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Optimizing Agricultural Water Use: A Comparative Analysis of Soil Moisture and Evapotranspiration-Based Irrigation Scheduling for Carrot Crop (*Daucus Carota*)

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Abstract

Crop production in Ethiopia is limited owing to water scarcity. Various technologies and management options are being used for efficient use of the available water resources in crop production. This study evaluated the performance of Soil Moisture (SM) and Evapotranspiration (ET) based irrigation scheduling methods on carrot yield and Water Use Efficiency (WUE), Water Productivity (WP) and field water use efficiency at water scarce areas of Arba Minch for two consecutive years/seasons of 2021 and 2022. The experimental design was a randomized complete block with three replicates. The treatments combined two scheduling techniques (soil moisture, SM, and evapotranspiration, ET). Water was delivered to furrows using an RBC flume, and data was analyzed with ANOVA at 5% significance level using SAS software and the graphs were drawn by Python. Across 2021 and 2022 seasons, SM-based irrigation consistently required less water than ET-based scheduling, achieving 5–5.4% water savings at full irrigation levels without reducing yields. Under moderate deficit irrigation (50–75%), both methods sustained comparable yields (42–43 t/ha), but SM-based treatments showed higher WUE, FWUE, and WP, with peak values at SM50% (WUE = 31.4 kg/m³; FWUE = 22.7 kg/m³; WP = 1.78 kg/m³) compared to ET50% (WUE = 25.8 kg/m³; FWUE = 18.1 kg/m³; WP = 1.78 kg/m³). Severe deficit irrigation (25%) drastically reduced yield and all efficiency indices in both methods. Economic analysis indicated that moderate irrigation levels (50%) maximized net benefits and cost-benefit ratios. Overall, SM-based irrigation was more efficient in water use, improved yield stability, and enhanced WUE, FWUE, and WP across irrigation levels. Thus, it demonstrated its suitability for sustainable carrot production under limited water resources. This saving is particularly relevant for Ethiopia where water scarcity limits crop production. It demonstrates a practical strategy for farmers to grow more food with less water while supporting sustainable resource management.

Keywords: Soil moisture; Furrow Irrigation; Crop evapotranspiration; ET-Based irrigation; SM-based irrigation

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1. INTRODUCTION

Carrot (*Daucus carota L.*) is an economically and nutritionally important vegetable crop in Ethiopia and other water-scarce regions as it provides income for smallholder farmers and a reliable source of vitamins for household nutrition (Mulugeta *et al*., 2025). However, its production is highly constrained by limited and inefficient use of irrigation water despite carrots being a relatively water-intensive crop that requires careful scheduling to ensure both yield and quality (Kowalczyk & Kuboń, 2022). Numerous studies are carried out on cereals utilizing various irrigation methods. Nonetheless, there is a lack of research on high-value horticultural crops such as carrots, particularly regarding the optimization of irrigation scheduling for efficient water use. In reality, farmers frequently depend on set irrigation schedules without taking into account soil moisture levels or the crop's evapotranspiration needs, resulting in over-irrigation, water wastage, and decreased productivity (Habtu, 2024).

Appropriate irrigation scheduling is paramount in modern agriculture, particularly in regions facing water scarcity. It is crucial to manage water resources in a manner that maximizes the profitability of an irrigated operation (Nikolaou *et al*., 2020). Irrigation scheduling is the process of deciding when and how much water to apply on a field to replenish soil moisture to the desired level. It can conserve water, reduce energy consumption, optimize production, and minimize environmental impacts (Gu *et al*., 2020a). Irrigation scheduling entails the systematic assessment and optimization of the volume and timing of irrigation practices. These include maximizing crop yields, minimizing water waste, and protecting the environment. By carefully planning irrigation activities, stakeholders can ensure that agricultural practices are efficient and sustainable (Wabela *et al.,* 2022).

Various methods are available for measuring soil moisture (SM-Based) (Rasheed *et al*., 2022). Specifically, two primary approaches such as directly soil moisture based and indirectly evapotranspiration based were mostly applied for agricultural production (Chen *et al.,* 2020). Others classify the methods into three irrigation scheduling methods such as plant, soil, and climate based (Dong, 2023); (França *et al*., 2024). Gu *et al*.,(2020b), found four common irrigation scheduling methods. These included evapotranspiration, water balance (ET-WB)-based, soil moisture-based, plant-water-index-based, and simulated model-based methods. Of these, different classifications such as soil moisture based (SM) and evapotranspiration based irrigation scheduling are considered typical methods (Gong *et al.*, 2024).

The ET-based method is the most common way to set irrigation schedules worldwide. It works on the idea that the amount of water given to crops should match what they use. This approach helps to ensure crops get the water they need based on the climate. However, it does have some limitations. Sometimes, the estimated water use can differ from what crops actually need. These differences can result from factors like the specific conditions of each field, changes in how crops grow each year, the type of plant material used, and the farming practices in place. Over time, these issues can add up and cause mistakes in how much water is provided during the growing season (Umutoni & Samadi, 2024).

Soil moisture-based irrigation scheduling relies on measuring soil water content with direct measurements to guide irrigation decisions, allowing precise control of water use for irrigation. This reduces waste, ensures crops get enough moisture to grow, promotes plant health, and prevents under- or over-irrigation (Gu *et al*., 2020c). It depends on the water-holding ability of the soil, which should be kept between field capacity (FC) and permanent wilting point (PWP). Tools used for this include automatic irrigation controllers, neutron scattering instruments, tension meters, capacitance sensors, electrical resistivity devices, heat pulse sensors, watermark sensors, and fiber-optic sensors (Tornese *et al*., 2024). Among these, time domain reflectometry (TDR) needs less maintenance and has a higher potential for commercial use (Curioni *et al*., 2019).

Several studies have investigated evapotranspiration (ET) based irrigation scheduling under deficit irrigation, focusing on carrot yield and water productivity (Léllis *et al*., 2017; Ashine *et al.*, 2024; El Bergui *et al*., 2024; Tlig *et al*., 2023). However, these studies do not consider actual soil moisture. The lack of consideration is due to insufficient comparative studies that evaluate the effectiveness of ET-based versus soil moisture (SM) based irrigation scheduling approaches. This creates a knowledge gap, particularly in understanding how these two methods are suitable for carrot production and water productivity under clay soil conditions. Therefore, this study evaluates the performance of SM-based and ET-based irrigation scheduling on carrot crop under clay soil on yield and water productivity at water scarce areas of Arba Minch, Ethiopia.

2. MATERIALS AND METHODS

2.1. Description of the Study Area

The research was conducted at the demonstration farmland of Arba Minch University, Gamo Zone, and Southern Ethiopia from 2021 to 2022. It is also situated at a distance of 454 km south of Addis Ababa. It is geographically located at an altitude of 1203 m. a.s.l. with a latitude of 6°040' N and longitude of 37°33'02'' E. The location of the study area is shown in Figure 1 below (Figure 1).

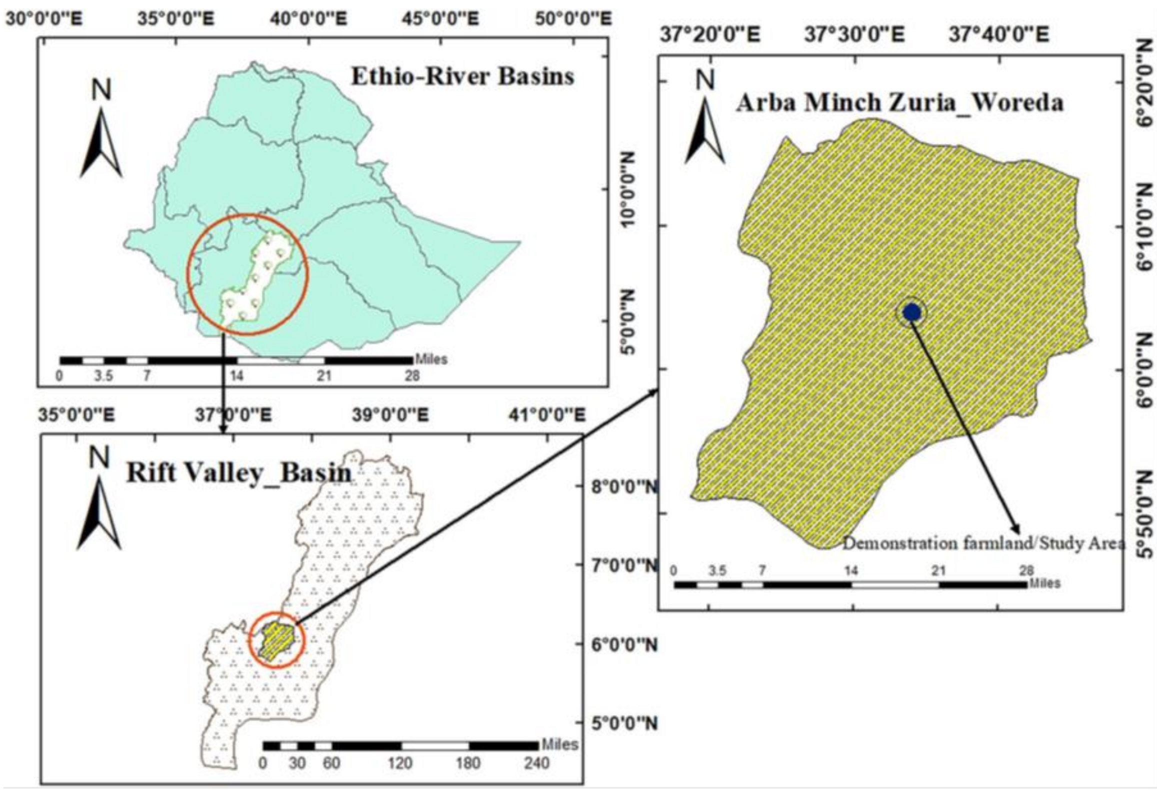

Figure 1: Description of the study area

2.1.1. Climate Characteristics of the Study Area

Based on the information obtained from meteorological station, monthly minimum and maximum air temperatures in the study area were 17.4°C to 33.43°C, respectively. The average annual rainfall in the study area was 750 mm and it was erratic and uneven in distribution. The average relative humidity was varied from 73% (May) to 58% (January). The average annual daily sunshine duration ranged from 8.9 hrs to 7.9 hrs.

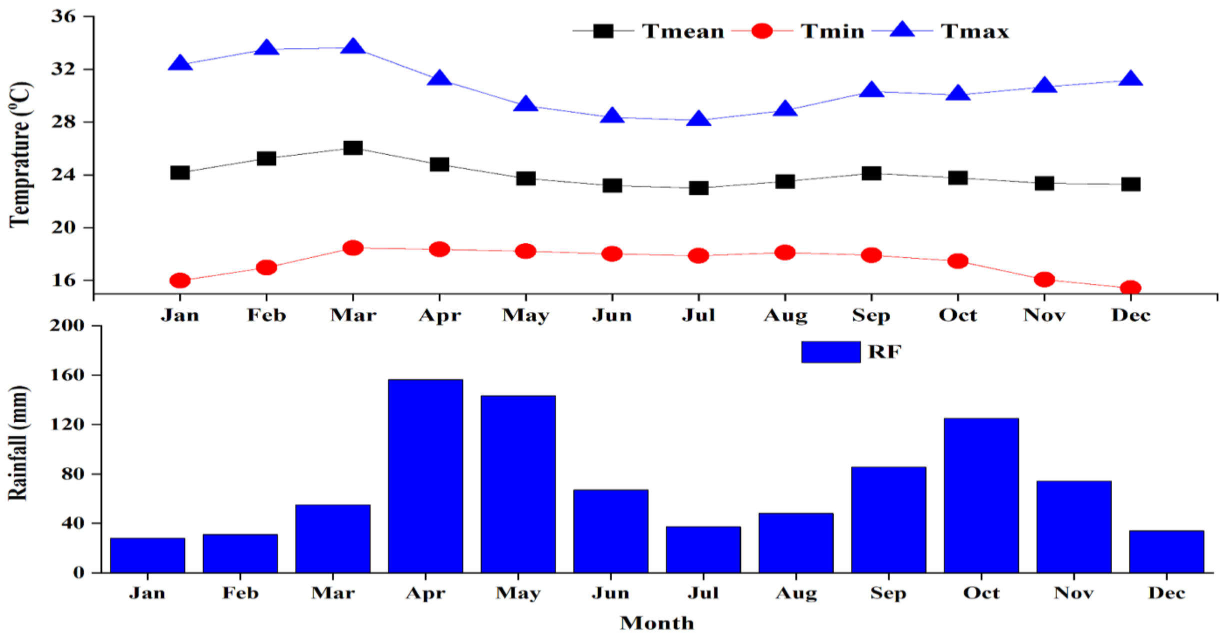

Figure 2: Climate characteristics of the study area

2.1.2. Soil Sampling Technique

For soil textural analysis and bulk density determination, disturbed and undisturbed soil samples were collected based on the root depth of carrot recommended in FAO irrigation and drainage manual No. 56 (Allen *et al.*, 1986). The result of laboratory soil analyses and field tests on physical characteristic for each corresponding depth layer was presented in Table 1. According to USDA soil textural classification system, the soil of the experimental field was classified as loam at all depths. The soil texture of the experimental site was loam. The FC and PWP soil moisture content were 37.52%, 18.65% respectively as shown in Table 1. The bulk density of soil was 1.25gcm^{-3}. The basic infiltration rate of the soil was 0.6 cm hr^{-1}. The permeable classification of this soil was moderately slow. The limit of moderately slow permeable soil was 0.508 cm hr^{-1} to 1.524 cm hr^{-1} (Kusumandari *et al.*, 2021).

2.2.Experimental Treatment Design and Allocation

The experiment included eight irrigation treatments, combining two irrigation scheduling methods and four irrigation levels. Soil moisture (SM)-based scheduling treatments were: SM100% (full irrigation), SM75% (75%), SM50% (50%), and SM25% (25%). Evapotranspiration (ET)-based scheduling treatments were: ET100% (full irrigation), ET75%

(75%), ET50% (50%), and ET25% (25%) (Table 2 and Figure 3) mostly used by many researchers for different crops (Abd-El Baki *et al.*, 2024; Yersaw & Lohani, 2022; Ashine *et al.*, 2024b; Yersaw *et al*., 2024).

Table 1: Soil physic-chemical properties the experimental site

Soil Physical properties	Soil Layer (cm)			Average
	0-25	25-50	50-75	
Clay (%)	51.17	43.17	43.00	45.78
Silt (%)	32.6	34.01	34.00	33.54
Sand (%)	16.00	22.83	22.99	20.61
Soil Texture	Clay	Clay	Clay	Clay
Bulk density (g/cm^3)	1.12	1.15	1.02	1.10
FC (%)	39.46	38.88	38.21	38.85
WP (%)	26.12	25.22	24.4	25.25
TAW (mm/m)	133.4	136.6	138.1	136
Soil Physical properties				
pH (1:2.5)	5.20	4.78	4.69	4.89
ECs(dS/c.m)	30.7	34.6	35.0	33.4
Ca(meq/100gm)	3.47	3.12	2.88	3.16

Table 2: Treatment design

Treatments	Description
SM100%	Full irrigation at soil moisture based Irrigation scheduling
SM75%	75% irrigation at soil moisture based Irrigation scheduling
SM50%	50% irrigation at soil moisture based Irrigation scheduling
SM25%	25% irrigation at soil moisture based Irrigation scheduling
ET100%	Full irrigation at Evapotranspiration based Irrigation scheduling
ET75%	75% irrigation at Evapotranspiration based Irrigation scheduling
ET50%	50% irrigation at Evapotranspiration based Irrigation scheduling
ET25%	25% irrigation at Evapotranspiration based Irrigation scheduling

The experimental treatments were arranged using Random complete Block Design (RCBD) with three times replication to minimize the effect of spatial variability of soil and slope ensuring that each block had relatively uniform conditions as shown in Figure 3. Each block contained all eight treatments. Full irrigation water was applied in Treatment 1 (100% back to FC) and considered as controlled treatment. This experimental research was done for two consecutive years/seasons of 2021/2022. The total number of plots was six where the area of each plot was $12m^2$ (3mx4m). The space between plots and replications (blocks) was 1m and 1m respectively to protect the contribution and influence of water movement from one treatment to other treatments. The spaces between plant-to-plant and consecutive rows were 15 and 65 cm respectively. The total area of the experimental field was $210m^2$ and the net irrigated plot area of the experiment was $72m^2$. Carrot was sown at the seed rate of the area (15 kg ha^{-1}) and all the recommended and cultural practices in the area were applied during the growing season.

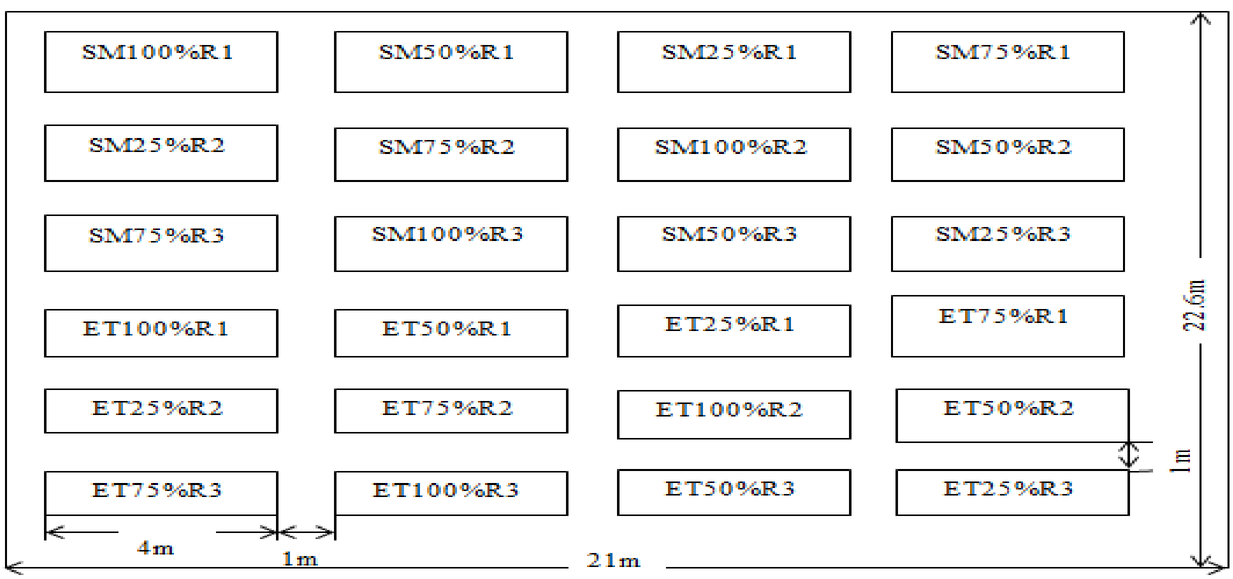

Figure 3: RCBD field treatment allocation

2.3. Irrigation Scheduling Development

2.3.1. Evapotranspiration-based Irrigation Scheduling

Two irrigation scheduling methods were tested in these experimental researches which differed in the amount of water applied and water stored in the soil during crop growing season. Crop Evapotranspiration (ETc) and Reference Evapotranspiration (ETo) method estimated using climate data were collected from meteorological station located at the research site and carrot crop coefficient in CROPWAT8.0 software.

Daily climatic data (June/23/2021 to September/12/2021) of maximum and minimum temperature, relative humidity, wind speed, sunshine hour were collected and Reference Evapotranspiration (ETo) (mm/day) values were computed from the collected data using CROPWAT 8.0 software and repeated at 2022, based on FAO-56. The growth stage and Kc used were 15 days (initial stage), 20 days (development), 30days (mid), and 20 days (late stage), and Kc were 0.75 (Initial), 1.05 (Mid)), and 0.95 (late stage) (Allen *et al.,* 1986). In the crop coefficient approach, the Crop Evapotranspiration, ETc, was calculated by multiplying the reference Crop Evapotranspiration, ETo, by a Crop Coefficient, Kc obtained from FAO Irrigation and Drainage Paper No. 56 of carrot using Equation 1 (Allen *et al*,. 1986).

$$ETc = Kc*ETo \quad (1)$$

Where; ETc = crop evapotranspiration (mm d^{-1}), Kc = crop coefficient (dimensionless), ETo = reference crop evapotranspiration (mm d-1).

Irrigation water was applied when the soil moisture reached at depletion level. Management Allowed Depletion (MAD) was important to determine how much water should be in the soil before starting irrigation. The MAD Determined the level of Plant Available Water (PAW) used by the plant or evaporated before irrigation without exposing the crops to water stress. According to FAO Irrigation and Drainage Paper No. 5 (Allen *et al.*, 1986), Management Allowed Depletion (MAD) of carrot is 35%.

The time of irrigation was based on 35% depletion of total available soil moisture content in control treatment or 65% of moisture content left in the soil. The total available water (TAW) was determined by Equation 2 (Allen *et al*., 1986).

$$TAW = \left(\frac{FC - PWP}{100}\right) * Zr \quad (2)$$

Where, TAW = total available soil water content (mm), FC = soil moisture content at field capacity (%), PWP = soil moisture content at field permanent wilting point (%), and Zr = crop rooting depth (mm).

Readily available soil water was computed by Equation 3.

$$RAW = TAW \times MAD \ldots\ldots\ldots\ldots \quad (3)$$

Where; RAW = Readily available water (mm), TAW = Total available soil water content (mm), and MAD = Maximum allowable depletion (mm) (MAD for carrot =35%) (Allen *et al.,* 1986).

Net Irrigation Requirement (IRn) at evapotranspiration based irrigation scheduling was determined by using Equation 4 (Allen *et al*., 1986).

$$\mathrm{IRn} = \mathrm{ETc} - \mathrm{Pe} \ldots\ldots\ldots\ldots \quad (4)$$

Where; IRn = Net irrigation requirement (mm), ETc = Crop evapotranspiration (mm), and Pe = Effective rainfall (mm).

Irrigation interval is the time gap between two consecutive irrigations and was computed using Equation 5 (Ashine *et al.,* 2024b).

$$\text{Irrigation interval} = \frac{\mathrm{IRn}}{\mathrm{ETcpeak}} \ldots\ldots\ldots\ldots \quad (5)$$

Where; ETc_{peak} = Maximum crop evapotranspiration in mm/day and IRn = Net irrigation depth.

2.3.2. Soil Moisture-based Irrigation Approach (SM)

The soil moisture content was monitored using Time Domain Reflectometry (TDR) methods at the respective depths. TDR (Time Domain Reflectometry) calibration by gravity-based measurements was aimed to refine TDR-derived parameters by offsetting intrinsic precision limits and systematic biases in TDR. Soil moisture measurements were taken in both the dry and wet seasons due to the variation of TDR sensitivity, as shown in Figure 4 below. By linking gravimetric soil moisture reference to the TDR response, the gravimetric approach anchors TDR calibration to a precise, physically grounded standard, thereby lowering uncertainty. This integration improves reliability for more accurate moisture assessments while compensating for calibration drift and measurement noise in TDR. Then, the samples were oven-dried at 105°C for 24 hours. Next, their weights were measured to determine the dry weight with the loss of water quantified during drying. Separately, soil-moisture based irrigation used laboratory measurements of soil water to apply the correct quantity of irrigation at the appropriate time. The

TDR was calibrated at one month interval for dry and wet season to reduce the error. The calibration equations for the TDR and gravimetric soil moisture relationship were developed using simple linear regression between observed TDR readings and corresponding gravimetric moisture contents for both dry and wet seasons. The calibrated value of TDR was y=1.06x+-0.03489 with R^2 of 0.90 and Y= 0.71x+11.60x with R^2 of 0.89 for dry and wet season experiments, respectively.

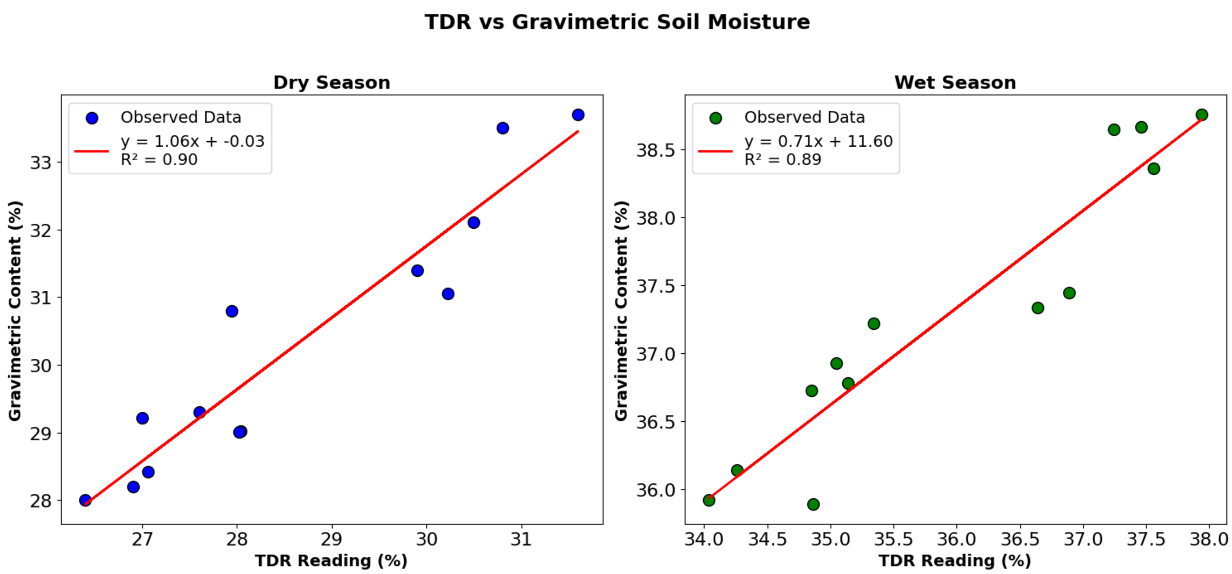

Figure 4: TDR calibration in dry and wet seasons

Net Irrigation Requirement (IRn) at soil moisture-based irrigation scheduling is the difference between the field capacity and the soil moisture content in the root zone before irrigation, as shown in Equation 6 (Bennett et al., 2014).

$$\mathrm{IRn} = (\mathrm{FC} - \theta\mathrm{i}) \times \mathrm{Dr} \times \mathrm{p_b} \quad (6)$$

Where; IRn = Net irrigation (mm), FC = Field capacity (%), θi = Soil moisture (%), Dr = Crop root depth (cm) and ρ_b is soil bulk density.

Gross Irrigation Requirement (IRg) is the ratio of the net depth of irrigation to application efficiency as shown in Equation 7 (Allen *et al.*, 1986) and (Bennett *et al.,* 2014).

$$\mathrm{IRg} = \frac{\mathrm{IRn}}{\mathrm{Ea}} \quad (7)$$

Where; IRg = Gross irrigation requirement (mm) and Ea = Field irrigation application efficiency of a short, end diked furrow was taken as 70%.

The gross irrigation depth was converted to volume of water by multiplying the gross Irrigation Requirement (IRg) with the area of the plot as shown in Equation 8 (Doorenbos, 1975).

$$V = A * IRg \qquad (8)$$

Where; V = Volume of water in (m^3), A = Area of plot (m^2), and IRg = Gross irrigation requirement (mm)

2.4.Discharge Measurement and Water Application Method

Water was applied to the field using a conventional furrow irrigation system. The Kulfo River is the source of the irrigation water and Water is supplied from the main earthen canal to the experimental plot through an off-taking lined canal. The field channel up to the plot was covered with plastic membrane to control infiltration loss in the field channel. Irrigation water for the crop rows was supplied via an RBC flume fixed in place to control side flow, located at the upper part of the plot. The discharge of water was conducted by calibrating head of water flowing through the flume. The calibration of the partial flume was conducted using Equation 9 and validated by volumetric check (tank and timed level rise).

$$Q = 0.001035[H + 0.75]^{1.853} \qquad (9)$$

Where; Q = discharge of flowing water through RBC flume (l/s), and H = Head of water (mm).

The time required to deliver the desired depth of water into each plot was calculated using Equation 10 (Doorenbos, 1975) and (Kifle, 2018).

$$t = \frac{IRg \times A}{6Q} \qquad (10)$$

Where; t = application time (min), IRg = Gross irrigation requirement (mm), A = Area of experimental plot (m^2) and Q = flow rate (discharge) (l/s).

2.5.Agronomic Data Collection

The irrigation practice applied and agronomic data were collected from 23/June/2021 to 12/Sep/2021 and repeated in 2022 at the same season. The study collected growth-related data in 10-day's interval from initial to end. For yield parameters, mature carrot crops were manually harvested, and from each plot, ten carrot samples were randomly selected from the two central ridges. Measurements included plant height (cm), number of leaves, root length (cm), root diameter (cm), dry above-ground biomass (ton/ha), and total carrot yield (ton/ha). Plant height was recorded from the soil surface to the tip of the leaves for 10 plants using a ruler. Root diameter was measured at the widest point of the root in a plane perpendicular to the root using a Vernier caliper. Root length was determined by measuring from the shoulder to the tip of the harvested carrot roots with a ruler. The mean values of these measurements were used for subsequent analyses. Dry above-ground biomass, and total carrot yield were weighed with a sensitive balance, and the average values were used in the analysis.

2.6.Water Use Efficiency, Water Productivity and Field Water Use Efficency

i. Water Use Efficiency (WUE)

The water use efficiency is the ratio of crop yield to total water used by the crop in the process of evapotranspiration (ETc) using Equation 11 (Raes *et al*., 2022; Liu *et al*., 2002).

$$\mathrm{WUE} = \frac{\mathrm{Y}}{\mathrm{ETc}} \quad (11)$$

Where; WUE = Crop water use efficiency (kg m^{-3}), Y = Crop yield harvested (kg ha^{-1}) and ETc = Crop evapotranspiration (mm).

ii. Water Productivity

Water productivity is the ratio of biomass to transpiration as shown in Equation 12 (Raes *et al*., 2022).

$$\mathrm{WP} = \frac{\text{Biomass produced (kg)}}{\text{Water transpired } (\mathrm{m}^3)} \quad (12)$$

iii. Field Water Use Efficiency (FWUE)

Field water use efficiency is the ratio of crop yield to the total amount of water (gross depth of irrigation water) used in the field. It is expressed in the following Equation 13 (Asres *et al*., 2022).

$$\mathrm{FWUE} = \frac{\mathrm{Y}}{\mathrm{IRg}} \quad (13)$$

Where; FWUE = Field water use efficiency (kg m^{-3}), Y = Crop yield harvested (kg ha^{-1}) and IRg = Gross irrigation requirement (mm).

2.6.1. Estimation of Irrigation Water Saved (WS)

The amount of WS per hectare was obtained by subtracting the amount of water consumption of particular deficit irrigation from the full irrigation requirement using Equation 14 (Yersaw & Lohani, 2022).

$$WS = \frac{(WFI - WDI) \times 100}{WFI} \quad (14)$$

Where; WS = Water saved (%), WFI = Total water used at full irrigation (mm), and WDI = Total water used at each deficit irrigation level (mm).

2.6.2. Additional Yield from Saved Water

The additional yield from saved water was calculated by using Equation 15 (Yersaw & Lohani, 2022).

$$AYWS = \frac{(YD \times WS) \times 100}{Ign} \quad (15)$$

Where; AYWS = Additional yield from water saved water (Kg/ha), YD = Yield from each deficit level (Kg/ha), WS = Water saved (m^3/ha), and Ign = Net irrigation water applied at each deficit level (m^3/ha).

2.6.3. Economic Analysis

Economic analysis of carrot production centers on the balance between variable costs and gross benefits at the margin. The variable costs include seeds, fertilizer, and irrigation, labor for planting and harvesting, water, land preparation, pesticides and insecticides. For determining the variable cost, the irrigation cost was assumed 3ETB for 1 m^3 of irrigation water and the benefit gained was considered 7ETB for Gera and 8.50 ETB at Arba Minch per kg of carrot during the experiment time. The marginal Rate of Return (MRR) was calculated using Equation 16 (Ashine et al., 2024b).

$$MRR = \frac{\text{change in net benefit}}{\text{Totla variable cost}} \times 100 \quad (16)$$

The Benefit–Cost (BC) was calculated to evaluate the economic feasibility and profitability of each irrigation treatment presented in Equation 17. The BC expresses the relationship between the gross returns obtained from crop production and the total cost incurred during the cropping season, including all inputs such as seeds, fertilizers, labor, irrigation water, and other operational expenses. It provides a quantitative measure of the economic efficiency of irrigation or management practice, indicating how much benefit is obtained from every unit of cost invested.

$$\mathrm{BC} = \frac{\text{Total benefit}}{\text{Total cost}} \qquad (17)$$

2.7. Data Analysis

Data on growth parameters, root yield, yield attribute, and irrigation level were statically analyzed by Analysis of Variance (ANOVA) using SAS software and the graphs were drawn using Python. Mean comparisons were executed using the Least Significant Difference (LSD) at 5% probability level.

3. RESULTS AND DISCUSSION

3.1. Soil Moisture Variation under SM and ET based on Soil Moisture Irrigation Scheduling

Soil moisture shows variation under soil moisture (SM)-based and evapotranspiration (ET)-based irrigation scheduling as shown in Figure 5. Under SM-based Scheduling (TDR measurement), soil moisture content fluctuates within a relatively narrow band when soil water reaches a threshold level, keeping moisture close to the crop's optimal range. Unlike the soil-based approach, the ET-based method produces sharper increases and deeper decreases as irrigation is scheduled according to climatic water demand instead of direct soil conditions. This leads to greater variability in soil water content. However, SM-based scheduling maintains more consistent soil moisture conditions.

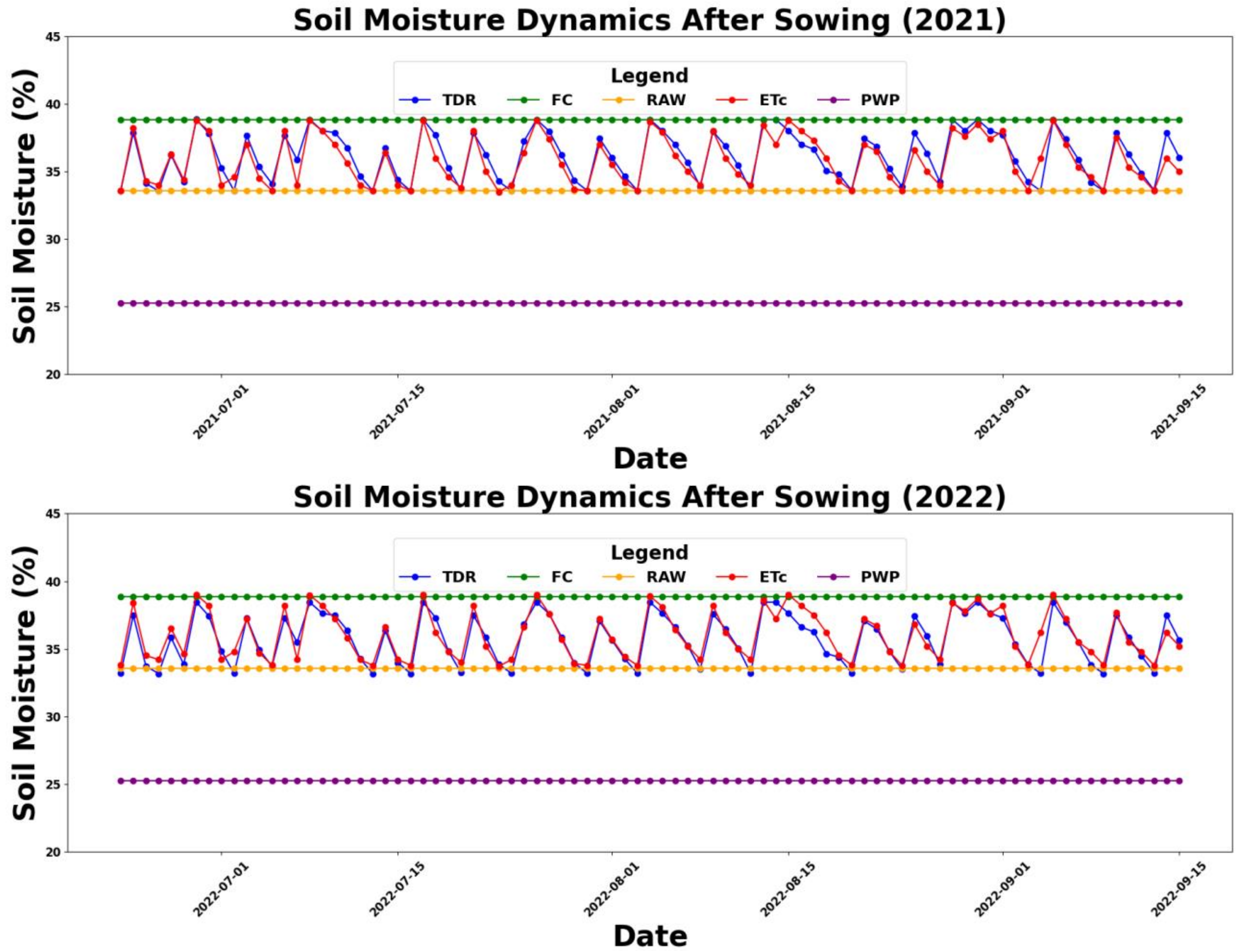

Figure 5: Soil moisture variation under SM and ET based of soil moisture irrigation scheduling

3.2.Comparison of Evapotranspiration and Soil Moisture-based Irrigation Methods

The net and gross irrigation depths required were shown in Table 3. In both 2021 and 2022, irrigation was scheduled using soil moisture (SM)-based and evapotranspiration (ET)-based approaches with variations in Irrigation Requirement (IRn) and Irrigation Gross (IRg) across seasons. During 2021, the cumulative irrigation requirement reached 236.1 mm under SM-based scheduling and 248.6 mm under ET-based scheduling while the corresponding gross irrigation was 337.3 mm and 355.1 mm, respectively. Similarly, in 2022, SM-based scheduling applied a seasonal irrigation requirement of 235.8 mm (337.0 mm gross) whereas ET-based scheduling required slightly higher amounts with 249.5 mm (356.3 mm gross). Overall, the results indicated that ET-based irrigation consistently applied more water compared to SM-based scheduling in both years. This suggested that SM-based irrigation scheduling was more water-efficient, requiring lower volumes of water while maintaining comparable irrigation frequency. The result was similar to that of Ashine *et al*., (2024b) at JARC. The crop water requirement and irrigation requirement of the crop planted at the end of September were 286.20 and 224.60 mm, respectively. A similar experiment by Carvalho et al. (2014) found water requirement of 240.8 mm for carrots in 2010 and 276.0 mm in 2011. Both were below 300 mm. In contrast, other results indicated the water need for carrots was 600-900 mm. This was due to high daily evaporation (6-7 mm/day) and a long crop season (190 days) which meant the water need was expected to be higher (Quezada *et al*., 2011).

The comparison of seasonal irrigation applications revealed that soil moisture (SM)–based scheduling saved a considerable amount of water compared to evapotranspiration (ET)–based scheduling in both years. In 2021, the gross irrigation under SM-based scheduling (337.3 mm) was lower than that of ET-based scheduling (355.1 mm), resulting in about 5.0% water saving. A similar trend was observed in 2022. SM-based irrigation applied 337.0 mm compared to 356.3 mm under ET-based scheduling. It can save 5.4% water. These results demonstrated that SM-based irrigation scheduling could enhance water-use efficiency by reducing the total irrigation requirement without compromising irrigation frequency. It is more sustainable option under limited water resources. A soil moisture based irrigation scheduling method saved 16% water compared to ET-based irrigation (Boltana et al., 2024). Irrigation scheduling, based on moisture stress sensitivity, could save 25.6% on the Bilate Watershed (Wabela *et al*., 2022b). However, the quantity of irrigation water saved varied with the above authors. Variations might come from many factors. These included topography, seasons, crop type, soil type, and irrigation method and irrigation manager's expertise, application of technologies, and climate (Ahmed *et al.*, 2023; Wang *et al*., 2023).

The ET-based method used a higher cumulative irrigation depth than the SM-based method as shown in Figure 6. This suggested that the ET-based method needed more water to meet the needs of the crops during the growing season. The difference between the two methods was more pronounced at the end of the observation period. This showed that the ET-based method applied much more water in the later stages of crop growth.

Table 3: Crop water requirement of carrot with two methods

2021						2022					
Date of irrigation	SM-Based		Date of irrigation	ET-Based		Date of Irrigation	SM-Based		Date of irrigation	ET-Based	
	IRn (mm)	IRg (mm)		IRn (mm)	IRg (mm)		IRn (mm)	IRg (mm)		IRn (mm)	IRg (mm)
23-Jun-21	6.1	8.7	23-Jun-21	6.5	9.3	23-Jun-22	5.5	7.9	23-Jun-21	6	8.6
27-Jun-21	7.9	11.3	27-Jun-21	7.0	10.0	27-Jun-22	7.3	10.4	27-Jun-21	7.3	10.4
			30-Jun-21	6.5	9.3	02-Jul-22	7.5	10.7	30-Jun-21	7.5	10.7
07-Jul-21	9.0	12.9	03-Jul-21	7.5	10.7	07-Jul-22	8.4	12	03-Jul-21	7.9	11.3
13-Jul-21	8.3	11.9	13-Jul-21	7.9	11.3	13-Jul-22	7.7	11	13-Jul-21	8.7	12.4
19-Jul-21	9.6	13.7	20-Jul-21	9.0	12.9	19-Jul-22	9.0	12.9	20-Jul-21	9.3	13.3
27-Jul-21	11.0	15.7	30-Jul-21	10.2	14.6	27-Jul-22	10.4	14.9	30-Jul-21	11.2	16
04-Aug-21	16.6	23.7	04-Aug-21	16.0	22.9	04-Aug-22	16.0	22.9	04-Aug-21	16.2	23.1
08-Aug-21	17.6	25.1	09-Aug-21	18.0	25.7	08-Aug-22	17.0	24.3	09-Aug-21	16.5	23.6
13-Aug-21	20.6	29.4	13-Aug-21	21.0	30.0	13-Aug-22	20.0	28.6	13-Aug-21	18	25.7
17-Aug-21	24.6	35.1	19-Aug-21	25.0	35.7	17-Aug-22	24.0	34.3	19-Aug-21	30.9	44.1
22-Aug-21	29.6	42.3	24-Aug-21	36.0	51.4	22-Aug-22	29.0	41.4	24-Aug-21	34	48.6
28-Aug-21	34.6	49.4	28-Aug-21	38.0	54.3	28-Aug-22	34.0	48.6	28-Aug-21	36	51.4
09-Sep-21	40.6	58.0	04-Sep-21	40.0	57.1	09-Sep-22	40.0	57.1	04-Sep-21	40	57.1
-			12-Sep-21	43.0	61.4	-	-		12-Sep-21	44	62.9
Sum	236.1	337.3		248.6	355.1		235.8	337.0		249.5	356.3

The ET-based method used a higher cumulative irrigation depth than the SM-based method as shown in Figure 6. This suggested that the ET-based method needed more water to meet the needs of the crops during the growing season. The difference between the two methods was more pronounced at the end of the observation period. This showed that the ET-based method applied much more water in the later stages of crop growth.

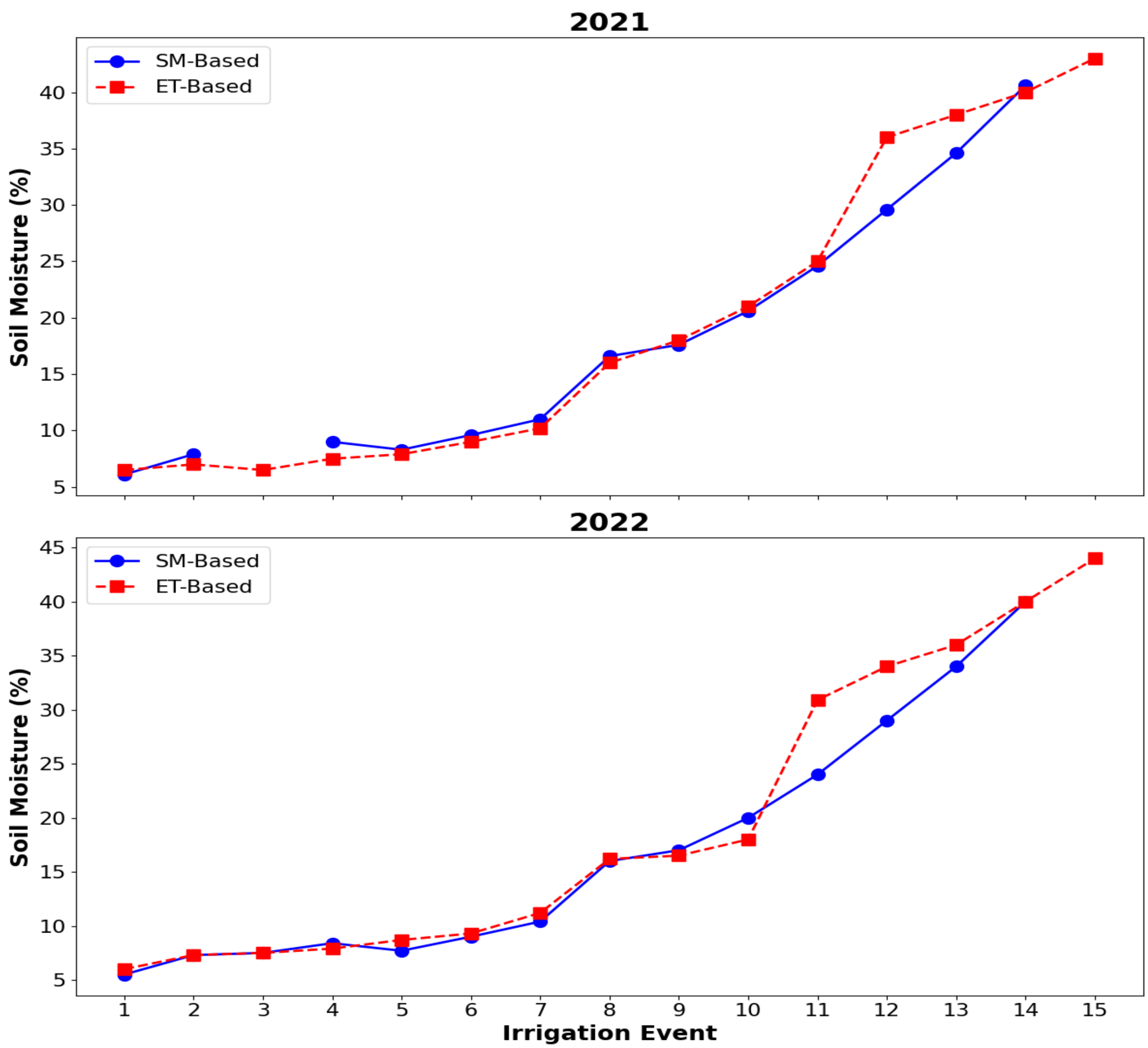

Figure 6: Soil Moisture variation in in SM and ET based irrigation scheduling in 2021 and 2022 crop seasons

3.3. SM- and ET-Based Irrigation Scheduling Effects on Yield under Deficit Irrigation

Soil moisture (SM)-based and evapotranspiration (ET)-based irrigation systems impact crop yield when different deficit irrigation levels are applied as shown in Table 4. The results showed that yield varied significantly across treatments (Fcal > Fprob) at $p < 5\%$). The comparative evaluation of soil moisture (SM)– and evapotranspiration (ET)–based irrigation scheduling demonstrated that both approaches performed similarly under full and moderate irrigation, but

SM-based scheduling showed clear advantages in water saving and biomass stability. Average carrot yields under SM100% (42.8 t/ha) and ET100% (42.7 t/ha) were statistically comparable and no significant differences were observed at 75% and 50% irrigation levels, where yields remained above 42 t/ha. This indicated that both scheduling methods were equally effective in maintaining carrot yield under sufficient water supply. However, SM-based irrigation consistently applied less gross water than ET-based irrigation 337.3 vs. 355.1 mm in 2021. Using the alternative method resulted in 5.4% water saving in 2022, as it only required 337mm of water compared to 356.3mm. At 100% irrigation, SM scheduling achieved 3.05 t/ha compared to 2.98 t/ha under ET scheduling, while under severe deficit (25%) biomass declined drastically to 1.17 t/ha in SM and only 0.91 t/ha in ET. Although ET- and SM-based methods were comparable for yield under full irrigation, SM-based scheduling was more water-efficient and slightly more resilient under deficit conditions, making it a more sustainable choice for optimizing carrot production in clay soils of Arba Minch.

Table 4: Effects of irrigation scheduling on yield

Treatments	Y (t/ha)			BM (t/ha)		
	2021	2022	Average	2021	2022	Average
SM100%	43.3^{a}	42.3^{a}	42.8^{a}	3.07^{a}	3.02^{a}	3.05^{a}
SM75%	43.1^{abc}	42.1^{ab}	42.6^{bc}	2.98^{b}	2.92^{bc}	2.95^{bc}
SM50%	42.9^{c}	41.9^{b}	42.4^{cd}	2.94^{b}	2.88^{d}	2.91^{cd}
SM25%	14.4^{d}	13.4^{c}	13.9^{e}	1.20^{c}	1.14^{e}	1.17^{e}
ET100%	43.2^{ab}	42.2^{ab}	42.7^{ab}	3.01^{ab}	2.95^{b}	2.98^{b}
ET75%	43.0^{bc}	42.0^{ab}	42.5^{bcd}	2.97^{b}	2.91^{c}	2.95^{bcd}
ET50%	42.9^{c}	41.9^{b}	42.4^{d}	2.94^{b}	2.88^{d}	2.91^{d}
ET25%	14.4^{d}	13.4^{c}	13.9^{e}	0.92^{d}	0.90^{f}	0.91^{f}
Fcal	2.725	2.173	2.725	5.474	14.463	11.277
Fprob	0.100	0.151	0.100	0.018	0.000	0.001
CV (t/ha)	0.304	0.419	0.308	1.337	0.474	0.715
LCD (5%)	0.191	0.256	0.191	0.059	0.020	0.031

N.B: The same letter in columns are not significantly different at $P \leq 0.05$, a, abc, c, d, ab significant levels, Fcal = calculated F-value, Fprob = probabilty F-value, CV = coefficient of variation, and LSD = Least Significant Difference.

3.4. Effects of Irrigation scheduling on Water Use Efficiency under Deficit Irrigation

The performance of irrigation treatments on the Water Use Efficiency (WUE) carrot is shown in Table 5. The results revealed significant variations in Water Use Efficiency (WUE), Water Productivity (WP), and Field Water Use Efficiency (FWUE) among the irrigation treatments over the two study years. The highest efficiencies were consistently recorded under the SM50% treatment, achieving an average WUE of 31.4 kg/m³, WP of 1.78 kg/m³, and FWUE of 22.7 kg/m³, indicating optimal water utilization under moderate soil moisture deficit. Similarly, the ET50% treatment also performed well with average WUE, WP, and FWUE values of 25.8, 1.78, and 18.1 kg/m³, respectively. In contrast, the lowest efficiencies were observed under the ET25% and ET100% treatments, reflecting reduced productivity under both excessive and minimal irrigation conditions. The statistical analysis (F-prob < 0.05) confirmed significant differences among treatments, highlighting that moderate water stress enhanced water productivity by improving plant water-use response without compromising yield potential. Somefun *et al*., 2024 and Kumar *et al*., (2023) reported that scheduling irrigation could effectively enhance WUE and increase crop yields using SM-based methods.

The study found that SM-based treatments had higher water use efficiency (WUE) than ET-based ones at the same irrigation levels. Among the treatments, SM50% and ET50% exhibited the highest WUE compared to the other irrigation levels. This trend showed the advantages of moderate water allocation by optimizing crop yield relative to water usage. Conversely, the SM100% and ET100% treatments yielded lower WUE values, suggesting diminishing returns on water application at maximum levels. In conclusion, the tests of CWUE, IWUE, and FWUE across various water treatments highlighted the need for balanced water management. The data suggested that SM- Based moderate water allocation could maximize water use efficiency, enhancing crop productivity while preserving vital resources. Future agricultural practices should prioritize similar strategies to ensure sustainability of food security in water-constrained environments. Comparative studies by (Touil *et al*., 2022) and (Asiimwe *et al.*, 2022) indicated that the SM-based method was more efficient than the ET-based on water saving.

Treatments with moderate reductions in soil moisture (SM75%, SM50%) and evapotranspiration (ET75%, ET50%) showed higher WUE compared to treatments with full soil moisture

(SM100%) and evapotranspiration (ET100%). However, severe water stress (SM25%, ET25%) resulted in significantly lower WUE, suggesting that excessive stress negatively impacts water use efficiency.

Table 5: Effects of irrigation scheduling on Irrigation water use efficiency under deficit irrigation

Treatments	WUE (kg/m^3)			WP (kg/m^3)			FWUE (kg/m^3)		
	2021	2022	Average	2021	2022	Average	2021	2022	Average
SM100%	18.3^{e}	17.9^{d}	18.1^{e}	1.01^{c}	0.99^{c}	1.01^{c}	12.8^{d}	12.6^{d}	12.7^{e}
SM75%	23.3^{c}	22.6^{c}	22.9^{c}	1.27^{b}	1.25^{b}	1.26^{b}	16.3^{c}	16.5^{c}	16.4^{c}
SM50%	32.1^{a}	30.8^{a}	31.4^{a}	1.79^{a}	1.76^{a}	1.78^{a}	22.5^{a}	22.8^{a}	22.7^{a}
SM25%	17.5^{f}	15.5^{e}	16.5^{f}	1.28^{b}	1.21^{b}	1.25^{b}	12.2^{e}	11.9^{e}	12.1^{f}
ET100%	14.8^{g}	14.4^{f}	14.6^{g}	0.99^{c}	0.97^{c}	0.98^{c}	10.4^{f}	10.1^{f}	10.3^{g}
ET75%	18.9^{d}	18.4^{d}	18.7^{d}	1.27^{b}	1.24^{b}	1.26^{b}	13.2^{d}	12.9^{d}	13.1^{d}
ET50%	26.2^{b}	25.4^{b}	25.8^{b}	1.79^{a}	1.76^{a}	1.78^{a}	18.4^{b}	17.8^{b}	18.1^{b}
ET25%	14.5^{g}	13.3^{g}	13.9^{h}	0.98^{c}	0.96^{c}	0.97^{c}	10.1^{f}	9.3^{g}	9.7^{h}
Fcal	1.141	3.541	3.01	9.642	2.252	9.642	13.187	5.297	23.869
Fprob	0.347	0.057	0.082	0.002	0.142	0.002	0.001	0.019	0.000
CV	0.973	1.079	0.811	1.516	2.991	1.516	1.277	1.654	0.839
LCD (5%)	0.353	0.374	0.287	0.034	0.066	0.034	0.325	0.412	0.211

N.B: The same letter in columns are not significantly different at $P \leq 0.05$, a, abc, c, d, ab………significant levels,, Fcal = calculated F-value, Fprob = probabilty F-value, CV = coefficient of variation, and LSD = Least Significant Difference.

3.5.Effects of Irrigation Scheduling Variation on Water Use Efficiency (WUE)

Figure 7 shows the Water Use Efficiency (WUE) of two different irrigation management strategies: SM-based and ET-based. . At each irrigation level, Soil Moisture (SM) values are consistently higher than Evapotranspiration (ET). At 100% and 75%, SM showed moderate to high values while ET remained lower but followed a similar trend. At the 50% level, SM peaked with the highest values whereas ET rose but stayed noticeably below SM. Moving to 25%, SM decreased but still exceeded ET. Across the full spectrum (100%, 75%, 50%, 25%), SM remained consistently greater than ET with widest gap at 50% owing to pronounced peak of SM while ET remained modest. This suggested that SM-based irrigation management could be more efficient in utilizing water resources and maximizing crop yields compared to SM-based irrigation.

Generally, the WUE, WP and FWUE of carrot were higher at 50% and 75% both at SM-Based and ET-Based irrigation levels. This indicated that applying these irrigation levels improved the yield and WUE of the crop rather than applying full and 25% irrigation levels. The obtained result was also in line with the result reported by (Yersaw & Lohani, 2022) who suggested that the application of deficit irrigation below 50%ET was optimal for enhancing the crop yield conducted at Arba Minch and Ethiopia on onion crop using furrow irrigation system. Similarly, (Gebreigziabher & Assefa, 2024; Gebreigziabher, 2024 ; Patanè *et al*., 2020) observed that the highest levels of water use efficiency in tomatoes occurred with 50% irrigation replacement The water use efficiency is higher in relation to irrigation suspension. This efficiency increases with the number of days without irrigation before a harvest.

The performance of SM-based and ET-based irrigation treatments across different water-saving levels (100%, 75%, 50%, and 25%) are shown in Table 6. The analysis of irrigation water use efficiency and yield response showed clear differences among treatments. The highest yield (42.8 t/ha) and biomass (3.05 t/ha) were obtained under full soil moisture irrigation (T1), serving as a control. Moderate deficit irrigation (T2 and T3) under both SM- and ET-based scheduling achieved comparable yields (42.4–42.6 t/ha) while saving substantial amounts of water up to 776 m^3/ha (11.5%) in T2 and 1497.5 m^3/ha (22.1%) in T3. This resulted in higher water-use efficiency (16.4–22.6 kg/m^3) and water productivity (1.26–1.77 kg/m^3), indicating that moderate deficit irrigation improved water utilization without significant yield penalties.

In contrast, severe deficit irrigation (T4 and T8) reduced yield drastically to 13.9 t/ha and biomass to 1.17–0.91 t/ha, corresponding to yield losses of nearly 49% despite saving 28–33% irrigation water. Over-irrigation under ET-based full irrigation (T5) resulted in negative water saving (–11.8%) and lower efficiency (10.2 kg/m^3), highlighting the risk of water wastage without yield benefit. Overall, the results demonstrated that moderate deficit irrigation (50–75% of requirement) optimized the yield and water saving whereas severe deficit and over-irrigation reduced system performance.

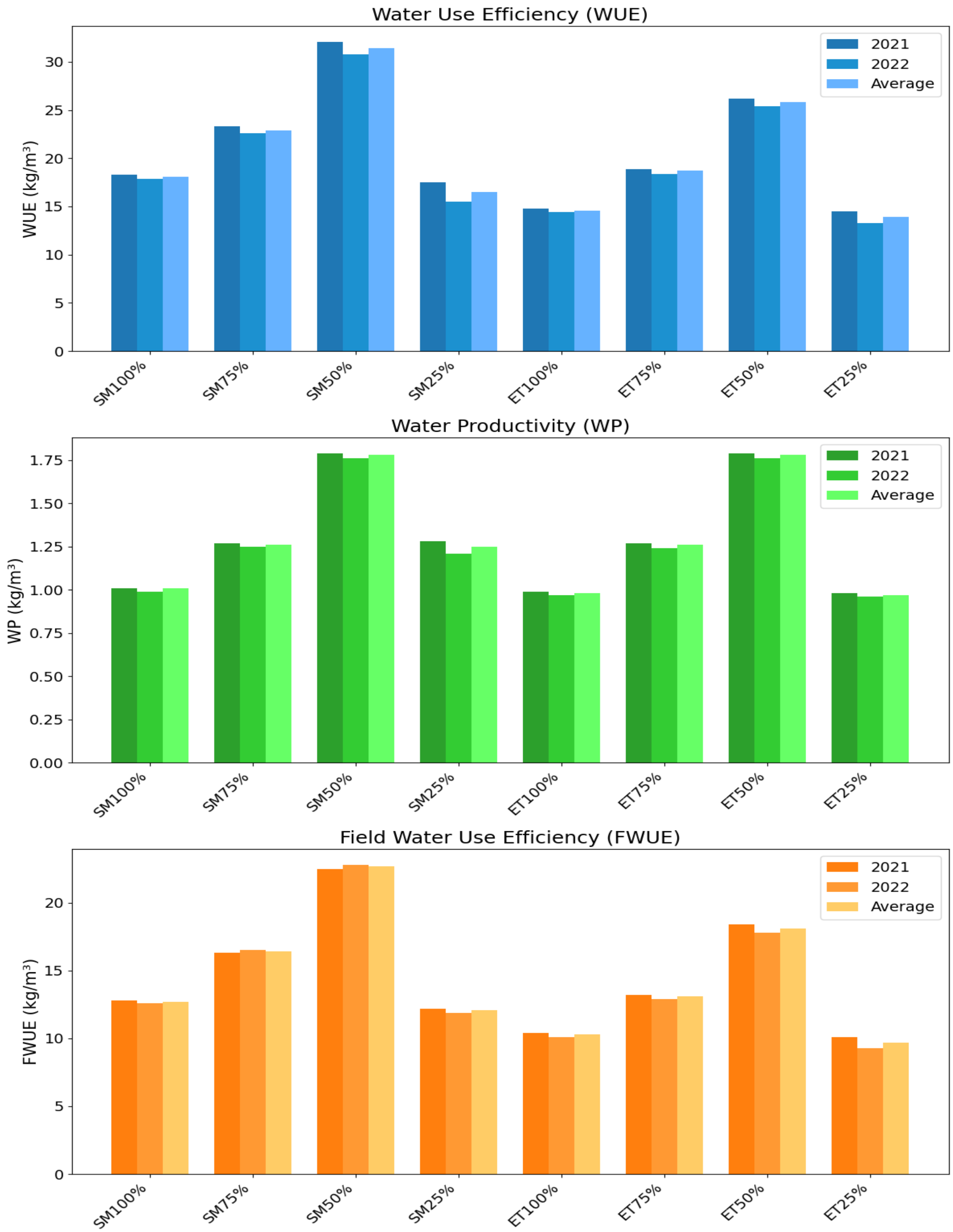

Figure 7: WUE, WP, and FWUE at Different Irrigation Levels

In short, the SM-based method demonstrated better performance in optimizing water use and yield gains rather than ET-Based. The Soil Moisture-Based Method focused on optimizing irrigation using carefully chosen soil moisture thresholds to boost water-use efficiency. When combined with strategies that consider both soil moisture and crop stress cues, such as the SIM approach, this method could substantially improve irrigation water use efficiency (IWUE by more than 35% for tomato and up to 80% for maize in Italian studies by (Corbari & Mancini, 2023) and (Corbari *et al*., 2021). In addition to efficiency gains, the SM-based approach could also enhance yields; for example, fresh yield increased by about 16% with sweet corn when compared to methods relying on Evapotranspiration (ET) alone. When it results in lower fresh yields was compared to the SM-based method, the grain yield was less affected except 7% reduction under stress condition (Asiimwe *et al*., 2022).

The superior performance of Soil Moisture (SM)-based methods in optimizing water use and yield gains could be attributed to several factors. SM-based systems utilize real-time data from soil moisture sensors, allowing for precise irrigation scheduling. It directly responds to the actual water needs of crops by reducing water wastage (Paul *et al*., 2024a). In contrast, ET models often rely on estimations that can lead to over- or under-irrigation due to their inherent variability and assumptions about environmental conditions (Belarbi & El Younoussi, 2025). Sensor precision is enhanced by smart-m monitoring (SM)-based approaches, which use sophisticated sensors to deliver accurate, real-time soil moisture data and support irrigation that closely matches crop needs (Paul *et al*., 2024b). These systems also offer dynamic responses, adapting to changing environmental conditions such as rainfall and temperature shifts, thereby improving water-use efficiency. Additionally, traditional ET models tend to overestimate water requirements owing to broad assumptions about crop and environmental interactions. Traditional evapotranspiration (ET) models can result in unnecessary water application. Clay soils, which retain moisture better, can particularly benefit from optimized irrigation schedules that prevent over-watering (Belarbi & El Younoussi, 2025).

Table 6: The performance of SM-Based and ET-Based irrigation scheduling

Treatment	Y (t/ha)	ETc (mm)	WS (m^3/ha)	WS (%)	YL (ton/ha)	YL (%)	YG (from saved water	YI	WUE (kg/m^3)
Year- 2021									
T 1	43.3	306	-	-	-	-	-	-	14.2
T 2	43.1	239	10.03	10.0	0.2	0.3	12.1	11.9	18.0
T 3	42.9	171	20.21	20.2	0.4	0.7	33.9	33.5	25.1
T 4	14.4	104	30.24	30.2	28.9	48.8	28.0	-0.9	13.9
T 5	43.2	364	-8.68	-8.7	0.1	0.2	-6.9	-7.0	11.9
T 6	43	282	3.59	3.6	0.3	0.5	3.7	3.4	15.3
T 7	42.9	198	16.17	16.2	0.4	0.7	23.4	23.0	21.7
T 8	14.4	116	28.44	28.4	28.9	48.8	23.6	-5.3	12.4
Year-2022									
Treatment	Y (t/ha)	ETc (mm)	WS (m^3/ha)	WS (%)	YL (ton/ha)	YL (%)	YG (from saved water	YI	WUE (kg/m^3)
T 1	42.3	306	-	-	-	-	-	-	13.82
T 2	42.1	239	710	10.03	0.20	0.34	11.8	11.60	17.62
T 3	41.9	171	1410	20.21	0.40	0.68	33.1	32.68	24.50
T 4	13.4	104	2110	30.24	28.90	48.82	26.0	-2.87	12.88
T 5	42.2	364	0	-8.68	0.10	0.17	-6.7	-6.82	11.59
T 6	42	282	710	3.59	0.30	0.51	3.6	3.27	14.89
T 7	41.9	198	1410	16.17	0.40	0.68	22.9	22.45	21.16
T 8	13.4	116	2110	28.44	28.90	48.82	21.9	-6.95	11.55

3.6.Economic Comparison using Net Return and Benefit to Cost Ratio

The economic analysis of various irrigation treatments reveals significant differences as shown in Table 7. The economic analysis of the irrigation treatments revealed that moderate irrigation levels provided the most favorable returns. Net benefits were highest under SM50% and ET50% treatments at 147,732.7 ETB/ha and 146,592.7 ETB/ha, respectively, indicating that these levels optimized the balance between yield and input costs. Similarly, the Marginal Rate of Return (MRR) was positive and above 12% for most treatments with SM50% and ET50%, achieving the highest efficiency in terms of investment return. Benefit –cost (B/C) ratios further confirmed the economic advantage of moderate irrigation, reaching 1.99 and 1.98 for SM50% and ET50% whereas low irrigation (25%) resulted in negative net benefits and very low BC ratios (0.66), demonstrating that under-irrigation was not economically viable. Overall, the analysis highlighted that 50% irrigation, based on either soil moisture or evapotranspiration, maximized profitability and water use efficiency, making it the most sustainable and cost-effective strategy for crop production. These findings aligned with previous studies, showing that moderate deficit irrigation could conserve water which is economically viable whereas severe reductions in water supply would not be advisable because of negative impacts on profitability (Kuşçu *et al*., 2017); (Montazar *et al*., 2020); (Calderon-Orellana, 2020). Thus, excessive water limitations could negatively affect crop yield and quality especially during sensitive growth periods by potentially reducing future profitability (Calderon-Orellana, 2020). Consequently, farmers might be cautious about adopting severe deficit irrigation because of its possible adverse effects on crop performance.

3.7.The Implications of SM-based Irrigation to Water Scarce Region

The adoption of Soil Moisture-based (SM) irrigation scheduling offers significant benefits for water-scarce regions by optimizing water use and enhancing agricultural sustainability. This technology leverages real-time data to align irrigation with crop needs, reducing water wastage and improving crop Water Use Efficiency (WUE). In water scarce areas, SM-based systems can decrease water application by up to 20% without affecting yield, allowing for larger cultivation areas or better drought management. The scalability and cost-effectiveness of sensor-based systems make them accessible to smallholder and commercial farmers, promoting resilience and sustainable agricultural intensification in arid and semi-arid regions.

Water conservation and efficiency can be significantly enhanced through Soil Moisture (SM)-based irrigation. Depending on the crop type and irrigation approach, this method can cut water use by as much as 30% with even greater savings up to 78% achieved in semi-arid regions (Diallo *et al*., 2024); (Karkhanis, 2024). The ability to measure soil moisture in real time enables more precise irrigation scheduling, which improves crop Water Use Efficiency (WUE) and supports the implementation of controlled deficit irrigation strategies (Feng *et al*., 2024). By minimizing wastage and optimizing water use, this management approach helps conserve resources for future needs (Baruah *et al*., 2024).

Table 7: Economic comparison of SM and ET based irrigation scheduling

Year-2021					
Treat ments	Irrigation (m^3/ha)	Adjusted Yield (Kg/ha)	Gross Benefit (ETB/ha)	Cost of Irrigation water (ETB/ha)	Labour Cost (ETB/ha)
T1	3060.0	43300	303100	9180.00	41667
T2	2390.0	43100	301700	7170.00	41667
T3	1710.0	42900	300300	5130.00	41667
T4	1040.0	14400	100800	3120.00	41667
T5	3640.0	43200	302400	10920.00	41667
T6	2820.0	43000	301000	8460.00	41667
T7	1980.0	42900	300300	5940.00	41667
T8	1160.0	14400	100800	3480.00	41667

Treat ments	Gross Cost (ETB/ha)	Net Benefit (ETB/ha)	MRR (%)	BC
T1	152427.30	150673	12.56	1.99
T2	150417.30	151283	12.61	2.01
T3	148377.30	151923	12.67	2.02
T4	146367.30	-45567	-3.80	0.69
T5	154167.30	148233	12.36	1.96
T6	151707.30	149293	12.45	1.98
T7	149187.30	151113	12.60	2.01
T8	146727.30	-45927	-3.83	0.69

Year-2022					
Treat ments	Irrigation (m^3/ha)	Adjusted Yield (Kg/ha)	Gross Benefit (ETB/ha)	Cost of Irrigation water (ETB/ha)	Labour Cost (ETB/ha)
T1	3060.0	42300	296100	9180.00	41667
T2	2390.0	42100	294700	7170.00	41667
T3	1710.0	41900	293300	5130.00	41667
T4	1040.0	13400	93800	3120.00	41667
T5	3640.0	42200	295400	10920.00	41667
T6	2820.0	42000	294000	8460.00	41667
T7	1980.0	41900	293300	5940.00	41667

T8	1160.0	13400	93800	3480.00	41667

Treat ments	Gross Cost (ETB/ha)	Net Benefit (ETB/ha)	MRR (%)	BC
T1	152427.30	143673	11.98	1.94
T2	150417.30	144283	12.03	1.96
T3	148377.30	144923	12.08	1.98
T4	146367.30	-52567	-4.38	0.64
T5	154167.30	141233	11.78	1.92
T6	151707.30	142293	11.86	1.94
T7	149187.30	144113	12.02	1.97
T8	146727.30	-52927	-4.41	0.64

The implications of sensor-based Deficit Irrigation (DI) systems in water-scarce regions are significant particularly under conditions of limited water availability. These systems enhance Water Productivity (WP) by optimizing irrigation practices, allowing for effective crop growth while conserving water resources. The following sections outline the key aspects of this approach. Deficit irrigation can markedly boost Water Productivity (WP) in researches reporting notable WP gains for crops like maize and cotton even when water supplies are reduced (Wani and Karuku, 2022a; (Xu *et al*., 2024). Maize showed a WP increase up to 24.8 kg ha^{-1} mm^{-1} under 50% irrigation, illustrating intentional moderate water deficits could improve efficiency without causing substantial yield losses (Wani & Karuku, 2022b).

Yield Implications: Although deficit irrigation often reduces total yields compared with full irrigation, it can yield a favorable balance when considering water use. Cotton, for instance, experienced about 15% yield drop under deficit irrigation, yet WP rose by approximately 7.39% (Xu *et al*., 2024). The capacity to reallocate the saved water to irrigate additional arable land can offset these losses, making deficit irrigation a viable strategy for sustainable agriculture in regions with limited water resources (Asmamaw *et al*., 2021). Implementing technological integration significantly benefits agricultural practices. This methodology not only enhances Water Productivity (WP) but also increases the reliability of irrigation (Xu *et al*., 2024).

3.8.Limitation of the study

While the study provided valuable insights into the economic and agronomic performance of soil moisture (SM) and evapotranspiration (ET)-based irrigation scheduling, several limitations should be acknowledged. First, the experiment was conducted in a single season and location, which may limit the generalizability of the results to other regions with different soil types, climatic conditions, or water availability. Second, the study focused primarily on irrigation levels and economic parameters, without incorporating detailed measurements of soil nutrient dynamics, pest pressures, or long-term soil health impacts which could influence crop productivity and sustainability. Third, the study did not consider the potential effects of climate variability, including extreme rainfall or temperature fluctuations which may affect both irrigation efficiency and carrot yield. Finally, while SM50% and ET50% treatments showed optimal economic performance, these results were based on short-term observations and might not fully capture seasonal variations in water use efficiency and crop response.

3.9.Future Research Directions

To build on the findings of this study, future research should consider multi-season, multi-location trials and in different soil types to validate the optimal irrigation strategies across different agro-ecological zones in Ethiopia. Studies should integrate soil nutrient management, pest and disease monitoring, and long-term soil health assessments to better understand the sustainability of moderate irrigation levels. Incorporating climate-smart irrigation modeling and forecasting, could improve the resilience of SM- and ET-based irrigation schedules under variable weather conditions. Additionally, future work should explore precise irrigation technologies, automated soil moisture sensors, and remote sensing approaches to optimize water use efficiency and reduce labor requirements. Finally, combining economic analysis with environmental impact assessment will provide a more comprehensive understanding of irrigation strategies in water-scarce regions, supporting both sustainable agriculture and resource conservation.

4. CONCLUSION

The comparative assessment of Soil Moisture (SM)-based and Evapotranspiration (ET)-based irrigation scheduling demonstrated that SM-based irrigation was more effective in optimizing water use, maintaining crop yield, and enhancing economic returns for carrot production under deficit irrigation conditions in Arba Minch, Ethiopia. SM-based scheduling maintained more stable soil moisture levels throughout the crop growth, preventing extreme fluctuations observed in ET-based scheduling, which relied on climatic demand rather than real-time soil water status. Across seasons in 2021 and 2022, SM-based irrigation consistently required lower cumulative water depths than ET-based irrigation, achieving 5–5.4% water savings at full irrigation without compromising yield.

The analysis of yield responses indicated that both SM- and ET-based irrigation maintained comparable yields under full (100%) and moderate deficit (75% and 50%) irrigation levels with average carrot yields ranging from 42–43 t/ha. However, SM-based irrigation showed clear advantages in terms of biomass stability and resource efficiency particularly under deficit irrigation conditions. Severe water stress (25% irrigation) significantly reduced yield, biomass, and all water efficiency indices, highlighting the importance of moderate water management.

Water Use Efficiency (WUE), field Water Use Efficiency (FWUE), and Water Productivity (WP) were consistently higher under SM-based irrigation with the highest values recorded at SM50% (WUE = 31.4 kg/m^3, FWUE = 22.7 kg/m^3, WP = 1.78 kg/m^3). This demonstrated that moderate irrigation levels could optimize the trade-off between water use and yield, enhancing both productivity and sustainability. In contrast, ET-based irrigation, while effective at maintaining yields under sufficient water supply, required more water but was less efficient in terms of WUE, FWUE, and WP.

Economic analysis confirmed that moderate irrigation levels (50% of requirement) achieved the highest net benefits and cost-benefit ratios for both SM- and ET-based scheduling. Over-irrigation under ET-based full irrigation resulted in lower water-use efficiency without corresponding yield benefits while severe deficit irrigation negatively impacted profitability.

Generally, the results indicated that SM-based irrigation provided a more precise, efficient, and sustainable approach for carrot production in water-limited environments. By integrating real-time soil moisture monitoring with irrigation management, farmers could maintain optimal crop growth, conserve water resources, improve economic returns, and enhance resilience against water stress. Therefore, adopting SM-based irrigation strategies particularly at moderate deficit levels would be recommended as a practical solution for sustainable carrot cultivation in clay soils and similar agro-ecological regions.

Data availability

The data used to support the findings of this manuscript in this study will be available from the corresponding author upon request.

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Authors' Contributions

We conceptualized the study, designed the experimental methodology, conducted data analysis. The first author did manuscript writing and revisions. The second author assisted data collection, supported data interpretation, and prepared figures and tables. The third author did literature review, statistical analysis, and critically reviewed and edited the manuscript for intellectual content. . Eventually, all authors reviewed critically and approved the final manuscript for journal submission.

Conflict of interest

The authors declare that there is no potential conflict of interest.

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