i. The application of 2 g/plant NPK soil-based fertilizer level is recommended since it enhanced the growth, quality and yields for carrots compared to other fertilizer levels in two seasons.

- ii. It is recommended to apply 100% of ET_c since it produced satisfactory growth, quality and yield parameters for carrots compared to other water application levels in both seasons.

5.3 Further Research

Since the application of nutrients through foliar feeding may not satisfy the complete nutrient requirement of the crop; further study on carrot productivity should be conducted using soil-based NPK fertilizer and foliar fertilizer in combination with organic fertilizers under various water application levels for comparative purposes.

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Carrot Productivity under Various Levels of Irrigation and Fertilization

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Carrot (*Daucus carota* L.) is normally grown under irrigation system. In Tanzania, carrot productivity is still low, mainly due to poor agronomic practices as a result of limited information on optimal levels of irrigation water that enhance crop production. Thus, a study was conducted to evaluate the interactions between various irrigation levels under drip irrigation and soil-based NPK fertilizer for optimal growth, yield, and sugar content of carrots in Morogoro, Tanzania. The crop water requirement was calculated in terms of crop evapotranspiration (ET_c) as the product of ET_o , K_c , and the ground cover reduction factor (K_r). Soil-based fertilizer was applied at a level of 150 kg NPK ha⁻¹, while irrigation levels applied were 100, 80, and 60% of ET_c . It was found that the growth, yield, and sugar content of carrots were affected differently at various irrigation water (IW) application levels. The growth parameters of carrots improved consistently to optimum IW levels. Further, the highest yield of 33.0 tons ha⁻¹ of carrots was obtained under 100% of IW, and the lowest yield of 18.47 tons ha⁻¹ was obtained at 60% of IW. The 60 and 80% IW level yields did not differ significantly ($p>0.05$). Carrots grown at a deficit irrigation water level of 80% were found to have the highest content of sugar. Therefore, for optimal growth and yield, an irrigation level of 100% is recommended for carrots. However, for high sugar content, an irrigation level of 80% is recommended.

Keywords: Drip irrigation; carrot yield; carrot growth; reference evapotranspiration; NPK fertilizer.

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1. INTRODUCTION

Carrots are one of the most consumed vegetables in the world owing to their delicious flavour and high carotene content, which has a number of health benefits [1]. Despite their importance, carrot production remains low in most parts of sub-Saharan Africa (SSA) due to various challenges exacerbated by a lack of information on crop water requirements (ET_c) and their respective levels, which would improve carrot production.

Crop water requirements play a key role in irrigation arrangement, designing, and water management in irrigated agriculture [2]. In agreement with this, the literature is rich in studies on ET_c and its effects, especially for common crops such as maize [3], wheat [4], and paddy rice [2]. However, limited information is found on carrots, especially for the part of SSA. Although the crop is normally grown under irrigation, very limited information is found on how best the drip irrigation system can be used for irrigated carrot production in SSA and its respective irrigation water requirements. Such kinds of information have assisted in improving carrot production elsewhere; for instance, [5] reported that the water requirement to achieve carrot production is 460.6 mm in Chile. Conversely, [6] stated that 97% of ET_c promoted the yield of carrots in Brazil. While these studies may not necessarily benefit Tanzanian carrot farmers directly, there is limited information as to which irrigation water level can enhance carrot production in Tanzania. As a result, the levels of irrigation water applied are either insufficient or excessive for good quality carrots [7].

In addition, both irrigation and fertilizer have positive or negative effects on plant development. For instance, [8] reported that 75% of ET_c combined with 150 kg N ha⁻¹ enhanced the yield of carrots in Germany [9] stated that full irrigation in interaction with 120 kg N ha⁻¹ enhanced the growth and yield of carrots in Egypt. In Tanzania, there is a dearth of information on the interaction between the irrigation water and fertilizer levels and their effects on carrot production [10]. There is a need to provide information on crop water requirements for carrots as the crop has gained an increasing demand, hence the need for higher production. Given that the price of carrots has increased internationally by about 50 dollars per ton [11], and dwindling fresh water resources, there is a need to increase its production using

an efficient and more precise means of irrigation that saves water. Therefore, this study was aimed at determining the ET_c by applying various amounts of water to the carrot crop using drip irrigation and assessing their influences in combination with fertilizer levels on the growth, quality, and yield of carrots. The study evaluated: (1) the effect of various water application and soil-based fertilizer levels on the growth, yield, and quality of carrots; and (2) the effect of the interaction between water application and soil-based fertilizer levels on the growth, yield, and quality of carrots.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

The field experiment was carried out at the School of Engineering and Technology (SoET) research field (grid zone 350 213.19 E, 9 243 788.94 N, 37M; 512 m above sea level) as shown in Fig. 1. The SoET is part of the Sokoine University of Agriculture (SUA) and is situated 3 km from the town center within Morogoro Municipality, Tanzania.

2.2 Experimental Design

A factorial arrangement of treatments was laid out in a split-plot design. Two factors, factor 1 being irrigation water application, which was at 3 levels (100%, 80%, and 60%), and factor 2, being fertilizer application, which was at 3 levels (1, 1.5, and 2 g per plant), were investigated in a 3 x 3 factorial with three replications. There were a total of 9 treatment combinations (plots) for each replication. Each subplot measured 1.5 m x 2 m in size and was separated from the next by a 0.5 m buffer zone.

Drip irrigation system was used for the irrigation of carrots, with gate valves installed at the head of each lateral feeding the whole plot. The discharge of one emitter corresponding to full irrigation, i.e., 100% of readily available water (I_{100}) application level, was 2 liters per hour (L h⁻¹). The discharges of the other emitters corresponding to water application levels of 80% and 60% of ET_c (I_{80} and I_{60}) were attained based on the 2 L h⁻¹ discharge by measuring the discharge from an emitter using graduated cylinders and adjusting the valves. The measurements were taken at three positions (at the beginning, middle, and end) of the lateral. To achieve the desired spacing of 10 cm between

plants, thinning has been done two weeks following the crop emergence, which gave 45 plants per sub-plot with a row spacing of 20 cm. No control for zero irrigation was applied because the experiment took place during the dry season. The applied water depth was 475.83 mm (I_{100}), 380.67 mm (I_{80}), and 285.498 mm (I_{60}) in season one, while in season two it was 233.64 mm (I_{100}), 186.92 mm (I_{80}), and 140.19 mm (I_{60}).

2.3 Crop Water Requirements

The reference crop evapotranspiration (ET_o) was determined using the Penman-Monteith equation [12] with the aid of INSTAT plus (v3.6) software

[13]. Climatic data were obtained from the Tanzania Meteorological Agency for the Sokoine University of Agriculture meteorological station.

The crop water requirement was determined as follows:

$$ET_c = ET_o \times K_c \tag{1}$$

Where,
 ET_c : Crop evapotranspiration ($mm\ day^{-1}$)
 ET_o : Reference evapotranspiration ($mm\ day^{-1}$)
 K_c : Crop coefficient
 Source: [14].

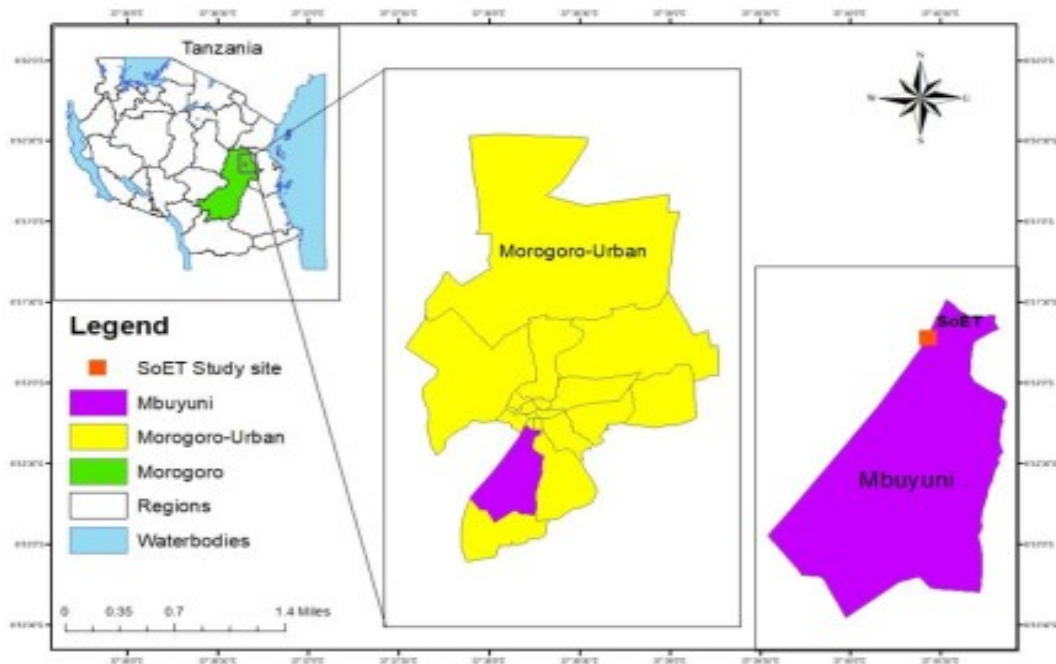


Fig. 1. Map showing the location of the study site

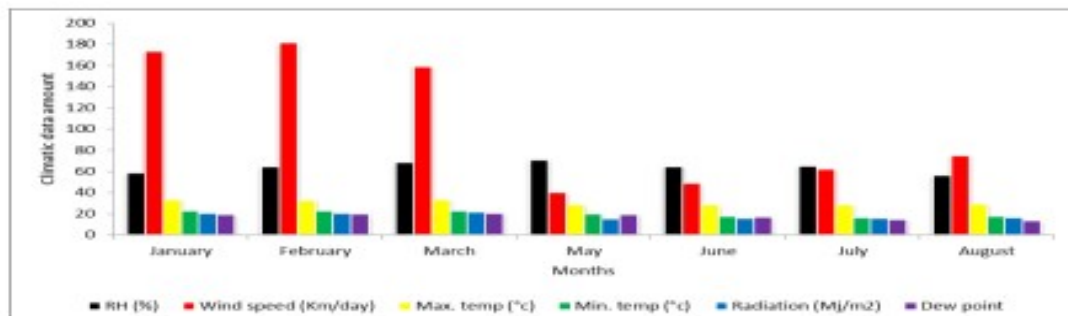


Fig. 2. Mean monthly climatic data during the experiment

2.4 Crop Growth Parameters

The plant growth parameters that were gathered include plant height, number of leaves per plant, and the length of leaves. From each treatment, the height of 5 tagged carrot plants was measured using a ruler from the ground level to the top of the root shoot. On the same plants, the length of leaves was measured from the bulb neck to the tip of the leaf using a ruler. The number of fully expanded leaves was counted and recorded as the number of leaves per plant.

2.5 Yield Parameter

Yield data was obtained after harvesting. The same carrots that have been used to take data for the plant growth parameters were also used for the determination of fresh root weight by using a weighing scale balance. The obtained weights were recorded in kilograms.

2.6 Root Growth Parameters

The same carrots that have been used to take data for the plant growth parameters were also used for the determination of the root growth and quality of carrots. The root length was determined using a vernier caliper starting from the shoulder to the end of the tap root. The shoulder and core diameter of roots were measured at 0.5 cm from the top of the shoulder

using a vernier caliper, and measurements were recorded in mm.

2.7 Quality Parameter

The total soluble solids were measured using a hand-held refractometer (0–30% Brix) and recorded in percentage.

2.8 Statistical Analysis

Analysis of variance (ANOVA) on the data collected was done using Genstat statistical software. The mean separation was carried out using Duncan's multiple range test (DMRT) at the 0.05 probability level [15].

3. RESULTS AND DISCUSSION

3.1 Soil and Irrigation Water Analysis

Tables 1 and 2 show the characteristics of soil and of irrigation water. According to the categorization suggested by [16], the soil texture was sandy clay. Sandy clay soil is suitable for vegetable production but needs regular watering and fertilizing to ensure healthy development [17]. According to [18], the sodium adsorption ratio (SAR) was low. Irrigated water with low SAR is safe with regard to causing sodicity [19].

Table 1. Physical and chemical properties of the soil in the study area

Soil properties	Values	Description
pH 1:2.5 in H ₂ O	6.12	Medium acidic soil
Total Nitrogen (%)	0.11	Low
Extractable Phosphorus (mg kg ⁻¹)	0.28	Low
EC _e (dS/m)	0.16	Normal
Potassium (Cmol kg ⁻¹)	0.208	Medium
Particle size distribution (%)		
Clay	39.76	Sandy clay
Sand	54.56	
Silt	5.68	

Table 2. Irrigation water quality

Parameters	Results	scription
pH	7.8	Normal
Sodium (me L ⁻¹)	9.95	Slight to moderate high
EC _w (dSm ⁻¹)	1.013	Medium
Phosphorus (mg L ⁻¹)	0.04	Non-problem
SAR (meq L ⁻¹)	1.33	Low
Bicarbonate (meq L ⁻¹)	0.38	Good
Carbonate (meq L ⁻¹)	1.38	Medium
Nitrogen (mg L ⁻¹)	0.03	Normal

3.2 Effect of Different Water Application Levels on the Growth, Yield, and Quality Parameters of Carrots

3.2.1 Plant height

Irrigating carrots with full irrigation resulted in the highest plant height in season one (44.59 cm) and season two (42.14 cm), while 60% water application level resulted in the shortest plant height in season one (37.82 cm) and season two (38.1 cm) (Table 3). However, during the first season, the plant heights were not significantly different ($p>0.05$) between the 80 and 100% water application levels, but both differed significantly ($p<0.05$) from the 60% water application level. In the second season, plant heights differed significantly among the three water application levels. Results (Table 3) show that the carrot height was positively influenced by the availability of water at the proper timing and amount, therefore, the plant height increased under full irrigation. However, in season one, the plant height was positively affected by irrigation water levels more than in season two. The difference between seasons may be related to temperature and evapotranspiration, as also pointed out by [20].

3.2.2 Number of leaves

Full irrigation resulted in high number of leaves per plant in season one (12) as well as in season two (11). The lowest number of leaves per plant in the first season (10) as well as in the second season (9) was obtained from the 60% water application level (Table 3). The number of leaves differed significantly ($p<0.05$) among the three irrigation water levels in season one as well as in

season two, leaf lengths under the 60 and 80%; 80 and 100% water application levels did not differ significantly ($p>0.05$); however, leaf lengths significantly differed ($p<0.05$) between the 60 and 100% water application levels.

These results could be attributed to better water application during the vegetative stage, which helped the crop to utilize the nutrients and make the plant more efficient in attaining its potential photosynthetic activity that enhanced the length of leaves. In connection with this, [20] reported that the length of leaves increases if optimal irrigation water and nutrition are applied during the vegetative stage.

3.2.4 Fresh root weight

The highest fresh root weight in the first season (33.0 tons ha^{-1}) as well as in the second season (29.13 tons ha^{-1}) was recorded under full irrigation, while the lowest fresh root weight in the first season (20.53 tons ha^{-1}) as well as in the second season (18.47 tons ha^{-1}) was obtained under the 60% water application level (Table 3). Further, the fresh root weight did not differ significantly ($p>0.05$) between the 60 and 80% water application levels, but both were significantly different from the full irrigation in both seasons at a level of 65.23%. These results could be attributed to the availability of optimal water level, which increased root size, resulting in a higher fresh root yield. This is in agreement with [5], who found that full irrigation produced the highest fresh root weight of carrots compared to deficit irrigation.

3.2.5 Root length

Table 3. Effect of different water application levels on the growth and yield parameters of carrots

Water level	Plant height (cm)	Number of leaves	Leaf length (cm)	Fresh root weight (tons ha ⁻¹)	Root length (cm)	Root core diameter (mm)	Root shoulder diameter (mm)	TSS (%)
First season								
60%	37.82 a	10 a	10.86 a	20.53 a	15.15 a	15.3 a	24.27 a	8.994 a
80%	42.39 b	11 b	11.62 b	25.2 a	16.6 ab	17.39 a	29.28 b	9.978 b
100%	44.59 b	12 c	12.57 c	33.0 b	17.17 b	21.76 b	33.48 c	8.441 a
LSD (5%)	2.553	0.268	0.588	1.94	1.616	2.115	3.755	0.696
Second season								
60%	38.1 a	9 a	9.81 a	18.47 a	14.36 a	14.96 a	24.07 a	8.5 a
80%	40.16 b	10 b	10.64 ab	23.43 a	15.8 ab	16.72 b	28.51 b	8.8 b
100%	42.14 c	11 c	11.08 b	29.13 b	17.02 b	18.21 c	30 c	8.1 c
LSD (5%)	1.409	0.558	1.152	1.656	1.761	0.962	0.934	0.275

TSS: Total Soluble Solids, LSD: Least Significance Difference

Means followed by the same letter (s) in the same column are not significantly different according to DMRT

3.2.6 Root core and shoulder diameter

Results (Table 3) show that the root core diameter was not significantly different ($p>0.05$) between the 60 and 80% water application levels, but both differed significantly ($p<0.05$) from that under full irrigation in season one. In season two, root core diameter differed significantly among the three water application levels. On the other hand, the root shoulder diameter differed significantly ($p<0.05$) among the three water application levels in both seasons.

The maximum root core diameter of 21.76 mm for season one and 18.21 mm for season two was obtained under full irrigation, while the minimum root core diameter of 15.3 mm for season one and 14.96 mm for season two was obtained under the 60% water application level. Likewise, the maximum root shoulder diameter in season one (33.48 mm) and season two (30 mm) was obtained under full irrigation, while the minimum root shoulder diameter in season one (24.27 mm) and season two (24.07 mm) was obtained under the 60% water application level.

These results under full irrigation could be due to the absorption of sufficient irrigation water during the growing period that enabled lower soil strength, nutrient absorption, and an appropriate physical environment for better root growth, resulting in increased root volume as pointed out by [23].

3.2.7 Total Soluble Solids (TSS)

As shown in Table 3, the highest TSS in season one (9.978%) and season two (8.8%) were obtained under the 80% water application level, while the lowest TSS in season one (8.441%) and season two (8.1%) were obtained under full

who reported that higher irrigation water levels reduce TSS on carrot roots.

3.3 Effect of Soil-based NPK Fertilizer on the Growth, Yield and Quality Parameters of Carrots

3.3.1 Plant height

Results (Table 4) show that the plant heights under the 1.5 and 2 g per plant fertilizer levels did not differ significantly ($p>0.05$), but both were significantly different ($p<0.05$) from those under the 1 g per plant fertilizer level in season one. However, in season two, plant heights were significantly different ($p<0.05$) among the three fertilizer rates. The maximum plant heights in season one (44.16 cm) as well as season two (42.21 cm) were obtained under the 2 g per plant fertilizer level, while the shortest plant heights in the first season (38.43 cm) and the second season (37.57 cm) were obtained under the 1 g per plant fertilizer level.

These results reflect the role of potassium and nitrogen as essential elements in metabolism and a variety of other processes necessary for plant growth including plant height and its development. The findings are consistent with those of [25]. Another study by [26] found that increasing NPK fertilization rate resulted in increased carrot height.

3.3.2 Number of leaves

As indicated in Table 4, the number of leaves differed significantly ($p<0.05$) among the three fertilizer levels in season one. In season two, the number of leaves under the 1 and 1.5 g per plant and 1.5 and 2 g per plant fertilizer levels did not differ significantly ($p>0.05$). However, there was

3.3.3 Leaf length

Table 4 shows that the leaf length did not differ significantly ($p>0.05$) between the 1.5 and 2 g per plant fertilizer rates, and that both differed significantly ($p<0.05$) from the 1 g per plant fertilizer rate in both seasons. Applying the fertilizer at a rate of 2 g per plant resulted in the maximum length of leaves in season one (12.26 cm) as well as in season two (11.08 cm). Likewise, the 1 g per plant fertilizer rate recorded the minimum length of leaves in the first season (11.07 cm) as well as in the second season (9.57 cm).

These results under the highest fertilizer level could be related to the fact that a high NPK fertilizer level eliminates problems like fixation and immobilization of nutrients by entering the cells rapidly and fulfilling the nutrient demand of the growing plant, resulting in enhanced length of the leaf. Similar observations were also made by [22] and [30].

3.3.4 Fresh root weight

Fresh root weights did not differ significantly ($p>0.05$) between the 1 and 1.5 g per plant fertilizer levels but both differed significantly ($p<0.05$) from those under the 2 g per plant fertilizer level in both seasons. The highest fresh root weight in the first season (32.27 tons ha^{-1}) as well as in the second season (29.53 tons ha^{-1}) were recorded under the 2 g per plant fertilizer level, while the lowest fresh root weight in the first season (22.37 tons ha^{-1}) as well as in the second season (18.5 tons ha^{-1}) were obtained under the 1 g per plant fertilizer level.

The findings (Table 4) reveal that the values of fresh root weight increased when fertilizer rates were increased up to the 2 g per plant fertilizer rate. This is consistent with the findings of [26], who found that increasing nitrogen and potassium fertilizer levels gradually and expressively improved root production.

3.3.5 Root length

Results (Table 4) show that the root length was not significantly affected by the rate of fertilizer application. Nevertheless, the highest rate of 2 g per plant resulted in the maximum length of root in season one (17.11 cm) as well as in season two (16.07 cm). The minimum root length in season one (15.59 cm) as well as in season two (15.47 cm) was recorded under the 1 g per plant fertilizer rate.

The increase in root length could, however, be associated with the increased nutrient use efficiency of both macro and micro nutrients from the NPK high level. This is logical as the macro and micro nutrients contribute to cell division and elongation, which in turn increases the root length of the carrots. This is in line with the results of [31], [28], [32].

3.3.6 Root core and shoulder diameter

Table 4 shows that root shoulder and core diameters under the 1.5 g per plant fertilizer level were not significantly different ($p>0.05$) from those under the 1 and 2 g per plant fertilizer levels, but those under the 1 g per plant fertilizer level were significantly different from those under the 2 g/plant fertilizer level in season one. However, in season two, the root core diameter was significantly different ($p<0.05$) among the three fertilizer rates, but root shoulder diameter did not significantly differ ($p>0.05$) between the 1.5 and 2 g per plant fertilizer rates, but both were significantly different from the 1 g per plant fertilizer rate. The maximum root core diameter in the first season (20.11 mm) as well as in the second season (18.38 mm) was obtained under the 2 g per plant, while the minimum root core diameter in the first season (16.33 mm) as well as in the second season (15.05 mm) was obtained under the 1 g per plant fertilizer level. Likewise, the maximum root shoulder diameter in the first season (31.76 mm) as well as in the second season (28.55 mm) was obtained under the 2 g per plant fertilizer level, while the minimum root shoulder diameter in the first season (27.06 mm) as well as in the second season (26.24 mm) was obtained under the 1 g per plant fertilizer level.

The increase in the root core and shoulder diameters under the highest fertilizer rate could be attributed to the adequate nutrients distributed by NPK soil-based fertilizer to enhance soil structure and allow shoulder and core of carrot roots to easily expand, as also stated by [30] and [25].

3.3.7 Total Soluble Solids

Results (Table 4) show that the TSS did not differ significantly ($p>0.05$) between the 1 and 1.5 g per plant fertilizer rates, but were both significantly different from those under the 2 g per plant fertilizer level in season one. However, TSS were significantly different ($p<0.05$) among

the three fertilizer rates in season two. The maximum TSS in season one (9.756 %) and season two (9.656%) were obtained under the 2 g per plant fertilizer rate, while the lowest TSS in the first season (8.702%) and the second season (6.922%) were obtained under the 1 g per plant fertilizer rate.

The improvement in the TSS in roots as a result of a high fertilizer rate could be related to the mode of action of macro nutrients in enhancing the photosynthetic activity and enzymes of carbohydrate transformation. This is in agreement with the findings by [33] and [34], who found that TSS increased as potassium, nitrogen, and phosphorus levels increased.

3.4 Effects of the Interaction between Water Application and Soil-Based NPK Fertilizer Levels on the Growth of Carrots

3.4.1 Plant height

Results (Table 5) show that the highest water application level combined with the highest fertilizer rate resulted in a higher plant height. Such interaction differed significantly ($p < 0.05$) in season one but wasn't as clearly defined in season two. The maximum plant height in season one (49.22 cm) and season two (44.19 cm) was obtained under full irrigation in combination with the 2 g per plant fertilizer level, while the minimum plant height in season one (35.5 cm) and season two (34.74 cm) was obtained under the 60% water application level \times 1 g per plant fertilizer level. This could be attributed to favourable soil moisture levels for enhanced translocation of nutrients to promote photosynthesis, regulate temperature, and keep

cells turgid, resulting in better plant growth [35]. Reported that the highest water application level favored by the transformation of organic matter derived from inorganic fertilizer owing to the optimal level of soil moisture resulted in plant height enhancement.

3.4.2 Number of leaves

As shown in Table 6, the number of leaves followed the same trend as that of the plant height in both seasons in terms of statistical significance. The maximum number of leaves in season one (12.97) and season two (11.37) were produced under full irrigation in combination with the 2 g per plant fertilizer rate, while the minimum number of leaves in season one (9.83) and season two (9.47) were produced under the 60% water application level \times 1 g per plant fertilizer level.

The increased number of leaves under full irrigation and 2 g per plant fertilizer rate might be due to the availability of more nutrients from irrigation water and NPK fertilizer that possibly increased the rate of cell division and elongation, leading to the production of more plant leaves, as stated by [36].

3.4.3 Leaf length

Table 7 shows that the leaf length did not differ significantly ($p > 0.05$) between the 60% water application level \times 1.5 g per plant, 60% water application level \times 2 g per plant, and 80% water application level \times 1 g per plant fertilizer levels in season one. In season two, the length of leaves differed significantly between the 60% water application level \times 1 g per plant and the

Table 5. Effects of the interaction between water application and soil-based NPK fertilizer levels on the plant height

Fertilizer levels	1 g	1.5 g	2 g
Water levels	Plant height		
	First season		
60%	35.5 a	37.84 ab	40.11 abcd
80%	37.97 abc	46.04 ef	43.15 de
100%	41.83 bcde	42.71 cde	49.22 f
LSD (5%)	4.296		
	Second season		
60%	34.74 a	39.15 bc	40.43 bcd
80%	37.88 b	40.6 cd	42.01 de
100%	40.11 bcd	42.13 de	44.19 e
LSD (5%)	2.44		

TSS: Total Soluble Solids, LSD: Least Significance Difference

Means followed by the same letter (s) in the same column are not significantly different according to DMRT.

Table 6. Effects of the interaction between water application and soil-based NPK fertilizer levels on the number of leaves

Fertilizer levels	1 g	1.5 g	2 g
Water levels	Number of leaves		
First season			
60%	9.83 a	10.5 bc	10.77 c
80%	10.23 ab	10.93 c	11.57 d
100%	10.5 bc	11.6 d	12.97 e
LSD (5%)	0.585		
Second season			
60%	9.47 a	9.47 a	9.96 ab
80%	9.8 ab	10.3 abc	10.67 bcd
100%	10.1 abc	11.03 cd	11.37 d
LSD (5%)	0.967		

TSS: Total Soluble Solids, LSD: Least Significance Difference

Means followed by the same letter (s) in the same column are not significantly different according to DMRT

Table 7. Effects of the interaction between water application and soil-based NPK fertilizer levels on the leaf length of carrots

Fertilizer levels	1 g	1.5 g	2 g
Water levels	Length of leaves		
First season			
	10.38 a	10.91 ab	11.27 ab
60%			
80%	11.25 ab	11.65 bc	11.95 bc
100%	11.57 bc	12.59 cd	13.55d
LSD (5%)	1.019		
Second season			
60%	8.79 a	10.25 ab	10.37 ab
80%	10.03 ab	10.85 ab	11.03 ab
100%	9.88 ab	11.52 b	11.85 b
LSD (5%)	1.996		

TSS: Total Soluble Solids, LSD: Least Significance Difference

Means followed by the same letter (s) in the same column are not significantly different according to DMRT

full irrigation × 2 g per plant fertilizer rates. The maximum length of leaves in season one (13.55 cm) and season two (11.85 cm) was obtained under full irrigation in combination with the 2 g per plant fertilizer rate. The minimum length of leaves in season one (10.38 cm) and season two (8.79 cm) was obtained under the 60% water application level × 1 g per plant fertilizer rate.

The maximum leaf length under full irrigation and the 2 g per plant fertilizer rate could be attributed to the physiochemical and biological improvements that happened in the soil, such as favourable temperature and moisture levels and nutrient accessibility that occurred in the carrot plant. For this reason, photosynthesis and stomatal conductance increased and the

leaves became longer, as also observed by Jahan I [37].

4. CONCLUSION

The application of the 2 g per plant fertilizer level enhanced the growth, quality, and yields of carrots compared to other fertilizer levels in both seasons. Full irrigation found to be the best for carrot production in both seasons compared to other water application levels. Carrots under 80% IW level had the highest content of sugar. The interaction between full irrigation in combination with 2 g per plant fertilizer rate enhanced the growth, yield, and quality parameters of carrots compared to other combinations. Therefore, for optimum growth and yield, an IW level of 100% is recommended for carrots. For

high sugar content, an IW level of 80% is recommended.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Effect of Foliar Fertilizer and Irrigation Levels on Carrot Productivity

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Carrot (*Daucus carota L.*) productivity is still low in Tanzania due to inadequate management. There is dearth of information from the literature on the best management practices with respect to irrigation water (IW) and fertilizer levels for optimal carrot production. Consequently, farmers have limited access to means of boosting carrot productivity levels. Thus, a study was conducted to evaluate the effect of various levels of irrigation for carrots using drip irrigation and their interaction with foliar fertilizer on the growth, yield, and sugar content of carrots at the School of Engineering and Technology (SoET) research field, Sokoine University of Agriculture (SUA) in Morogoro region, Tanzania. Crop water requirement (ET_c) was calculated using established procedures upon which water application levels were based. Foliar fertilizer was applied at levels of 1 (F_1), 1.5 (F_2), and 2 (F_3) g/L/plant, while irrigation levels applied were 60 (I_1), 80 (I_2), and 100 (I_3) percent of ET_c . The experiment was a 3x3 factorial with treatment combinations F_1I_1 , F_1I_2 , F_1I_3 , F_2I_1 , F_2I_2 , F_2I_3 , F_3I_1 , F_3I_2 , and F_3I_3 conducted over two seasons during 2020/2021 and 2021/2022. The highest yield of 30.9 t ha⁻¹ of carrots was obtained under 100% ET_c , and the lowest yield of 15.1 t ha⁻¹ was obtained under the 60% ET_c . Carrots under a deficit irrigation water level of 20%, i.e., 80% ET_c were found to have the highest content of sugar. On the other hand, the highest yield of 26.1 t ha⁻¹ of carrots was obtained under the 2 g/L/plant fertilizer level, and the lowest yield of 17.9 t ha⁻¹ of carrots was obtained under the 1 g/L/plant fertilizer level. Carrots under the 1.5 g/L/plant fertilizer level were found to have the highest content of sugar. Therefore, for optimum growth and yield, full irrigation in combination with foliar fertilizer application at a level of 2 g/L/plant is recommended for carrots under Morogoro conditions. However, for high sugar content, irrigation at 80% ET_c in combination with foliar fertilizer application at a level of 1.5 g/L/plant is recommended.

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1. INTRODUCTION

Carrots (*Daucus carota* L.) are one of the important and major root vegetables used for different purposes in the daily human diet [1]. It is rich in beta-carotene, which enhances resistance to blood and eye diseases, and a large amount of carrots in the diet has a favorable effect on the nitrogen balance [2,3].

Due to the importance of the crop for human existence, increased production to maximize yield is inevitable. However, in most parts of sub-Saharan Africa (SSA), carrot yield has persistently been low due to limited information on appropriate agronomic factors such as irrigation water level [4] and rate of fertilizer application [5]. Elsewhere, carrot yield has reportedly been increased under improved management. Gutezeit [6] reported that carrot growth, quality, and yield were positively affected by a 75% irrigation level in Germany. On the other hand, El-nasr and Ibrahim [7] reported that the foliar application of potassium at a level of 3 ml/L/plant significantly enhanced the growth, yield, and root quality of carrots in Egypt. In Tanzania, information on the best management practices in managing irrigation water (IW) and fertilizer levels for optimal carrot production is limited. Therefore, farmers have limited access to means of boosting carrot productivity levels.

In addition, interaction between fertilizer and irrigation water application plays an important role in the production of carrots [8]. According to Kifle et al. [9], various studies have been conducted, but these studies have mainly concentrated on carrot production and productivity. As a result, it remains unclear as to which fertilizer rate in combination with irrigation water level produces the best quantity and quality of carrots. For instance, Quezada et al. [10] reported that the growth, yield, and quality parameters of carrots are significantly enhanced by foliar application of potassium under full irrigation, while the application of foliar fertilizer in combination with a 75% water application level positively affected the growth of carrots [11]. These studies point to the need for full investigation on the interactions between irrigation levels and the rates of fertilizer application and their effects on the growth, yield, and quality of carrots. There is a need to provide Tanzanian farmers with the information to know at what rate of fertilizer application and irrigation

level the yield, quality, and growth of carrots would be enhanced as the increase in demand dominates the current production. In Tanzania, the average per capita daily carrot consumption is approximately 50 g, while the recommended daily consumption is at least 80 g [12,13]. This indicates that the production of carrots is still low mainly due to poor agronomic practices and a lack of information on optimal levels of irrigation and of fertilizer application that enhance crop production, therefore prompting increased production under irrigation and fertilization systems.

2. MATERIALS AND METHODS

2.1 Description of the Soil and Irrigation Water in the Study Area

The soil texture in the experimental area was sandy clay and the pH of the irrigation water was 7.8. Tables 1 and 2 in results show the details of the physical and chemical properties of the soil and irrigation water.

2.2 Experimental Design

A factorial arrangement of treatments was laid out in a split-plot design. Two factors, factor 1 being three irrigation levels (100, 80, and 60% ET_c), and factor 2, being three foliar fertilizer levels (1, 1.5, and 2 g/L/plant), were investigated in a 3 x 3 factorial with three replications. There were a total of 9 treatment combinations (plots). Each subplot measured 1.5 m x 2 m in size and was separated from the next by a 0.5 m buffer zone.

Drip irrigation system was used for the irrigation of carrots, with gate valves installed at the head of each lateral feeding the whole plot. The discharge of one emitter corresponding to full irrigation, i.e., 100% ET_c (I_3), was 2 litres per hour (L/h). The discharges of the other emitters corresponding to water application levels of 80 and 60% ET_c (I_2 and I_1) were attained based on the 2 L/h discharge by measuring the discharge from an emitter using graduated cylinders and adjusting the valves. The measurements were taken at three positions (at the beginning, middle, and end) of the lateral. Thinning has been done two weeks after the emergence of the crop to attain the required spacing of 10 cm between plants, which gave 45 plants per sub-plot with a row spacing of 20 cm. No control for zero

irrigation was applied because the experiment took place during the dry season. The applied water depth was 475.83 mm (I_3), 380.67 mm (I_2), and 285.498 mm (I_1) in season one, while in season two it was 233.64 mm (I_3), 186.92 mm (I_2), and 140.19 mm (I_1).

2.3 Crop water Requirements

The reference crop evapotranspiration (ET_o) was determined using the Penman-Monteith equation [14] with the aid of INSTAT plus (v3.6) software [15].

The crop water requirement was determined as follows:

$$ET_c = ET_o \times K_c \quad (1)$$

Where,

ET_c : Crop evapotranspiration (mm day^{-1})

ET_o : Reference evapotranspiration (mm day^{-1})

K_c : Crop coefficient

Source: [16].

2.4 Crop Growth, Yield, and Root Parameters

The plant growth parameters like plant height, the number of leaves per plant, and the length of leaves were measured. From each treatment, the height of 5 tagged carrot plants was measured using a ruler from the ground level to the top of

the root shoot. The obtained measurements were recorded in cm. On the same plants, the length of leaves was measured from the bulb neck to the tip of the leaf using a ruler. The number of fully expanded leaves was counted and recorded as the number of leaves per plant.

The yield data was obtained after harvesting. The obtained weights were recorded in tons/ha.

For the root growth parameter study, the same carrots that had been used to take data for the plant growth parameters were also used for the determination of the root growth and quality of carrots. The root length was determined using a vernier caliper. The shoulder and core diameter of roots were measured at 0.5 cm from the top of the shoulder using also a vernier caliper, and measurements were recorded in mm.

2.5 Quality Parameter

Quality parameter like the total soluble solids, i.e., sugar level in carrots was measured using a hand-held refractometer (0–30% Brix) and recorded in percentage.

2.6 Statistical Analysis

Analysis of variance (ANOVA) on the data collected was done using Genstat statistical software. The mean separation was carried out using Duncan's multiple range test (DMRT) at the 0.05 probability level [17].

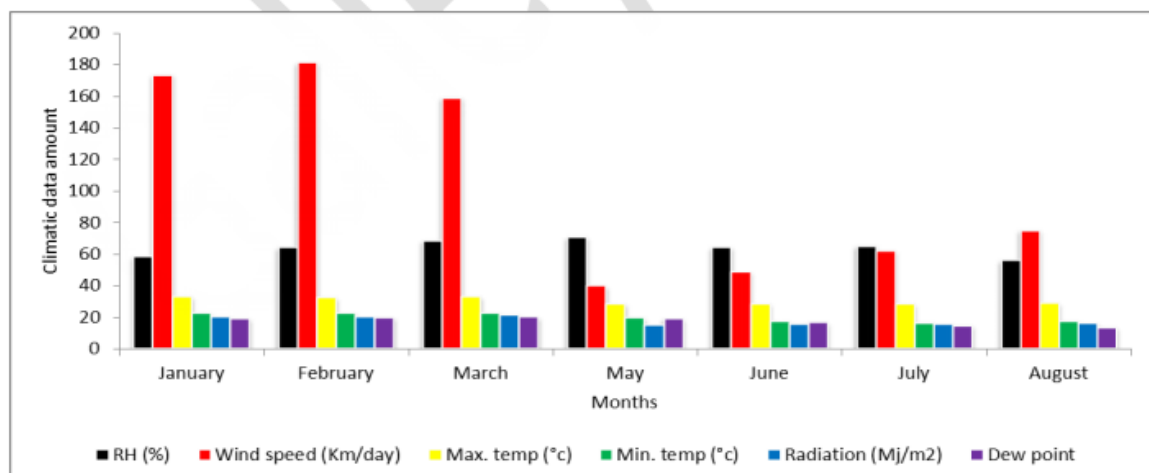


Fig. 1. Mean monthly climatic data during the experiment

3. RESULTS AND DISCUSSION

3.1 Soil and Irrigation Water Analysis

Tables 1 and 2 show the results of soil and irrigation water tests in the study area. According to the classification suggested by [18], the soil texture was sandy clay. Sandy clay soil is suitable for vegetable production but needs regular watering and fertilizing to ensure healthy development [19]. According to Park et al. [20], the sodium adsorption ratio (SAR) was low. Irrigated water with low SAR is safe with regard to sodicity hazard [18].

3.2 Effect of Different Irrigation Levels on the Growth, Yield, and Quality of Carrots

3.2.1 Plant height

Carrots irrigated at 100% ET_c produced the highest plant height in the first season (43.27 cm) and second season (40.92 cm) compared to 60% and 80% ET_c , while 60% ET_c resulted in the least plant height in the first season (37.4 cm) as well as the second season (37.42 cm) (Table 3). However, during the first season, the plant heights for 80% and 100% ET_c were not significantly different at the 5% level, but both differed significantly ($p < 0.05$) from the 60% ET_c .

In the second season, plant height differed significantly ($p < 0.05$) among the three irrigation levels.

It is evident that the plant height increased gradually as irrigation water levels increased up to full irrigation. This could be attributed to the favorable soil moisture for proper plant growth associated with the rapid increase and expansion of plant cells that play vital roles in the biological and physiological processes of carrot plants, resulting in an increase in the plant height. This is in agreement with the findings by Ludong [21], who reported that the height of carrots increased with increasing levels of irrigation water.

3.2.2 Number of leaves

Irrigating carrots at 100% ET_c produced the highest number of leaves in the first season (10.6) as well as in the second season (10.4) compared with the other treatments. The lowest number of leaves per plant was obtained from the 60% ET_c in both seasons (Table 3). The number of leaves per plant was not significantly different ($p > 0.05$) between the 60% and 80% ET_c , but both differed significantly ($p < 0.05$) from the 100% ET_c in the first season. However, in the second season, the number of leaves per plant differed significantly ($p < 0.05$) among the three irrigation levels.

Table 1. Physical and chemical properties of the soil in the study area

Soil properties	Values	Description
pH 1:2.5 in H_2O	6.12	Medium acidic soil
Total Nitrogen (%)	0.11	Low
Extractable Phosphorus ($mg\ kg^{-1}$)	0.28	Low
EC_e (dS/m)	0.16	Normal
Potassium ($Cmol\ kg^{-1}$)	0.208	Medium
Particle size distribution (%)		
Clay	39.76	Sandy clay
Sand	54.56	
Silt	5.68	

Table 2. Irrigation water quality

Parameters	Results	Description
Ph	7.8	Normal
Sodium ($me\ L^{-1}$)	9.95	Slight to moderate
EC_w (dSm^{-1})	1.013	Medium
Phosphorus ($mg\ L^{-1}$)	0.04	Non-problem
SAR ($meq\ L^{-1}$)	1.33	Low
Bicarbonate ($meq\ L^{-1}$)	0.38	Good
Carbonate ($meq\ L^{-1}$)	1.38	Medium
Nitrogen ($mg\ L^{-1}$)	0.03	Normal

Table 3. Effect of different water application levels on the growth, quality, and yield of carrots

Water level	Plant height (cm)	Number of leaves	Leaf length (cm)	Fresh root weight(t/ha)	Root length (cm)	Root core diameter (mm)	Root shoulder diameter (mm)	TSS (%)
First season								
60%	37.4a	9.6 a	10.66a	16.7 a	14.25a	13.19 a	23.77 a	8.15a
80%	41.54 b	9.9 a	10.76a	21.9 b	16.07b	16.53 b	26.82 b	8.5a
100%	43.27b	10.6 b	11.34a	30.9 c	17.07 b	18.83 c	29.08 c	8.11a
LSD (5%)	2.185	0.366	0.716	1.3	1.008	1.728	1.816	0.499
Second season								
60%	37.4 a	8.7 a	9.53 a	15.1 a	13.82 a	12.8 a	23.39 a	6.38 a
80%	38.83 b	9.7 b	10.06 b	21.2 b	15.36 b	14.03 b	25.90 b	7.67b
100%	40.92 c	10.4 c	10.54 c	28.4 c	16.94 c	15.98 c	27.13 b	6.34 a
LSD (5%)	0.606	0.378	0.325	1.19	1.02	1.025	2.073	1.107

TSS: Total Soluble Solids, LSD: Least Significance Difference, DMRT: Duncan's Multiple Range Test. Means followed by the same letter (s) in the same column are not significantly different according to DMRT

From the results, it is evident that irrigation levels of 60 and 80% decreased the number of leaves per plant. This could be due to the effect of water deficit which decreased the photosynthetic capacity that led to decreased leaf stomata conductance due to stomata closure as pointed out by [22].

3.2.3 Leaf length

Results in Table 3 show that irrigating carrots at 100% ET_c resulted in the maximum length of leaves in the first season (11.34 cm) as well as in the second season (10.54 cm). Likewise, the 60% ET_c recorded the minimum length of leaves in the first season (10.66 cm) as well as in the second season (9.53 cm). Further, the leaf lengths were not significantly different ($p > 0.05$) among the three irrigation levels in the first season. However, in the second season, the three irrigation levels differed significantly ($p < 0.05$) in relation to leaf length. The increase in the leaf length as irrigation level increased up to 100% ET_c could be attributed to the better utilization of nutrients using adequate soil moisture. These results are in agreement with those found by Jahan [23], who reported an increase in the leaf length of carrots as irrigation level increased up to full irrigation.

3.2.4 Fresh root weight

The highest fresh root weight in the first season (30.9 t ha⁻¹) as well as in the second season

(28.4 t ha⁻¹) was recorded under the 100% ET_c, while the lowest fresh root weight in the first season (16.7 t ha⁻¹) as well as in the second season (15.1 t ha⁻¹) was obtained under the 60% ET_c. Fresh root weight was significantly different ($p < 0.05$) among the three irrigation levels in both seasons (Table 3).

The reduced fresh root weight under the 60% ET_c could be due to the soil water stress that caused the carrot plants to absorb inadequate nutrients essential for root growth. In connection with this, Li et al. [24] reported that drought stress throughout the entire growth period of carrots caused a more severe reduction in the root production.

3.2.5 Root length

Full irrigation resulted in the maximum length of roots in the first season (17.07 cm) as well as in the second season (16.94 cm), while the minimum root length in the first season (14.25 cm) as well as in the second season (13.82 cm) was recorded under the 60% ET_c. Further, the root length was not significantly different ($p > 0.05$) between the 80 and 100% ET_c, but both differed significantly ($p < 0.05$) from that under the 60% of ET_c in the first season. However, in the second season, the root length differed significantly ($p < 0.05$) among the three irrigation levels (Table 3).

The increased root length due to higher water application levels could be due to availability of sufficient moisture which helped in rapid cell elongation leading to longer root formation. This is consistent with findings by Afrin et al. [25] and Ahmad et al. [26], who reported that root length of carrots was higher with higher amount of water level.

3.2.6 Root core and shoulder diameters

The maximum root core diameter of 18.83 mm in the first season and 15.98 mm in the second season were obtained under the 100% ET_c , while the minimum root core diameter of 13.19 mm in the first season and 12.8 mm in the second season were obtained under the 60% ET_c . Likewise, the maximum root shoulder diameter in the first season (29.08 mm) and in the second season (27.13 mm) were obtained under the 100% ET_c and the minimum root shoulder diameter in the first season (23.77 mm) and in the second season (23.39 mm) were obtained under the 60% ET_c (Table 3). Further, the root core diameter differed significantly ($p < 0.05$) among the three irrigation levels in the first as well as the second season. On the other hand, the root shoulder diameter followed the same trend as that of the root core diameter in the first season in terms of statistical significance but during the second season the root shoulder diameter under the 80 and 100% ET_c did not differ significantly ($p > 0.05$).

Deficit irrigation (60 and 80% ET_c) produced the lowest values in root core and shoulder diameters for carrots. This could be due to the effect of prolonged water stress, with consequent reduction in overall growth. In confirmation of this, Reid and Gillespie [27] reported that water deficits cause water stress in plants, prevent plant and root growth, and reduce the absorbing areas and capacities of plant roots.

3.2.7 Total Soluble Solids (TSS)

As shown in Table 3, the highest TSS in the first season (8.5%) and the second season (7.67%) were obtained under the medium water application level (80% ET_c), while the lowest TSS in the first season (8.11%) and the second season (6.34%) were obtained under full irrigation. Further, the TSS were not significantly influenced by irrigation levels in the first season. However, in the second season, the TSS under the 60 and 100% ET_c differed significantly ($p < 0.05$) from those under the 80% ET_c .

The abundance of TSS content in the roots of the lesser irrigated carrot plants is more of a physiological characteristic that could be explained by plant photosynthate redistribution into the roots as a result of the water deficit, which resulted in lower water content but increased sugar content. A similar observation has also been made by Fikselová et al. [28], who reported that increased moisture has a negative influence on TSS content on carrot roots.

3.3 Effects of Foliar Fertilizer on the Growth, Yield, and Quality of Carrots

3.3.1 Plant height

Spraying foliar fertilizer at a level of 2 g/L/plant resulted in the most plant height in the first season (43.27 cm) and the second season (41.14 cm), while the foliar fertilizer level of 1 g/L/plant resulted in the least plant height in the first season (37.55 cm) as well as the second season (36.18 cm). The plant heights under 1.5 and 2 g/L/plant fertilizer levels were not significantly different at the 5% level in the first season, but both differed significantly ($p < 0.05$) from the 1 g/L/plant fertilizer level. However, in the second season, plant height differed significantly ($p < 0.05$) among the three fertilizer levels. The results (Table 4) show that carrot height consistently increased with fertilizer rate. The application of higher fertilizer rates has the potential to fulfill the requirements of the plant for nutrients than lower fertilizer rates. This observation was also made by Badr et al. [29], who reported that the highest level of foliar feeding produced the most carrot height compared to the lowest fertilizer level. In their study, Alhariri and Boras [30] reported that foliar application of up to 1.5 g/L/plant fertilizer significantly enhanced carrot growth by increasing carrot height. A study by El-nasr and Ibrahim [7] reported that spraying carrot plants with foliar fertilizer at a level of 3 ml/L/plant produced the highest values of plant height compared to control treatment (without foliar application) in two seasons.

3.3.2 Number of leaves

As shown in Table 4, the number of leaves per plant followed the same trend as that of plant height in the two seasons in terms of statistical significance. Spraying foliar fertilizer at a level of 2g/L/plant produced the highest number of leaves per plant in the first season (10.4) as well as in the second season (10.08) compared with

Table 4. Effect of different rates of foliar fertilizers on the growth and yield parameters of carrots

Fertilizer level	Plant height (cm)	Number of leaves	Leaf length (cm)	Fresh root weight (t/ha)	Root length (cm)	Root core diameter (mm)	Root shoulder diameter (mm)	TSS (%)
First season								
1	37.55 a	9.4 a	10.47 a	19.8 a	15.53 a	13.09 a	22.6 a	8.27b
1.5	41.39 b	10.2 b	10.92 ab	23.6 ab	15.71 a	17.28 b	28.15 b	8.88 c
2	43.27 b	10.4 b	11.37 b	26.1 b	16.16 a	18.18 b	28.92 b	7.6 a
LSD(0.05)	2.185	0.366	0.716	1.3	1.008	1.728	1.816	0.499
Second season								
1	36.18 a	9.2 a	9.45 a	17.9 a	15 a	11.49 a	20.38 a	6.36a
1.5	39.85 b	9.7 b	10.29 b	22.9 b	15.42 a	15.11 b	27.53 b	8.25b
2	41.14 c	10.08 c	10.39 b	24.03 b	15.7 a	16.21 c	28.51 b	5.78 a
LSD(0.05)	0.606	0.378	0.325	1.19	1.02	1.025	2.073	1.107

the other treatments. The lowest number of leaves per plant was obtained from the 1 g/L/plant fertilizer level in both seasons.

In agreement with this, El-Helaly [31] stated that the use of high foliar feeding levels improved the number of leaves on carrots compared to low fertilizer levels. Badr [5] reported that among the different fertilizer levels (0.5, 1, 1.5 and 2 ml/L/plant), 2 ml/L/plant produced the highest number of leaves.

3.3.3 Leaf length

Spraying foliar fertilizer at a level of 2 g/L/plant resulted in the maximum length of leaves in the first season (11.37 cm) as well as in the second season (10.39 cm). Likewise, the 1 g/L/plant fertilizer level recorded the minimum length of leaves in the first season (10.47 cm) as well as in the second season (9.45 cm). Further, the leaf lengths were not significantly different ($p>0.05$) between the 1 and 1.5 g/L/plant fertilizer levels in the first season as was the case for the 1.5 and 2 g/L/plant fertilizer levels but the 1 g/L/plant fertilizer level was significantly different ($p<0.05$) from the 2 g/L/plant fertilizer level. In the second season, the leaf lengths under the 1.5 and 2 g/L/plant fertilizer levels were not significantly different ($p>0.05$) but both differed significantly ($p<0.05$) from the 1 g/L/plant fertilizer level (Table 4).

Foliar nutrition using a high fertilizer level can eliminate problems like fixation and immobilization of nutrients by penetrating the stomata of the leaf, entering the cells rapidly and fulfilling the nutrient demand of the growing plant,

resulting in enhanced length of the leaf [33]. This is in agreement with the findings of Anub [11], who reported that an increased application level of foliar feeding to carrots enhanced the length of the leaves.

3.3.4 Fresh root weight

The highest fresh root weight in the first season (26.1 t/ha) as well as in the second season (24.03 t/ha) were recorded under the 2 g/L/plant fertilizer level, while the lowest fresh root weight in the first season (19.8 t/ha) as well as in the second season (17.9 t/ha) were obtained under the 1 g/L/plant fertilizer level. Fresh root weight followed the same trend as that for leaf length in terms of statistical significance in both seasons (Table 4). The fresh root weight consistently increased with increasing fertilizer levels. In their study, Shibairo et al. [34] reported that higher fertilizer levels directly increased the root fresh weight by producing heavier roots than the lower rates.

3.3.5 Root length

Results (Table 4) indicate that the root length was not significantly influenced by the levels of fertilizer application in both seasons. Nevertheless, the highest level of 2 g/L/plant resulted in the maximum length of root in both seasons, while the minimum root length was recorded under the 1 g/L/plant fertilizer level in both seasons. This positive effect on the root length due to increased fertilizer levels could be attributed to the favorable fertilizer nutrients for proper plant growth associated with rapid increase and expansion of plant cells that play

vital roles in the biological and physiological processes of carrot plants, resulting in an increase of the root length. A similar observation was also made by Badr and Helmy [5], who reported that higher fertilizer levels produced longer roots than the lowest fertilizer levels.

3.3.6 Root shoulder and core diameters

Results (Table 4) indicate that the root shoulder diameter did not differ significantly ($p>0.05$) between the 1.5 and 2 g/L/plant fertilizer levels in the first as well as the second seasons but both differed significantly ($p<0.05$) from that under the 1 g/L/plant fertilizer level. On the other hand, the root core diameter did not differ significantly ($p>0.05$) between the 1.5 and 2 g/L/plant fertilizer levels in the first season, but during the second season, the root core diameter differed significantly ($p<0.05$) among the three fertilizer levels. The maximum root core diameter of 18.18 cm in the first season and 16.21 mm in the second season was obtained under the 2 g/L/plant fertilizer level, while the minimum root core diameter of 13.09 mm in the first season and 11.49 mm in the second season was obtained under the 1 g/L/plant fertilizer level. Likewise, the maximum root shoulder diameter in the first season (28.92 mm) and the second season (28.51 mm) was obtained under the 2 g/L/plant fertilizer level. The minimum root shoulder diameter in the first season (22.6 mm) and the second season (20.23 mm) was obtained under the 1 g/L/plant fertilizer level. These results are in agreement with those of Badr et al. [29]. Other studies Arshad et al. [35], El-nasr and Ibrahim [7], and Sharangi and Paria [36] reported that higher fertilizer levels directly increased the root core and shoulder diameters than the lower fertilizer levels.

3.3.7 Total Soluble Solids (TSS)

The highest TSS in the first season (8.88%) and the second season (8.25%) were obtained under the 1.5 g/L/plant fertilizer level, while the lowest TSS in the first season (7.6%) and the second season (5.78%) were obtained under the 2 g/L/plant fertilizer level. Further, the TSS were significantly influenced by fertilizer levels in the first season. However, TSS under the 1 g/L/plant fertilizer level did not differ significantly ($p>0.05$) from that under the 2 g/L/plant fertilizer level during the second season (Table 4). The highest fertilizer level (2 g/L/plant) resulted in decreased sugar levels in the carrots. This is an intriguing result as it tends to suggest that there is an

optimal level of fertilization for TSS accumulation. In confirmation of this, Evers [37], Mbatha [38], and Noella et al. [32] reported that less fertilized treatments had a greater tendency to increase sugar content in carrots than the most fertilized treatments.

3.4 Effect of the Interaction between Irrigation Water and Foliar Fertilizer Levels on the Growth, Yield, and Quality of Carrots

3.4.1 Plant height

The interaction between full irrigation \times 2 g/L/plant fertilizer level produced the highest plant height in the first season (46.43 cm) as well as in the second season (43.08 cm) compared to other interactions, while 60% $ET_c \times$ 1 g/L/plant fertilizer level resulted in the least plant height in the first season (33.83 cm) as well as in the second season (34.49 cm). Further, the plant height under the 60% $ET_c \times$ 1 g/L/plant fertilizer level differed significantly ($p<0.05$) with other combinations in both seasons (Table 5). The height of carrots increased consistently with fertilizer and irrigation water increments, up to 2 g/L/plant in combination with full irrigation. This could mean that the nutrients from irrigation water (full irrigation) in combination with the nutrients from foliar feeding enhanced photosynthesis which resulted in better plant growth. The findings are in harmony with those by Batra [39] and Prabhakar [40], who reported that the increase in irrigation water and fertilizer levels resulted in increased carrot height.

3.4.2 Number of leaves

Results (Table 6) show that the number of leaves per plant under the full irrigation \times 2 g/L/plant fertilizer level differed significantly ($p<0.05$) with other combinations in the first season. However, in the second season, the 60% $ET_c \times$ 1 g/L/plant fertilizer level differed significantly ($p<0.05$) with other combinations. Application of full irrigation in combination with 2 g/L/plant fertilizer level produced the highest number of leaves in the first season (11.27) as well as in the second season (10.51), while the lowest number of leaves in the first season (8.93) as well as in the second season (8.16) was obtained under the 60% $ET_c \times$ 1 g/L/plant fertilizer level. A similar explanation as that advanced for the case of plant height for the full irrigation \times the 2 g/L/plant fertilizer level combination would seem to be the case for the number of leaves produced [41].

Table 5. Effects of the interaction between water application and foliar fertilizer levels on the plant height

Fertilizer levels	1 g	1.5 g	2 g
Water levels	Plant height		
	First season		
60%	33.83 a	38.49 b	39.87 bc
80%	39.11 b	42 bc	43.50 cd
100%	39.7 bc	43.69 cd	46.43 d
LSD (5%)	3.784		
	Second season		
60%	34.49 a	38.29 c	39.5 d
80%	35.74 b	39.91 de	40.85 ef
100%	38.31 c	41.37 f	43.08 g
LSD (5%)	1.105		

Table 6. Effects of the interaction between water application and foliar fertilizer levels on the number of leaves

Fertilizer levels	1 g	1.5 g	2 g
Water levels	Number of leaves		
	First season		
60%	8.93 a	9.93 bc	9.97 bc
80%	9.47 ab	10.17 bc	10.14 bc
100%	10.03 bc	10.5 c	11.27 d
LSD (5%)	0.635		
	Second season		
60%	8.16 a	8.88 b	9.31 bc
80%	9.16 bc	9.75 cd	10.43 de
100%	10.36 de	10.43 de	10.51 e
LSD (5%)	0.65		

Table 7. Effects of the interaction between water application and foliar fertilizer levels on the leaf length of carrots

Fertilizer levels	1 g	1.5 g	2 g
Water levels	Leaf length		
	First season		
60%	9.72 a	10.85 ab	11.41 b
80%	10.48ab	10.66 ab	11.14 b
100%	11.22ab	11.24 ab	11.56 b
LSD (5%)	1.241		
	Second season		
60%	9 a	10.09 cde	9.5 abc
80%	9.47 ab	10.28 de	10.42 de
100%	9.87 bcd	10.51 e	11.25 f
LSD (5%)	0.563		

3.4.3 Leaf length

The maximum leaf lengths in the first season (11.56 cm) as well as in the second season (11.25 cm) were obtained under the full irrigation in combination with the 2 g/L/plant fertilizer level. Likewise, the minimum leaf lengths in the first season (9.72 cm) as well as in the second

season (9 cm) were obtained under the 60% ET_c × 1 g/L/plant fertilizer level (Table 7). The leaf lengths were not significantly different ($p > 0.05$) among various interactions in the first season. However, in the second season, the full irrigation × 2 g/L/plant fertilizer level differed significantly ($p < 0.05$) from other combinations. A similar explanation as that given for the plant height and

number of leaves could be advanced for the case of the length of leaves [42,43].

4. CONCLUSION

Spraying foliar fertilizer at a level of 2 g/L/plant enhanced the growth and yield of carrots compared to other fertilizer levels in two seasons. However, 1.5 g/L/plant fertilizer level resulted in the highest sugar content in the roots. On the other hand, full irrigation increased carrot production in both seasons. However, carrots under a level of 80% ET_c were found to have the highest content of sugar. Therefore, for optimum growth and yield, full irrigation and foliar fertilizer application at a level of 2 g/L/plant is recommended for carrots under Morogoro conditions. On the other hand, for high sugar content, deficit irrigation at 80% ET_c in combination with foliar fertilizer application at a level of 1.5 g/L/plant is recommended.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Galley Proof

APPENDICES

Appendix 1: Morogoro urban mean monthly weather data (2015-2020)

TH	MON	MEAN RH (%)	WIND (Km/day)	TEMPERATURE (°C)		RADIATI ON (MJ/m ²)
				MAXIMUM	MINIMUM	
JAN		72.6	181.2	32.1	22.1	19.8
FEB		71.4	159.0	32.7	22.2	21.0
MAR		77.1	85.4	32.3	22.0	18.5
APR		84.2	49.4	29.6	21.5	15.2
MAY		82.7	39.9	28.2	19.9	13.9
JUN		76.6	48.2	28.2	16.9	15.4
JUL		71.5	61.7	27.9	16.1	15.2
AUG		68.7	83.7	28.8	17.2	16.4
SEP		66.1	109.7	30.6	17.7	18.2
OCT		66.6	118.7	31.5	19.5	18.2
NOV		68.4	144.9	31.7	21.2	19.7
DEC		70.9	173.5	32.6	22.2	20.0

Appendix 2: Morogoro mean monthly rainfall (mm) (1961-2020)

Months	Rainfall
January	93.7
February	71.7
March	131.6
April	208.5
May	71
June	12.7
July	5.85
August	5.7
September	4.3
October	26.05
November	50.35
December	73.4

Appendix 3: Values of K

Ground cover (%)	Keller and karmeli	Freemen Garzoil	and Decroix CTG REF
10	0.12	0.10	0.20
20	0.24	0.20	0.30
30	0.35	0.30	0.40
40	0.47	0.40	0.50
50	0.59	0.75	0.60
60	0.70	0.80	0.70
70	0.82	0.85	0.80
80	0.94	0.90	0.90
90	1.00	0.95	1.00
100	1.00	1.00	1.00

Appendix 4: Crop water requirements of carrots in the study area

Seasons	Variables	Initial stage	Development stage	Mid-season stage	Late season stage	Total
Season 1	Days	18	27	27	18	90
	K_c	0.37	0.92	1.006	0.89	
	ET_o (mm/day)	6.3	6.79	6.36	5.75	
	ET_c (mm/day)	2.34	6.25	6.4	5.12	
	ET_c (mm/stage)	42.12	168.75	172.8	92.16	
Season 2	K_c	0.33	0.92	0.96	0.88	233.64
	ET_o (mm/day)	3.003	3.19	3.18	3.38	
	ET_c (mm/day)	1	2.94	3.06	2.98	
	ET_c (mm/stage)	18	79.38	82.62	53.64	

Appendix 5: Lengths of crop development stages¹ for various planting periods and climatic regions (days)

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
Small Vegetables							
Broccoli	35	45	40	15	135	Sept.	Calif. Desert, USA
Cabbage	40	60	50	15	165	Sept	Calif. Desert, USA
Carrots	20	30	50/30	20	100	Oct/Jan	Arid climate
	30	40	60	20	150	Feb/Mar	Mediterranean
	30	50	90	30	200	Oct	Calif. Desert, USA
Cauliflower	35	50	40	15	140	Sept.	Calif. Desert, USA
Celery	25	40	95	20	180	Oct	(Semi) Arid
	25	40	45	15	125	April	Mediterranean
	30	55	105	20	210	Jan	(Semi) Arid
Crucifers ²	20	30	20	10	80	April	Mediterranean
	25	35	25	10	95	February	Mediterranean
	30	35	90	40	195	Oct; Nov	Mediterranean
Lettuce	20	30	15	10	75	April	Mediterranean
	30	40	25	10	105	Nov/Jan	Mediterranean
	25	35	30	10	100	Oct/Nov	Arid Region
	35	50	45	10	140	Feb	Mediterranean
Onion (dry)	15	25	70	40	150	April	Mediterranean
	20	35	110	45	210	Oct/Jan	Arid Region; Calif.
Onion (green)	25	30	10	5	70	April/May	Mediterranean
	20	45	20	10	95	October	Arid Region
	30	55	55	40	180	March	Calif. USA
Onion (seed)	20	45	165	45	275	Sept	Calif. Desert, USA
Spinach	20	20	15/25	5	60/70	Apr; Sep/Oct	Mediterranean

Appendix 6: Single (time-averaged) crop coefficients, K_c and mean maximum plant heights for non-stressed, well-managed crops in subhumid climates

Crop	K_c^{ini}	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop Height (h) (m)
a. Small Vegetables	0.7	1.05	0.95	
Broccoli		1.05	0.95	0.3
Brussel Sprouts		1.05	0.95	0.4
Cabbage		1.05	0.95	0.4
Carrots		1.05	0.95	0.3
Cauliflower		1.05	0.95	0.4
Celery		1.05	1.00	0.6
Garlic		1.00	0.70	0.3
Lettuce		1.00	0.95	0.3
Onions – dry		1.05	0.75	0.4
- green		1.00	1.00	0.3
- seed		1.05	0.80	0.5
Spinach		1.00	0.95	0.3
Radish		0.90	0.85	0.3
b. Vegetables – <i>Solanum</i> Family (<i>Solanaceae</i>)	0.6	1.15	0.80	
Egg P lant		1.05	0.90	0.8
Sweet Pepper (bell)		1.15 ²	0.90	0.7
Tomato		1.05 ²	0.70-0.90	0.6
c. Vegetables : Cucumber Family (<i>Cucurbitaceae</i>)	0.5	1.00	0.80	
Cantaloupe	0.5	0.85	0.60	0.3
Cucumber – Fresh Market	0.6	1.00 ²	0.75	0.3