Hindawi
Advances in Agriculture
Volume 2024, Article ID 3976619, 14 pages
https://doi.org/10.1155/2024/3976619

Research Article

Response of Carrot (*Daucus carota* L.) to Supplementary Irrigation under Rain-Fed Agriculture at Jimma and Gera, Jimma Zone, South West Ethiopia

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Received 18 August 2023; Revised 24 December 2023; Accepted 6 January 2024; Published 25 January 2024

Academic Editor: Amelia Salimonti

Evaluating supplementary irrigation under rain-fed agriculture could help to determine the amount of water depth for water management and increasing productivity. Thus, this study was conducted at the Jimma and Gera to determine the effect of supplementary irrigation (SI) on carrot production. Eight treatments with three replications on a field plot of 9 m^2 were used for conducting the experiment. Crop water requirement (ETc) was calculated from reference evapotranspiration (ETo) and crop coefficient (Kc) using CropWat 8.0 software. Yield and yield component data were collected from the field and analyzed using the statistical analysis system (SAS) software 9.0. The result revealed that root shoulder diameter, fresh biomass, and fresh root weight had significant ($p < 0.05$) effects between the treatments, but there was no significant difference ($p > 0.05$) between treatments on plant height and carrot root length at both locations. The highest and lowest plant heights were recorded at 75% SI and at a rain-fed treatment. A root shoulder diameters of 38.37 and 37.86 mm were recorded at Jimma and Gera, respectively, from the application of 75% and two SI at flowering and fruit setting treatment. The application of 75% SI gave the highest root length. A maximum fresh biomass of 3,038.6 kg/ha was obtained at 75% SI, and a minimum fresh biomass of 1,640.00 kg/ha was recorded from the rain-fed treatment at JARC. Application of 75% SI gave the maximum fresh biomass (2,388.9 kg/ha) at Gera, and a minimum fresh biomass of 1,277.8 kg/ha was recorded from rain fed. An application of 75% SI gave the highest fresh root weight of 7,430.6 kg/ha at JARC. In the study, the application of 75% SI gave the highest (6,388.9 kg/ha) fresh root weight, and the lowest was recorded at rain fed (3,883.3 kg/ha). Therefore, for optimum production, 75% SI was recommended for the production of carrots. The total net benefit from the production of carrots was in the range of 36,659–46,950 ETB per hectare at Jimma and from 24,828 up to 39,399 ETB per hectar at Gera. The maximum and minimum marginal return rate (MRR) at Jimma were 300.97%, which is at 75% SI and 43.69%, which is at 25% supplementary irrigation, respectively. At Gera, the maximum and minimum MRR were 490.95%, which were at 25% supplementary irrigation, and the minimum was 23.18%, which was at full supplementary irrigation. Therefore, to get an economic benefit, supplementing carrot crop at 75% irrigation was recommended for both Gera and JARC.

1. Introduction

Agriculture, which creates about 81% of the nation's export revenue and 34.8% of the GDP [1], is the backbone of Ethiopia's economy that has one of the highest population in Africa [2]. However, it is largely dependent on the fluctuating rainfall [3], and its production has been negatively impacted by erratic rainfall patterns forcing many to rely on famine relief support to sustain their lives [4, 5]. Thus, for sustainable food production and production under variable circumstances, on farm water managements are essential [6, 7]. In this regard, irrigation plays an increasingly important role in increasing yield of cultivated land [8]. Among the irrigation methods, supplementary irrigation is essential during the most sensitive growth stages of crops; for substantial yield improvement, water productivity, and when rainfall fails to provide essential moisture during critical growth stages that can lead to maximum yield [9, 10].

In Ethiopia, the production of vegetable and fruit crops through irrigation was very essential. Even though the area devoted to producing vegetables and fruits and its share in total crops grows fast, there was little to no growth in yields; due to this, there is a lower proportion of vegetable output marketed, and the proportion of marketed output has grown slowly [11]. However, their prices are increasing up to 40% from 2005 to 2019 and there is spatial and seasonal variability between the prices [12]. In the study conducted from 2005 to 2018 on six vegetable crops, namely, cabbage, lettuce, spinach, carrot, tomato, and onion, there was no change in vegetable and fruit yields, however, vegetable output grew by 85% from about 577,000 metric tons in 2005 to 1,069,000 metric tons in 2018 [13].

Carrots are one of the most consumed vegetables in the world because of their delicious flavor and high-carotene content. They have acquired worldwide acceptance due to their high vitamin A content, acceptable taste, ease of production, and relatively long storage life at low temperatures [14]. They are used in salads and as relishes and are served as cooked vegetables and in stews and soups. Ethiopia has a high-quality carrot production altitude of 1,800–2,500 m, depending on the variety. Even though there is no consistent production, 12,345.8 tons of carrots were produced in Ethiopia on 2,215 ha of land in 2010/11 [15], as cited by Tabor and Yesuf [14], because of increasing urbanization and income generation and nutrition sources of the crop. It is mainly produced in the central highlands of Ethiopia, and its market cost is high. Since there is a high demand from the urban dwellers, there is a government intervention to widely produce the crop through irrigation as an urban agriculture.

Carrots can be grown throughout the year if rain and irrigation water are available [16]. They are cool season vegetables that prefer sunny locations and fertile, deep, well-drained soils. Before planting, incorporating plenty of organic matter and a complete fertilizer into the area is essential for the development of the crop. Additionally, soil moisture management and its level has to be considered and managed effectively. Similar to other root crops, carrots prefer well-drained soil that is moist but not waterlogged. Because too much soil moisture can clog the soil pore and may cause root rot and other fungal disease, antagonistically too little moisture can make misshapen the crop. Therefore, it is essential to keep the soil moist but not soggy, especially during the germination and early growth stages [17, 18]. Its production can be very low and adversely affected in the dry season due to water stress [14]. Water stress causes carrots to become woody and hard, and antagonistically, too much water causes poor color and rot [17]. According to the study of Wan and Kang [19], the highest carrot yield was obtained at 75% and 100% E_{pan} due to low density and roots of greater size. However, because of excess water in the soil at 125% E_{pan}, it caused lower plant density and adversely affected the carrot root yield.

Even though there is a rising demand consumption and increasing market price of carrot, there is a limited study on carrot production improvement from research and other extension workers. In addition to this, due to the occurrence of climatic variability in Ethiopia, rainfall does not fullfill the needs of crops up to harvesting, especially during the crop sensitive stages [20]. Thus, evaluating supplementary irrigation under rain-fed agriculture could help to find out the quantity of water depth for increasing productivity. Its efficiency is driven by both an effective amount of rain at different growth stages and by a supplementary water depth [21, 22]. Therefore, this study was initiated with the objective of determining the effect of supplementary irrigation on the production of carrot (*Daucus carota* L.) at Jimma and Gera for the carrot irrigation water management.

2. Materials and Methods

2.1. Description of Study Site. The study was conducted at two sites of the Jimma Agricultural Research Center (JARC): JARC at the center and the Gera Agricultural Research Sub-Center (Figure 1). The experiment conducted at JARC was located in Jimma Zone, Oromia Regional State, in south west Ethiopia. Geographically, the site is situated at 7.67° latitude, 36.78° longitude, and 1,753 masl elevation, 377 km from the capital Addis Ababa and 12 km from Jimma town. It has an average annual rainfall of 1,541 mm, an average maximum and minimum temperature of 24 and 11.7°C, respectively. The site is characterized by a monomodal rainfall distribution pattern with alternate dry and rainy seasons, with the majority of the rain falling between June and September. The remaining months of the year, however, were dry.

The other experimental site, which is the Gera Agricultural Research Sub-Center, is located in Oromia Regional State, Jimma Zone, Gera District. Geographically, the site is situated at 7°7′ N latitude, 36°4′E longitude, and 1,940 masl elevation, 470 km from the capital Addis Ababa and 74 km from Jimma town. The climate is cool and humid, and it receives an annual rainfall of 1,906.3 mm, distributed unevenly in the year. It has a maximum and minimum temperature of 24.4 and 10.4°C, respectively.

The experimental sites represent two different research sites located under the Jimma Agricultural research with different agroecology and the different range of rainfall amount and distribution. The Gera site represents the high land and the rural community, the rainfall amount is high, and the distribution is relatively high while, the JARC represent mid land altitude, the urban community and the rainfall amount and distribution is low. In these two sites the demand, the cost, and purpose for which they need the crop is different. Additionally, the soil type and irrigation method is also different.

2.2. Planting Materials. A carrot variety of Nantes (Napa) was used as a test crop in both locations. Before planting, the soil was plowed and harrowed, and a raised bed was prepared. This raised bed provides better irrigation management and more access to light, which improves the temperature of the roots. After preparing the raised bed, a furrow was dug, the seed was placed, and then the bed was covered with dry vetivar grass. This covering was essential for improving germination, which largely determines carrot yield. For germination, overhead irrigation, which helps to maintain more uniform moisture on the entire surface of the bed, which is a requirement for good seed germination, was applied through a water cane before treatment application. The same activity and procedure were done critically at both locations and managed effectively. The planting dates were September 25, 2015,

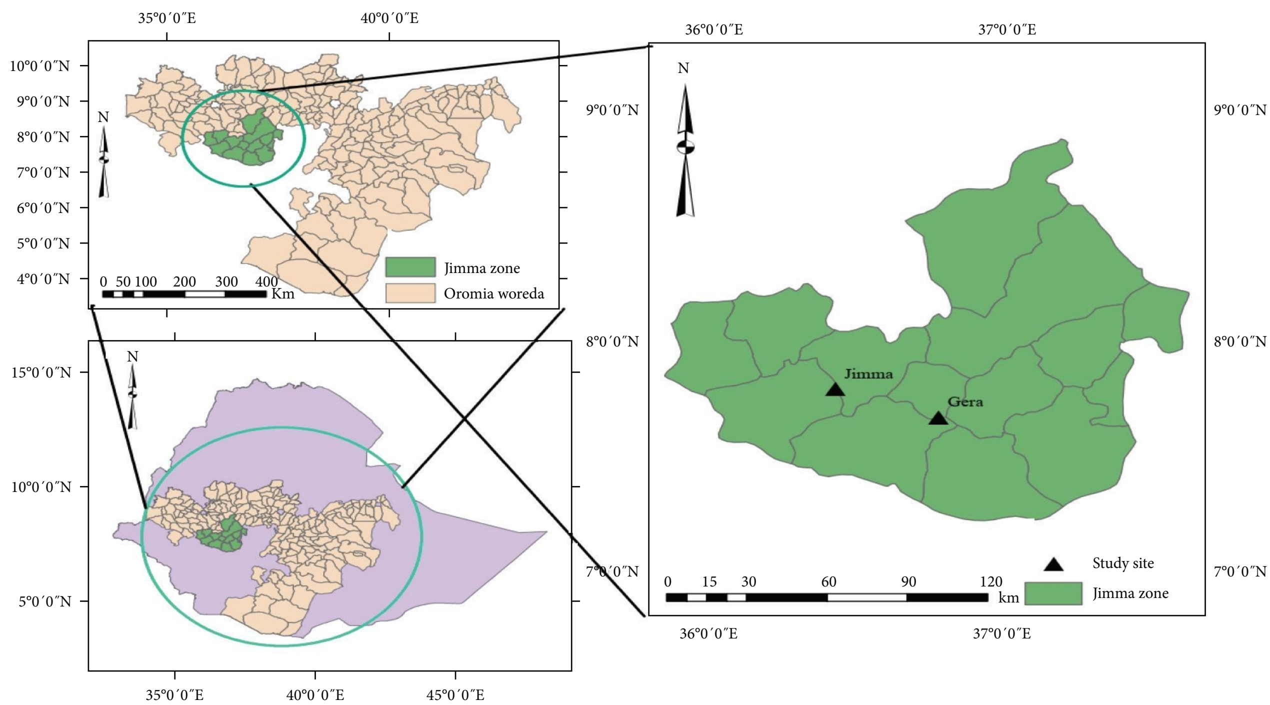

FIGURE 1: Geographical location of the study site.

at Jimma and October 30, 2015, at Gera, which represents the end of rainfall season and beginning of the dry season at each location, respectively.

2.3. Experimental Design. Eight treatments, which include only rain fed (no supplementary irrigation), 100% ETc Supplementary Irrigation (SI) throughout the season, 75% ETc SI throughout the season, 50% ETc SI throughout the season, 25% ETc SI throughout the season, 100% ETc SI once at the flowering stage, 100% ETc SI once at the fruit setting stage, and 100% ETc SI once at the flowering stage and once at the fruit setting stage, were used. Each treatment had three replications, making 24 experimental plots that were arranged in a randomized complete block design (RCBD) in the 2015/16 cropping season. Each plot had an area of 9 m^2 (3 m× 3 m) at both locations. The spacing between plots and replication was 1 and 2 m, respectively. Recommended fertilizer rate of 175 kg DAP ha^{-1} at transplanting which is the recommended rate for root production of fresh market carrots and urea (100 kg ha^{-1}) was top dressed to enhance vegetative growth.

2.4. Soil Sampling. A soil sample was collected from the experimental field. The physical and chemical properties of the soil were analyzed for both locations (Tables 1–4). A disturbed mixture of soil samples was taken using an auger for the analysis of soil moisture, texture, bulk density, FC, and PWP. Soil textural class was analyzed using the USDA textural triangle. Bulk density (BD) was calculated as the dry weight of soil divided by its volume. This volume includes the volume of soil particles and the volume of pores among soil particles.

TABLE 1: Soil physical properties and texture of the study site at JARC.

No.	Tested parameter (%)	Soil depth (cm)			
		0–30	30–60	60–90	Average
1	Sand	53.75	51.25	46.25	50.42
2	Clay	33.75	36.25	43.75	37.92
3	Silt	12.5	12.5	10	11.66
4	Soil textural class	SCL	SC	SC	SCL
5	Soil bulk density (g/cm^3)	1.20	1.30	1.32	1.27
6	FC	35.51	36.92	34.80	35.74
7	PWP	24.50	25.20	24.60	24.76
8	TAW	11.01	11.72	10.20	10.98

$$\text{Bulk density (BD)} = \frac{\text{Weight of dry soil (gm)}}{\text{Volume of the same soil (cm}^3\text{)}}. \quad (1)$$

The soil water content at field capacity and the permanent wilting point were determined in the laboratory by using a pressure plate apparatus. The pressure plate was adjusted to 33 and 15 bar to determine the field capacity and the permanent wilting point of a saturated soil sample, respectively. The soil analysis was carried out at Debrezeit Agricultural Research Center (DzARC). Total available water (TAW) in the root zone was computed as the difference in moisture content between field capacity (FC) and permanent wilting point (PWP) as follows:

Table 2: Soil chemical properties of the study site at JARC.

No.	Tested parameter (%)	Soil depth (cm)			
		0–30	30–60	60–90	Average
1	pH (1 : 2.5)	5.3	4.78	4.69	4.93
2	TN	0.3	0.31	0.22	0.28
3	Organic carbon	2.68	2.11	1.81	2.20
4	Organic matter	4.62	3.65	3.11	3.79
5	EC (dS/cm)	29.10	30.70	38.60	32.80
6	CEC (meq/100 gm)	20.39	20.16	19.56	20.04
7	Phosphorus (ppm, Bray)	2.11	1.86	0.89	1.62
8	Magnesium (meq/100 gm)	0.63	0.62	0.33	0.53
9	Ca (meq/100 gm)	3.09	3.53	1.28	2.63
10	Cl^- (meq/L)	0.40	0.48	0.40	0.43
11	Available K (m_{eq} k/100 gm)	2.30	1.42	0.57	1.43

Table 3: Soil physical properties of experimental site at JARC.

No.	Tested parameter (%)	Soil depth (cm)			
		0–30	30–60	60–90	Average
1	Sand	51	41	47	46.3
2	Clay	44	54	46	48.0
3	Silt	5	5	7	5.7
4	Soil textural class	SC	C	SC	SC
5	Soil bulk density (g/cm^3)	1.22	1.34	1.30	1.3
6	FC	35.37	35.14	38.17	36.2
7	PWP	10.23	27.73	26.33	21.4
8	TAW	25.14	7.41	11.84	14.8

Table 4: Soil chemical properties of the study site at Gera.

No.	Tested parameter	Soil depth (cm)			
		0–30	30–60	60–90	Average
1	pH (1 : 2.5)	6.15	5.85	5.6	5.87
2	EC (μs/cm)	30.1	37.1	29.9	32.37
3	Magnesium (meq/100 g)	0.7	0.52	0.33	0.52
4	Ca (meq/100 g)	2.9	0.38	1.28	1.52
5	Cl^- (meq/L)	0.32	0.72	0.4	0.48

$$\mathrm{TAW} = \frac{(\mathrm{FC} - \mathrm{PWP}) \times \mathrm{Dr}}{100} \times \mathrm{BD}, \tag{2}$$

where

TAW = total available water (cm), FC = water content at field capacity (%),

PWP = water content at permanent willing point (%), and Dr = effective root zone depth (cm).

The infiltration rate of the soil in the experimental field was determined using a double-ring infiltrometer before the start of the experiment. The double-ring infiltrometer was set up on the field surface and measured the depth at which water levels infiltrated continuously, and the rate at which water level lowered was calculated. This data were used as input for the CropWat 8.0 software to determine the crop's water requirement (CWR).

2.5. Determination of Crop Water Requirement (CWR). Crop water requirement (ETc) over the growing season was calculated from reference evapotranspiration (ETo) and crop coefficient (Kc) for the growing stage. Maximum and minimum temperatures (°C), humidity (%), wind speed (m/s or km/hr), sunshine hours (hr), and rainfall (mm) of the experimental site were collected on a daily basis from each meteorological station located at each center. They were used as input data for the CROPWAT 8.0 software to determine the CWR and irrigation requirement of the crop.

$$\mathrm{ETc} = \mathrm{kc} \times \mathrm{ETo}, \tag{3}$$

where

ETc = crop water requirement (mm), kc = crop coefficient, ETo = reference evapotranspiration (mm).

The net irrigation (IRn) at each stage was computed from the following expression:

$$\mathrm{IRn} = \mathrm{ETc} - P_{\mathrm{eff}}, \tag{4}$$

where P_{eff} = effective rainfall (mm).

The gross irrigation requirements (IRg) for each stage were obtained from the expression as follows:

$$\mathrm{IRg} = \frac{\mathrm{IRn}}{\mathrm{Ea}}. \tag{5}$$

The irrigation schedule was calculated by using the following formula:

$$\text{Irrigation interval (days)} = \frac{\mathrm{IRn}}{\mathrm{ETc}}. \tag{6}$$

The determined irrigation water was applied using a furrow irrigation system. A measured quantity of water was applied using a water cane at Gera and a partial flume was used for measuring applied water with an application efficiency of 60% at Jimma. It was installed in the experimental field to measure the flow rate into the plots. The time of irrigation required for a given head of water through the Parshall flume was calculated as follows:

$$t = \frac{A \times \mathrm{dg}}{6Q}, \tag{7}$$

where t = application time, A = area of plot, dg = required depth of water (cm), and Q = discharge (l/s).

2.6. Data Collection. Crop yield and growth parameter data such as plant height, root shoulder diameter, root length, fresh biomass, and fresh root weight were taken from each plot. Root shoulder diameter and root length were determined by a random selection of roots from each plot, excluding the border rows and border plants. The harvested fresh root

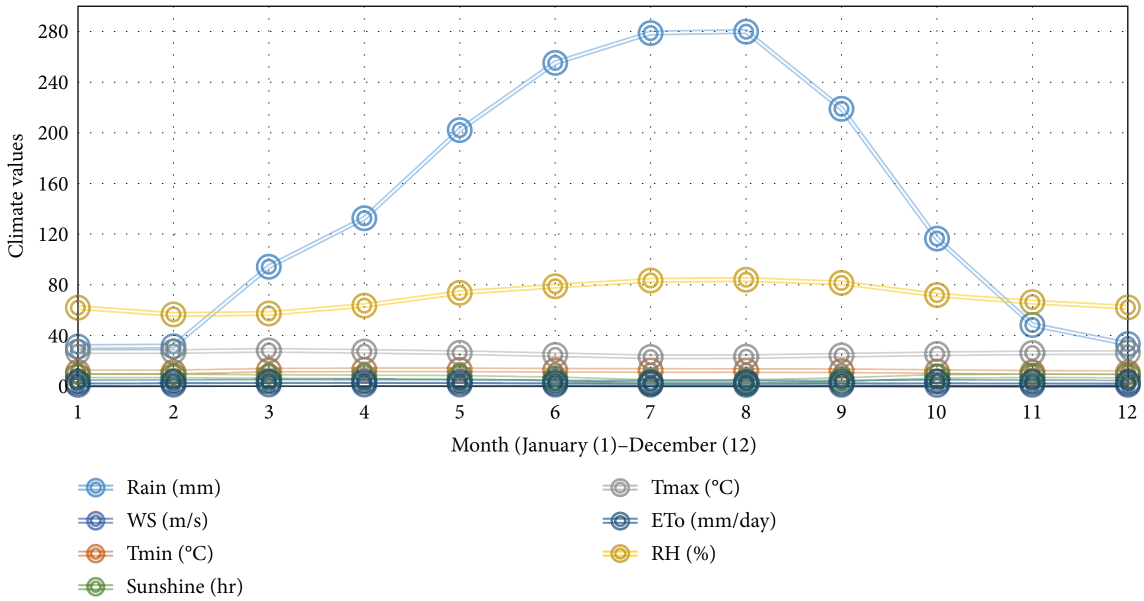

Figure 2: Average long year meteorological data of Jimma Agricultural Research Center (JARC).

weight (yield) was grouped based on its quality for the market according to the size and degree of damage.

Root length (cm): It was measured by using a caliper placed at the point of the leaf detached from tips of the matured root. Similarly, root diameter was also measured by using a caliper placed at the widest point in the middle portion of the matured root.

To determine carrot root yield; marketable root yield was determined as the total weight of roots free from soft rot, and free from damage caused by growth, cracks, sunburn, pithiness, woodiness, oil spray, dry rot, other diseases, or insects. According to USDA [23], to be considered as a root, yield, the length of each carrot has to be greater than 7.62 cm to accommodate both processing and fresh types of carrots per net plot area and conversion to $t\,ha^{-1}$, unless it is considered as an unmarketable root yield. Total root yield was determined as the sum of marketable and unmarketable roots in $t\,ha^{-1}$.

2.7. Partial Budget Analysis. The financial benefit of supplementary irrigation that will supplement rainfall for carrot production was assessed. Both the production cost (variable cost for water, fertilizer, and labor) and the benefits that will be gained were determined. The root yield was adjusted to 10%, and then multiplied by the previous cost available during conducting the experiment. According to the study of CIMMYT [24], partial budget analysis was performed by using the average root yield outputs of the treatment, and for every treatment, the marginal rate of return. For determining the variable cost, the irrigation cost was assumed 1 ETB for 1 m^3 of irrigation water and the benefit gained was considered eight ETB for Gera and 8.50 ETB for Jimma per kg of carrot during the experiment time and all other expenses were similar for both locations.

$$\text{Marginal rate of return } (\%) = \frac{\text{Change in net benifit}}{\text{Change in total variable cost}} \times 100. \quad (8)$$

2.8. Data Analysis. The collected data were subjected to analysis of variance (ANOVA) using the statistical analysis system (SAS) software version 9.0 with the general linear model (GLM) procedure [25]. Mean separation was employed using the least significant difference (LSD) at a 5% probability level to compare the differences among the treatments.

3. Results and Discussion

3.1. Long Year Climatic Condition of the Site. For determining the rate of supplementary irrigation, analysis of the long year climatic condition of the study site is essential to know the quantity and distribution of the rainfall specifically. It is also essential for determining the suitability of the crop in the specified agroecology. From the analysis of the long-year average meteorological data collected from JARC for a period of 29 years (1981–2010), there was a high amount of rainfall during the 4 months of June–September (Figure 2). The result reveals that there was a minimum rainfall of 31.37 mm in January and a maximum rainfall of 278.86 mm in June. There was a relative humidity, wind speed, and sunshine hours of 70.13%, 1.11 km/hr, and 6.6 hr/day, respectively, and the minimum and maximum temperatures were 10.65 and 28.21°C, respectively (Figure 2).

The long-year meteorological data collected from the Gera Agricultural Research Sub-Center reveals that the average minimum and maximum rainfall range from 43 up to 284 mm per month, respectively. The minimum was in January, and the maximum was in June. There was high rainfall

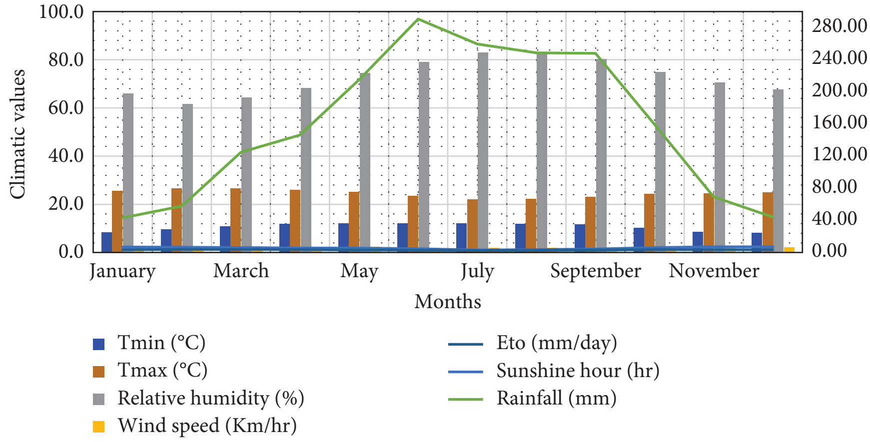

Figure 3: Average long year climatic conditions of Gera Agricultural Research Center.

from May up to September (Figure 3). The minimum and maximum temperatures were 8.0 and 26.54°C, respectively. In the study area, the long-year meteorological data revealed that there was a relative humidity, wind speed, and sunshine hours of 72.64%, 2.14 km/day, and 5.6 hr/day, respectively (Figure 3). Based on the study, there was no need of irrigation for the carrot crop during the months from May to September, because there was high rainfall and the effective rainfall could satisfy the CWR. In the remaining months, it requires full or supplementary irrigation based on the planting date of the crop and soil moisture condition.

3.2. Soil Physical and Chemical Properties. For the JARC condition, and the soil physical properties, the soil bulk density of the experimental area ranges from 1.20 to 1.32 g/cm^3. The results of this study showed that, the bulk density increases with soil depth. Regarding the particle size analysis, the average composition of clay, silt, and sand percentages were 37.92%, 11.66%, and 50.42%, respectively. Thus, according to the USDA soil textural classification, the soil texture of the experimental site was classified as sandy clay loam (SCL). Average soil moisture content on mass base at field capacity and permanent wilting point were 35.74% and 24.76%, respectively.

Among the soil chemical properties, the ability of soil pH is high, since it affects the soil physical, chemical, and biological properties [26]. The result of soil chemical analysis at JARC showed that the average pH value of the soil ranges from 4.69 to 5.3. The average soil pH of the study site was 4.93, which is acidic. The average electrical conductivity of the soil was 32.80 ds/cm. As shown in Table 2, soil pH is negatively related to soil electrical conductivity in the form of power function and not in the linear relationship. This is because there are several other factors such as soil mineral, porosity, soil texture, soil moisture, and soil temperature which also affect soil electrical conductivity in the soil. Additionally, soil pH is also affected by parent material, climate, living organism, topography, time, native vegetation, crop grown, organic material, precipitation, temperature, and human activities [27]. The average total organic carbon content of the testing soil is 2.2%, which was rated as moderate and gives the average structural condition and stability to the soil. Since soil is one of the major factor for crop development, its relation with other soil chemical and physical properties is essential and for JARC soil, it is shown in Figures 4 and 5 for Gera.

The ECe has shown an increasing trend from the upper top soil layer to the subsoil penology. This shows that the soil moisture in the lower layer has a potential to rise and withdraw through capillary force. Similarly, Chekol and Mnalku [28], identified that the higher value of ECe in the upper surface layers of fluvisols indicates that might be the shallow water depth, texture, and structure of the soil that enhance the draw up of moisture to the surface by capillarity and bring with it-dissolved salts, which will be left behind as the moisture evaporates.

For the Gera condition, the soil physical properties, soil bulk density of the experimental area ranges from 1.20 to 1.32 g/cm^3. The results of this study showed that the bulk density increases with soil depth. Regarding particle size analysis, the average composition of clay, silt, and sand percentages were 37.92%, 11.66%, and 50.42%, respectively. Thus, according to the USDA soil textural classification, the soil texture of the experimental site was classified as sandy clay (SC; Table 3). Average moisture content on mass base at field capacity and permanent wilting point were 36.2% and 21.4%, respectively.

From both the physical and chemical properties of the soil, the soil texture is SCL and SC, which is suitable for carrot production at both location. According to the study conducted by Cueto Wong [29], carrots are cultivated preferably in deep, loam textured, not stony, and well-drained soils. According to the study of Brady et al. [26], sandy soils are well-suited for carrot production. Even though sandy clay soils are suitable for vegetable production including carrots, it needs regular irrigation scheduling and fertilizer management to ensure healthy development [30].

3.3. Crop Water Requirement of the Crop. A carrot crop planted at the end of October in the agroecology of Gera requires 262.1-mm depth of water throughout the crop season. The irrigation requirement that has to be supplied was 192.4-mm depth of water (Table 5). At JARC, the CWR and irrigation requirement of the crop planted at the end of September were

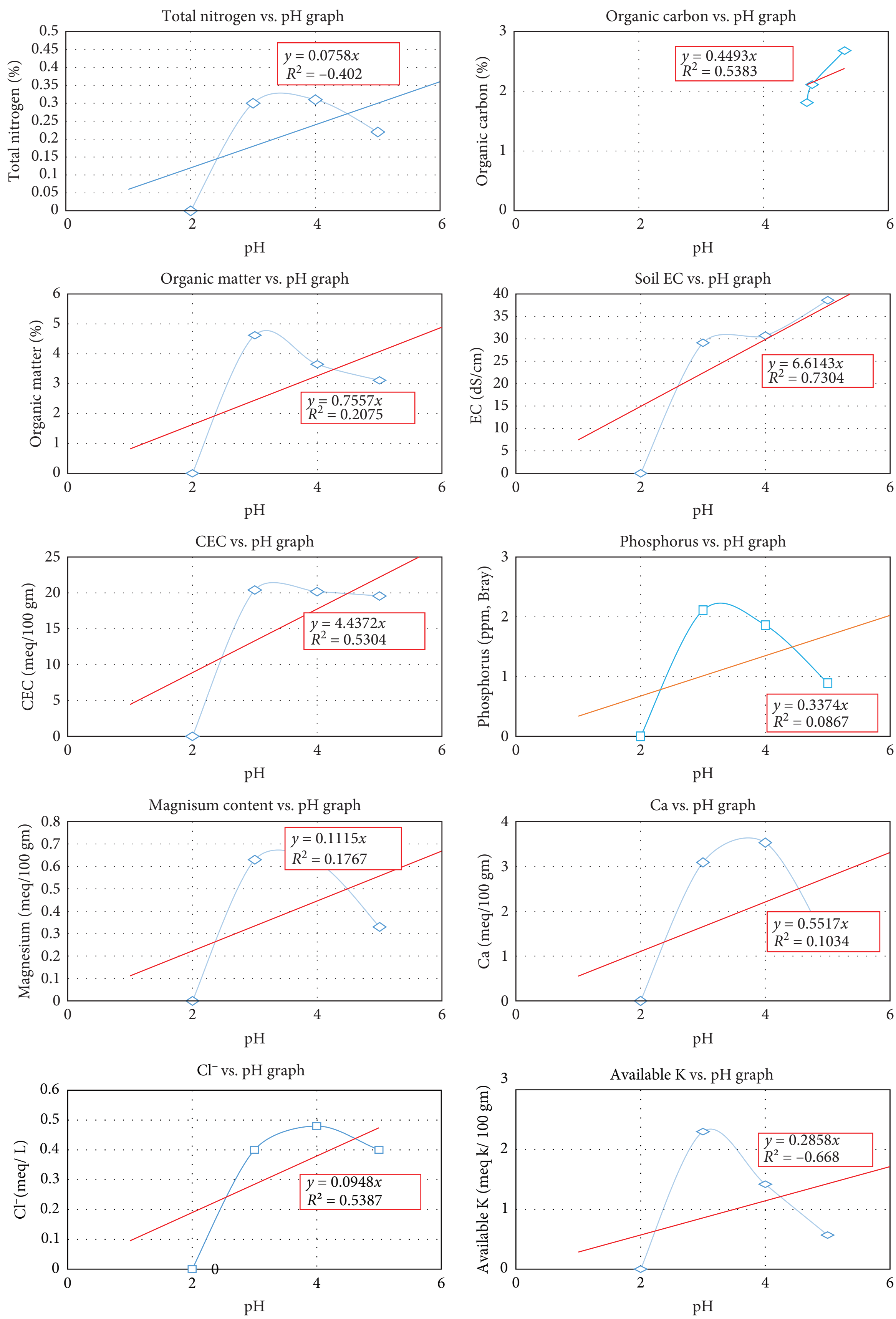

Figure 4: Relationship of soil pH at different depth with other chemical properties at JARC.

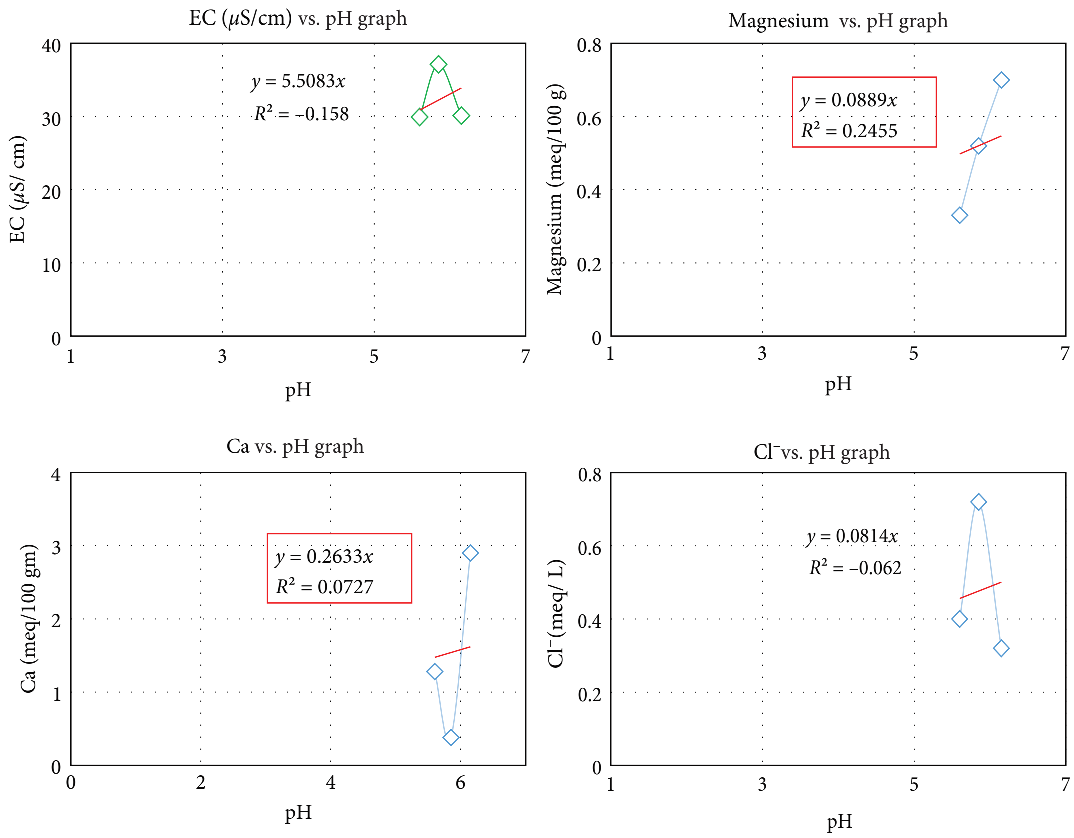

Figure 5: Relationship of soil pH at different depth with other chemical properties at Gera.

Table 5: Growth period, water requirement, and net irrigation requirement of carrot at Gera.

Growth stage	Length of growth period (Days)	ETc (mm/day)	Crop water requirement (mm)	Effective rainfall (mm)	Net irrigation requirement (mm)	Irrigation supplied (%)
Initial	18	2.19	31.00	21.50	9.50	30.65
Development	30	2.40	72.10	21.70	50.40	69.90
Mid-season	30	2.99	92.70	15.00	77.70	83.82
Late-season	16	2.92	66.30	11.50	54.80	82.65
Total	94	—	262.1	69.70	192.40	73.41

Table 6: Growth period, water requirement, and net irrigation requirement of carrot at Jimma.

Growth stage	Length of growth period (Days)	ETc (mm/day)	Crop water requirement (mm)	Effective rainfall (mm)	Net irrigation requirement (mm)	Irrigation supplied (%)
Initial	20	2.13	38.40	20.0	18.4	47.92
Development	30	2.86	85.90	21.7	64.2	74.74
Mid-season	30	3.02	107.30	15.0	92.3	86.02
Late season	10	3.00	54.60	4.9	49.7	91.03
Total	90	—	286.20	61.6	224.6	78.48

286.20 and 224.60 mm depth of water, respectively (Table 6). The irrigation water requirement was critical during the most sensitive stages at mid-season, and there was no effective rainfall during that period, so it has to be supplemented through irrigation. There is no difference in the crop season at both locations, but there is additional growing day at Gera. This was due to a low temperature at Gera, which takes a more time for germination of the seed. Since there was a different planting date, it was difficult to observe different irrigation requirements for the same crop.

A similar experiment conducted by Carvalho et al. [31], obtained a water requirement of carrot as 240.8 mm in 2010 and 276.0 mm in 2011 cropping season, respectively; which is below 300-mm depth of water. Unfortunately, there are other results, which indicate the water requirement of carrot in between 600 and 900 mm depth of water [32]. Based on their study, there is a high E_{pan} (6-7 mm/day) and a crop period of up to 190 days. Since, there is a high daily evaporation and long crop season, the water requirement is expected to be higher.

3.4. Effect of Different Supplementary Irrigation on the Growth Parameter and Yield of Carrots

3.4.1. Plant Height. The statistical analysis conducted at JARC revealed that there was no significant difference ($p > 0.05$) on the plant height. However, the highest plant height (36.07 cm) was recorded at 75% SI treatment and the shortest (30.13 cm) at a rain-fed treatment (Table 7). The statistical analysis showed that there was no significant difference between the treatments of one irrigation at the flowering stage, applying 50% ETc and 25% ETc. A similar experimental plot at Gera reveals that there was no statistically significant difference ($p > 0.05$) between the plant height. The highest plant height of (36.07 cm) was also recorded at 75% ETc and the lowest plant height was recorded at a treatment with no supplementary irrigation (Table 8). The statistical analysis revealed that there was no significant difference between the treatments of the two irrigations at flowering and fruit setting: one irrigation at flowering stage, ¼ irrigation/25% ETc and ½ irrigation/50% ETc (Table 8).

From this, it can be observed that supplementary irrigation has little or no effect on plant height. Similarly, SAS [33], also pointed out this; according to him, plant heights were not significantly different ($p > 0.05$) between the 80% and 100% water application levels. A similar experiment conducted on vegetable crop/potato showed that there was no statistically significant difference between treatments on plant height of potato, potato's plant height was not affected by the rate of supplementary irrigation [34]. This is because the crop takes the essential water for the development of the root rather than for the leaf.

3.4.2. Root Shoulder Diameter. Application of sufficient irrigation to the field is beneficial for nutrient absorption, provides an appropriate physical environment for better root growth, and can increase the root volume [35]. Root shoulder diameter was significantly influenced ($p < 0.05$) by the rate of supplementary irrigation at JARC. The statistical analysis at JARC showed that supplementary irrigation at a rate of 75% gave the highest root shoulder diameter of 38.37 mm (Table 7). The root shoulder diameter was also significantly ($p < 0.05$) affected by the rate of supplementary irrigation at Gera. The recorded data showed that supplementary irrigation at two irrigation sites at flowering and fruit setting influenced the productivity of carrots. There was no statistical difference between the remaining treatments from each other (Table 8). A root shoulder diameters of 38.37 and 37.86 mm were recorded at JARC and Gera, respectively, from the application of 75% and two supplementary irrigations at flowering and fruit settings.

3.4.3. Root Length. Carrot root length was not influenced ($p > 0.05$) by the rate of supplementary irrigation at both locations. At both locations, the same result was obtained; however, the application of 75% supplementary irrigation gave the highest root length. In this study, a minimum root length of 18.93 cm was recorded at 25% supplementary irrigation (Tables 7 and 8). This result agrees with the research conducted by Quezada et al. [32]. According to their study, there was no significant difference between root lengths due to the water applications. Unfortunately, carrots cultivated on ridges produced significantly longer roots compared to cultivate on flat ground [36, 37]. This may be because of the possibility of the root to obtain the required amount of water for the uptake and solubility of soil nutrients. This is in agreement with Ludong [38], who justified that the root length of carrots increased directly with the amount of water level applied.

3.4.4. Fresh Biomass. Fresh biomass was influenced ($p < 0.05$) by the rate of supplementary irrigation at JARC. The statistical analysis reveals that the application of 75% supplementary irrigation gave the highest fresh biomass. A maximum fresh biomass of 3,038.6 kg/ha was obtained at 75% supplementary irrigation, and a minimum fresh biomass of 1,640.00 kg/ha was recorded from the nonirrigated (rain-fed) treatment at JARC. There was a 46% fresh biomass difference between the 75% supplementary irrigation and rain fed (Table 7). Similarly, in the study conducted at Gera, there was a significant difference ($p < 0.05$) between the treatments, which affects the amount of fresh biomass. The statistical analysis reveals that 75% supplementary irrigation gave the maximum fresh biomass (2,388.9 kg/ha) at Gera, and the minimum fresh biomass of (1,277.8 kg/ha) was recorded from rain fed/no supplementary irrigation (Table 8). Similarly, at Gera, there was a fresh biomass advantage of 46% between the rain fed and application of 75% supplementary irrigation. At both locations there was no statistically significant difference between the other treatments ($p > 0.05$). From this, it could be observed that supplementary irrigation has an impact on the fresh biomass product.

3.4.5. Fresh Root Weight (Yield). Results in Table 7 show that, there was a statistically significant difference ($p < 0.05$) between treatments, revealing that the marketable fresh root weight was affected by the rate of supplementary irrigation at JARC. The recorded data reveal that an application of 75% supplementary irrigation gave the highest fresh root weight of 7,430.6 kg/ha. However, there was no significant difference observed between the remaining treatments. There was a yield difference of 30% between the maximum and the lowest treatments. Supplying inadequate water may adversely affect the crop yield due to a water scarcity problem. The result from Gera also showed that there was a significant difference ($p < 0.05$) between treatments. In the study, application of 75% supplementary irrigation gave the highest (6,388.9 kg/ha) fresh root weight, and the lowest was recorded at rain fed (3,883.3 kg/ha) (Table 8). There was a 39% yield increment between the highest and lowest fresh root weights. A study

Table 7: Effects of supplementary irrigation on the yield and yield components of carrot at JARC.

No.	Treatment	Plant height (cm)	Root shoulder diameter (mm)	Root length (cm)	Fresh biomass (kg/ha)	Fresh root weight (kg/ha)	Water productivity (kg/m^3)	HI (%)
1	Rain fed/no irrigation	30.13	34.50^{ab}	21.00	$1,640.00^{b}$	$5,201.4^{b}$	—	31
2	Full irrigation/100% ETc	35.67	36.43^{ab}	23.00	$2,419.20^{ab}$	$6,875.0^{ab}$	3.70^{d}	35
3	¾ Irrigation/75% ETc	36.07	38.37^{a}	22.27	$3,038.60^{a}$	$7,430.6^{a}$	5.34^{d}	41
4	½ Irrigation/50% ETc	31.60	35.90^{ab}	20.87	$2,130.90^{ab}$	$6,111.1^{ab}$	6.36^{d}	34
5	¼ Irrigation/25% ETc	32.80	31.73^{b}	18.93	$2,398.10^{ab}$	$5,902.8^{ab}$	11.19^{c}	41
6	One irrigation at flowering stage	33.53	34.77^{ab}	20.60	$2,577.80^{ab}$	$6,076.4^{ab}$	29.35^{a}	42
7	One irrigation at fruit setting stage	30.47	31.60^{b}	21.73	$1,765.70^{b}$	$6,388.9^{ab}$	15.29^{b}	27
8	Two irrigation at flowering and fruit setting	34.27	34.70^{ab}	21.00	$2,558.10^{ab}$	$6,902.8^{ab}$	5.78^{d}	37
—	LSD	Ns	5.98	Ns	1,125.70	1,849.60	3.46	—
—	CV	8.54	9.83	7.37	17.19	16.60	20.55	—

Means with the same letter are not significantly different at 5% significant level.

Table 8: Effects of supplementary irrigation on the yield and yield components of carrot at Gera.

No.	Treatment	Plant height (cm)	Root shoulder diameter (mm)	Root length (cm)	Fresh biomass (kg/ha)	Fresh root weight (kg/ha)	Water productivity (kg/m^3)	HI (%)
1	Rain fed/no irrigation	30.13	34.493^{ab}	21.00	1,277.8^{b}	3,883.3^{c}	—	33
2	Full irrigation/100% ETc	35.67	36.460^{ab}	23.00	1,888.9^{ab}	4,611.1^{bc}	2.40^{e}	41
3	¾ Irrigation/75% ETc	36.07	35.197^{ab}	22.27	2,388.9^{a}	6,388.9^{a}	4.41^{d}	37
4	½ Irrigation/50% ETc	31.60	35.900^{ab}	20.87	1,666.7^{ab}	5,111.1^{b}	5.29^{d}	33
5	¼ Irrigation/25% ETc	32.80	31.743^{ab}	18.93	1,888.9^{ab}	5,444.4^{ab}	11.28^{c}	35
6	One irrigation at flowering stage	33.53	34.770^{ab}	20.60	2,027.8^{ab}	4,861.1^{bc}	32.22^{a}	42
7	One irrigation at fruit setting stage	30.47	31.610^{ab}	21.73	1,388.9^{ab}	4,888.9^{bc}	19.45^{b}	28
8	Two irrigation at flowering and fruit setting	34.27	37.860^{a}	21.00	2,000.0^{ab}	5,522.2^{ab}	13.72^{c}	36
—	LSD	Ns	6.16	Ns	899.95	1,066.30	3.77	—
—	CV	8.53	10.12	7.37	28.29	11.96	19.42	—

Means with the same letter are not significantly different at 5% significant level.

Table 9: Partial budget analysis of carrot production through supplementary irrigation at JARC.

No.	Treatments	Yield (Kg/ha)	Adjusted yield (Kg/ha)	TVC (ETB)	TRC (ETB)	Net benefit (ETB)	Absolute MRR	MRR (%)
1	No SI	5,201.4	4,681.26	3,131	39,790.71	36,659	—	—
2	Full SI	6,875	6,187.5	7,318	49,500	42,182	1.319	131.89
3	¾ SI	7,430.6	6,687.54	6,550	53,500.32	46,950	3.010	300.97
4	½ SI	6,111.1	5,499.99	5,783	43,999.92	38,217	0.587	58.74
5	¼ SI	5,902.8	5,312.52	5,017	42,500.16	37,483	0.437	43.69
6	1SI at flowering stage	6,076.4	5,468.76	4,860	43,750.08	38,890	1.290	129.00
7	1 SI at fruit settling stage	6,388.9	5,750.01	5,071	46,000.08	40,929	2.201	220.07
8	2 SI at flowering and at fruit settling stage	6,902.8	6,212.52	6,250	49,700.16	43,450	2.177	217.71

Table 10: Partial budget analysis of carrot production through supplementary irrigation at Gera.

No.	Treatments	Yield (Kg/ha)	Adjusted yield (Kg/ha)	TVC (ETB)	TRC (ETB)	Net benefit (ETB)	Absolute MRR	MRR (%)
1	No SI	3,883.3	3,494.97	3,131	27.959.76	24,828	—	—
2	Full SI	4,611.1	4,149.99	7,385	33.199.92	25,815	0.2318	23.18
3	¾ SI	6,388.9	5,750.01	6,601	46.000.08	39,399	4.1998	419.88
4	½ SI	5,111.1	4,599.99	5,817	36.799.92	30,983	2.2911	229.11
5	¼ SI	5,444.4	4,899.96	5,033	39.199.68	34,166	4.9095	490.95
6	1SI at flowering stage	4,861.1	4,374.99	4,806	34.999.92	30,194	3.203	320.30
7	1 SI at fruit settling stage	4,888.9	4,400.01	4,907	35.200.08	30,293	3.0779	307.79
8	2 SI at flowering and at fruit settling stage	5,522.2	4,969.98	5,464	39.759.84	34,296	4.0589	405.89

Note: The cost were estimated based on the investment during the cropping season in 2015/2016 cropping season. Where, MRR, TVC, and ETB represented marginal rate of return, total variable cost, and Ethiopian birr, respectively.

conducted by Crosson et al. [18, 39], reveals that carrots prefer sunny locations and fertile, deep, and well-drained soils. One reason for the high production of high yield at 75 % supplementary irrigation could be the availability of air in the soil pore space and the draining ability of the soil due to the 25% reduction of water

According to the study of Muendo et al. [40], the maximum carrot yield was in the range of 30–100 tons/ha and the world average carrot production was 36.5 and 3.5 tons/ha in Ethiopia [41]. However, a maximum yield advantage of 95.3% and 94.5% at JARC and Gera was obtained through the supplementary irrigation, respectively. Similarly, a maximum yield advantage of 200% carrot was obtained through sprinkler irrigation, a more efficient irrigation method [37]. From this, it is clearly understood that the rate of supplementary irrigation has an influence on the production and productivity of carrots. Those consumers in the rural community as well as those who are interested in producing urban agriculture could get an optimum yield through the application of 75% supplementary irrigation for carrot production.

3.5. Water Productivity. Application of deficit irrigation, use of different irrigation methods, and irrigation scheduling can maximize water use efficiency (WUE). It can also be maximized through improving agricultural practices, which can increase crop yield. There was a significant difference ($p < 0.05$) between treatments on the water productivity at both locations. The result reveals that a maximum water productivity of 29.35 kg/m^3 was recorded at supplementing one irrigation at the flowering stage and a minimum (3.70 kg/m^3) was recorded at full supplementary irrigation at JARC (Table 7). At Gera, the maximum and minimum water productivity were 32.22 and 2.4 kg/m^3 recorded at supplementing one irrigation at the flowering stage and full irrigation (100% ETc), respectively (Table 8).

3.6. Harvest Index. Harvest index (HI) describes the plant capacity to allocate biomass (assimilates) into the formed reproductive parts. It is the ratio of biomass to total yield and is a measure of reproductive efficiency. In this study, it was determined by dividing fresh biomass with fresh yield of the crop. From this study, the maximum HI was obtained at one irrigation at flowering stage treatment at JARC case, which is 42% and the minimum, was at one irrigation at fruit setting stage, which is 27% (Table 7). On the other hand, at Gera the maximum and minimum HI of 42% and 28% were obtained from one irrigation at flowering stage and one irrigation at fruit setting stage, respectively (Table 8). The lowest HI indicates that there was a higher yield and vice versa.

3.7. Economic Analysis. The total net benefit from the production of carrots during the cropping season was in the range of 36,659–46,950 ETB per hectare at JARC and from 24,828 up to 39,399 ETB per hectar at Gera. The maximum and minimum marginal rate of returns (MRR) were 300.97%, which is at 75% SI and 43.69% which is at 25% supplementary irrigation, respectively, at JARC (Table 9). At Gera, the maximum and minimum MRR were 490.95%, which were at 25% supplementary irrigation, and the minimum was 23.18%, which was at full supplementary irrigation (Table 10). Therefore, to get an economic benefit, supplementing carrot crop at 75% irrigation water was recommended for both Gera and JARC. From the economic analysis result, the economic benefit gained at the mid altitude and urban area is higher than that of high altitude and rural areas. The consumption is also relatively low in the rural community.

4. Conclusion

This study is essential for irrigation water management in a rain-fed agriculture in relation to the supplementary irrigation for an effective management of scarce water resource. The efficiency of supplementary irrigation depends on the water losses that occur during and after the irrigation. Applying a high amount of water depth, without considering rainfall, may increase water losses through percolation or surface runoff.

Based on the study conducted at two sites, supplementary irrigation increases the fresh biomass and root weight at both locations. The application of 75% supplementary irrigation enhanced the fresh biomass and fresh root weight in Gera and JARC compared to the other treatments. Supplementary irrigation once at the flowering stage has the highest water productivity compared to the others, but the root weight and fresh biomass are the lowest, relatively. Therefore, for optimum production, 75% supplementary irrigation is recommended for the production of carrots. Additionally, from the study conducted at two sites, the productivity, consumption, and market price of carrot is relatively higher in the mid altitude areas.

Data Availability

All data are available on the paper itself.

Disclosure

The manuscript entitled "Response of Carrot (*Daucus carota* L.) to supplementary irrigation under Rain Fed Agriculture at Jimma and Gera, Jimma Zone, South West Ethiopia," is a research conducted at two sites of Jimma Agricultural Research Center in the same year by the responsible researchers namely Etefa Tilahun, Minda Tadesse and Adissu Assefa. We hereby declare that this research is our original work and all information in this document has been worked responsibly and with ethical conducts. We also declare that, as required by these rules and conducts, all sources of materials that are not original to this work have been cited and duly acknowledged.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors are thankful to the Ethiopian Institute of Agricultural Research for providing financial support for conducting the experiment. They also express appreciation for the Jimma Agricultural Research Center and staff members of Irrigation and Drainage Research division for their support and technical assistance in the field experimentation.

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