Nitrogen and Soil Moisture Optimization for Tomato Crops in Semi-Arid Areas of Ethiopia

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Nitrogen and Soil Moisture Optimization for Tomato Crops in Semi-Arid Areas of Ethiopia

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ABSTRACT: The productivity and quality of tomato crops are influenced by nutrient management and soil moisture levels. A study was conducted in Melkassa to find the best nitrogen fertilizer rate and soil moisture level for tomato crops. The experiment employed a split-plot design and was replicated three times. The combined impact of soil moisture and nitrogen levels greatly affects the height, branch count, fruit size, fruit length, marketable yield of tomatoes, tomato fruit quality, nitrogen use efficiency and water use efficiency ($p < .05$). The optimal combination of 75% ETc and 230 kg/ha resulted in the tallest tomato plant height and the highest branch number. The highest diameter and length of tomato fruits were obtained when 75% ETc and 184 kg/ha were combined. The highest marketable tomato yields were achieved by the interaction of 75% ETc and 184 kg/ha N. Applying 50% ETc with 184 and 138 kg/ha resulted in higher WUE. Interaction of 92 kg/h and soil moisture at all levels results in the maximum AUE. The maximum PFP obtained from 138 and 184 kg/ha with no significant difference. Excessive nitrogen rates (>184 kg/ha) did not increase tomato yield and WUE except for plant height and branch number. In general, the application of 75% ETc and 138 to 184 kg/ha of nitrogen is optimal for tomato production considering the measured parameter to improve water use efficiency and nutrient management in arid and semi-arid environment. The results gave valuable information and direction for the use of organic nitrogen and water in tomato production.

KEYWORDS: Tomato, soil moisture, nitrogen, quality, yield

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Introduction

Tomatoes are one of the most widely consumed and economically important crops in the world (Oprea et al., 2022; Yousafi et al., 2022). Tomatoes are also high-value vegetable crops commonly grown in Melkassa, located in the central Rift Valley of Ethiopia. They are popular in smart farms and have appreciable commercial and nutritional values. With its high demand and economic value, tomato growers must optimize their farming practices to ensure high yields and quality produce (Hao et al., 2016; Kenul, 2018).

The productivity and quality of tomato crops are influenced by various factors, including nutrient management and soil moisture levels. One crucial aspect of tomato crop optimization is the use of nitrogen fertilizer and maintaining appropriate soil moisture levels (deCastro Paixão et al., 2022; Matos et al., 2021). Tomato crops require a sufficient supply of nitrogen throughout their growth stages to maximize yield potential and achieve optimal fruit quality (Benzon & Lee, 2016; Kenul, 2018; Ogundare et al., 2015). Nitrogen is an essential nutrient for plants, including tomatoes (Andrade, 2020; Gheshm & Brown, 2018). It plays a vital role in various physiological processes such as photosynthesis, protein synthesis, and overall plant growth and development (Drobek et al., 2019; Muhamad-Hassan et al., 2022). Additionally, nitrogen fertilizer promotes the production of healthy and abundant foliage, which is crucial for efficient light interception and fruit development (Singh et al., 2018). The timing and rate of nitrogen fertilizer application are also crucial for crops production (Beyene & Mulu, 2019; Sitaula et al., 2020). However, the application of nitrogen fertilizers must be carefully managed to avoid negative impacts on tomato crop quality (Kenul, 2018).

The availability of water in the soil directly affects nutrient absorption by plant roots and ultimately influences crop yield and quality (Alaguero-Cordovilla et al., 2018). Soil moisture is also a critical factor in determining the growth and development of tomato crops (Q. Du et al., 2018). Proper soil moisture levels ensure optimal nutrient uptake and water retention, both of which are essential for the health and productivity of tomato plants (Sobrinho et al., 2022; Zhang et al., 2020). Insufficient soil moisture can lead to stunted growth, reduced fruit production, and poor fruit quality (Zhang et al., 2020). Additionally, excessive soil moisture can cause root rot and other diseases that can negatively impact the overall health of tomato plants (Jamiolkowska et al., 2019; J. Wang et al., 2022).

The maximum growth and yield of tomato could be produced when soil moisture content was maintained in the region of field capacity which progressively reduced in the drier treatments. This implies that maintaining soil moisture at field capacity, which is the maximum amount of water the soil can hold, is crucial for tomato crop growth and yield (Li et al., 2021; Gil-Ortiz et al., 2023). To ensure the successful cultivation of tomato crops, it is essential to determine the optimal soil moisture level that promotes healthy growth and maximizes yield (Q. Du et al., 2018; Matos et al., 2021).

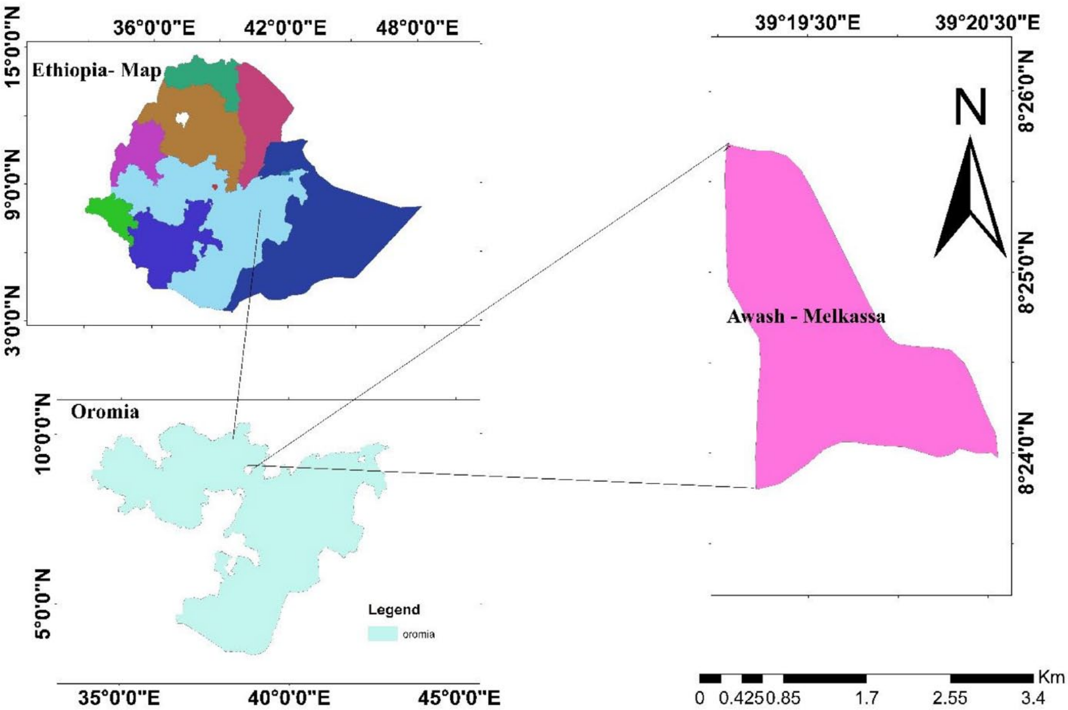

Figure 1. Map of the study area.

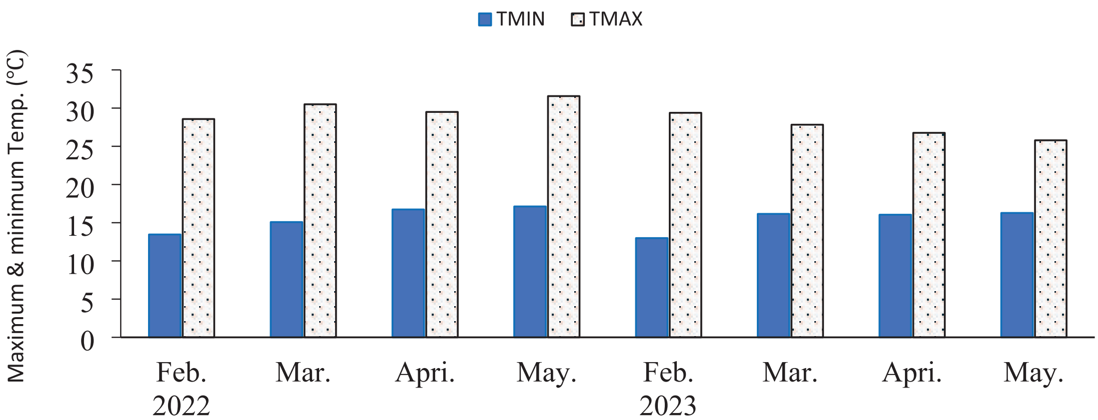

Figure 2. Maximum and minimum temperature of study area during study period.

Previous studies concentrated on nitrogen application and deficit irrigation separately. In practice, nitrogen and irrigation application need to be managed simultaneously. Therefore, it is essential to strike a balance and ensure that soil moisture levels are kept within the optimal range for tomato crops to achieve maximum growth and yield. To ensure this, the study is conducted to determine the optimum rate of nitrogen and required irrigation level for tomato crops, and to identify the interactive effect of nutrient and moisture levels on yield and yield quality.

Materials and Methods

Study area description

The field experiments were conducted during dry season in 2022 and 2023 in Melkassa agricultural Research Center, East Shewa Zone of the Oromia reginal state. Melkassa is located at a latitude and longitude of 8°23′51.98″N to 39°20′5.86″E and have an elevation of 1550 m (Figure 1). The average annual minimum and maximum temperatures are 12.3°C and 28.6°C. The minimum and maximum temperatures of the study area during the experimental season are shown in Figure 2. The total effective annual rainfall for these years was 504.8 and 916.3 mm, with 108.15 and 371.4 mm occurring during the experimental season (Figure 3). The dominant soil texture of study area is clay and clay loam. The soils have 36% and 21% of field capacity and permanent wilting point. The bulk density of the soil is also 1.1 g/cm^3. Maize, teff, onions, and tomatoes are the major crops grown in the study area. Tomato is cultivated for cash crops and dominant use in the Melkassa and in Central rift valley of Ethiopia (Figures 1–3).

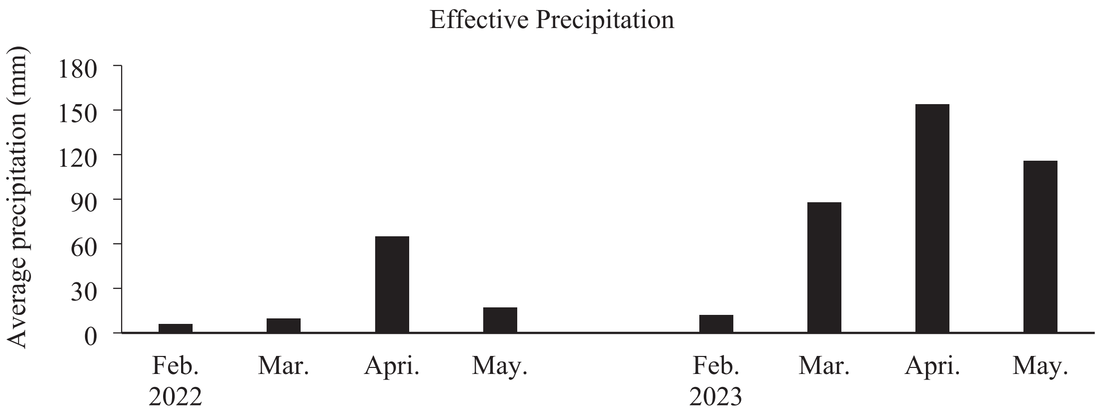

Figure 3. Distribution of rain fall during study period.

Table 1. Treatment Combination.

TREATMENT	*N* RATE (KG/HA)				
IRRIGATION INTERVALS	0	92	138	184	230
100% ETc	T1	T2	T3	T4	T5
75% ETc	T6	T7	T8	T9	T10
50% ETc	T11	T12	T13	T14	T15

Experimental design and treatments

To determine the optimal nitrogen fertilizer rate and soil moisture level for tomato crops in Melkassa, a study was conducted using a split-plot experimental design and replicated three times. The experiment included different nitrogen fertilizer rates (0, 92, 138, 184, and 230 kg N/ha). The soil moisture levels were also varied (50% ETc, 75% ETc, and 100% ETc) as indicated by the combinations in Table 1. The tomato plants were divided into different treatment groups, with each group receiving a specific combination of nitrogen fertilizer rate and soil moisture level. The results of the study can offer valuable insights into the optimal nitrogen fertilizer rate and soil moisture levels for tomato crops in Melkassa. The Gelillema tomato variety was used for the treatment materials. The varieties were obtained from Melkassa Agricultural Research Center and performed well compared to the other varieties present in Melkassa at the time of the experiment. The plot is 5 m wide and 5 m long, with a total area of 25 m^2. The spacing between rows of plants was 1 m, and there was a 0.3 m spacing between individual plants. Each experimental plot has a spacing of 1.5 m and a distance of 2.5 m between replications.

Crop management and practices

All agronomic practices were implemented for each plot, except for nitrogen and soil moisture level treatments. Land preparation, planting, field management, and harvesting were carried out accordingly and on time each year. Throughout the years, tractors have been utilized for tillage, land leveling, and layout preparation, with any mistakes being rectified manually. In December, the first plowing began. The tomato transplanting was done in mid-January on ridges of furrows with five rows in each plot for all three years. The urea (46-0-0) with rates of 0%, 92%, 138%, 184%, and 230% nitrogen (N) was used as a nitrogen source, while TSP (0-46-0) was utilized as a phosphorus (P) source. TSP was evenly applied to all plots. Half of the nitrogen was applied during transplanting, and the remaining half was top-dressed 45 days after transplanting. Weed management is carried out manually during the treatment season. The weeding took place randomly as the weeds emerged during the experimental periods. The diseases caused by various fungal pathogens, bacterial wilts, Fusarium wilt, and different pests were controlled by manually spraying chemicals such as mancozeb, karate, redo mail, and profit. These chemicals were applied before and after the emergence of these diseases and pests randomly during the experimental periods. Tomatoes were harvested regularly during their maturation stages until the fruits ripened. The experimental sample was collected from the middle three rows of the plot and used for analysis.

Irrigation scheduling

The irrigation scheduling was determined by using the CROPWAT 8 model. The reference crop evapotranspiration (ETo) was calculated using the Penman-Monteith method, which takes into account the climatic data of the area, such as maximum and minimum temperature, humidity, wind speed, and solar sunshine (Allen et al., 1998). The reference evapotranspiration (ETo) was estimated using the following equation.

$$ETo = \frac{0.40\Delta\left(\text{Rn} - \text{G}\right) + \gamma \frac{900}{T + 273} U2\left(es - ea\right)}{\Delta + \gamma\left(1 + 0.34u2\right)}$$

Were, ETo: reference evapotranspiration (mm/day), Rn: net radiation at the crop surface (MJ/m2/day),G: soil heat flux density (MJ/m2/day),T: mean daily air temperature at 2 m height (°C), U2: wind speed at 2 m height (m/s), es: saturation vapor pressure (kPa), ea: actual vapor pressure (kPa), es–ea: saturation vapor pressure deficit (kPa), Δ: slope of vapor pressure curve (kPa/°C), *Y*: psychrometric constant (kPa/°C).

Evapotranspiration (ETc) is a term used to describe the combined process of soil evaporation and the water consumed by a crop for both growth and cooling functions (Allen et al., 1998). It is determined by multiplying the reference evapotranspiration (ETo) by the crop coefficient (Kc) as described below.

$$ETc = Kc * ETo$$

Were, ETc: Evapotranspiration (mm/day) ETo: reference evapotranspiration (mm/day)

The amount of water available for crops in the root zone, known as total available water (TAW), was determined based on the measurements of field capacity and permanent wilting (Allen et al., 1998).

$$TAW = 1000\sum\left(\theta FC - \theta PWP\right) * BD \times D_Z$$

Were, TAW: volumetric total available water in the root zone (mm/m) FC: volumetric moisture content at field capacity(m^3/m^3) and PWP: volumetric moisture content at permanent wilting point (m^3/m^3). BD: bulk density (g/cm^3)

Readily available water (RAW) refers to the quantity of water that crops can access from the root zone without undergoing water stress. It is calculated based on the total available water (TAW) and the permissible soil moisture depletion level (P).

$$RAW = \rho \times TAW$$

Were, RAW: readily available water in mmf

ρ is in fraction for allowable permissible soil moisture depletion for no stress and *p* is taken as .4 for tomato crops (Allen et al., 1998).

The net irrigation water requirement (NIR) refers to the amount of water needed for irrigation in order to meet the evapotranspiration needs of crops and any additional water needs that are not met by water already stored in the soil or received through precipitation.

$$NIR = ET_c - P_e$$

Were, I: the net irrigation depth in mm, ETc: the crop water requirement in mm, Pe: the effective rainfall in mm.

Irrigation interval (I) also determined from the net irrigation interval and crop water requirement.

$$I = \frac{NIR}{ETc} = \frac{ETc - Pe}{ETc}$$

Were, I: irrigation interval (days)

The irrigation water was applied to each experimental plot using a two-inch Parshall flume, and the time was calculated to determine the volume of water entering the plot.

$$T = \frac{AD}{6Q}$$

where T is the time in min, A is the plot area (m^2), D is the application depth (mm) or the amount of water that needs to be applied to an irrigated system when soil water is reduced to the specified depletion level, and Q is the discharge rate (l/s).

Irrigation water use efficiency (WUE) and nitrogen use efficiency

Water use efficiency is the ratio of the total economic yield to the total irrigation water supplied to the treatments (Yang et al., 2017)

$$WUE = \frac{Y}{I_t}$$

Where WUE (/tha/mm) represents water use efficiency, *Y* (/tha) denotes total economic yield, and I_t (mm) indicates the total amount of irrigation water applied.

Nitrogen use efficiency is determined by two methods of nutrient use efficiency; partial factor productivity and agronomic efficiency of nitrogen.

Partial factor productivity is the kg harvested product to per kg nutrient applied (Dobermann, 2007).

$$PFP = \frac{Y}{F}$$

F = amount of Nitrogen applied(kg/ha); *Y* = Yield of tomato(kg/ha); and PFP = Partial factor productivity.

Agronomic use efficiency (AE) is agronomic efficiency of applied nitrogen (kg/ha) to harvested tomato (kg/ha) (Dobermann, 2007).

$$AUE = \frac{Y - Y_0}{F}$$

Were, *F* = amount of Nitrogen applied(kg/ha); *Y* = Yield of tomato(kg/ha); and Y_O = tomato yield in control treatment with no *N*.

Table 2. Effect of Irrigation Level and Nitrogen Rate on Growth Parameters and Yield.

TREATMENT	PLANT HEIGHT (CM)	BRANCH NUMBER	FRUIT DIAMETER (MM)	FRUIT LENGTH (MM)	MARKETABLE YIELD (TON/HA)
100% ETc	62.1[a]	9.1[ab]	54.3[b]	72.4[ab]	38.7[a]
75% ETc	62.5[a]	9.4[a]	57.9[a]	74.6[a]	39.8[a]
50% ETc	59.9[b]	8.7[b]	51.3[c]	70.7[b]	35.0[b]
CV	1.56	5.82	4.3	3.18	6.2
$LSD_{0.05}$	1.0	0.54	1.79	2.29	2.76
N230	65.0[a]	9.6[a]	54.7[c]	72.2[b]	38.0[b]
N184	64.7[a]	9.3[ab]	59.5[a]	77.0[a]	42.1[a]
N138	63.3[b]	9.1[ab]	57.0[b]	75.7[a]	41.1[a]
N92	59.4[c]	8.8[bc]	53.0[c]	72.1[b]	34.9[c]
N0	55.1[d]	8.6[c]	48.4[d]	61.9[c]	33.1[c]
CV	1.69	5.93	3.24	3.11	7.19
$LSD_{0.05}$	0.93	0.51	2.28	2.24	2.28

Note. Letter with different letter in the same column was significant different at 5% probability level.

Determination of fruit quality parameters

Parameters such as total soluble solids (TSS), soluble sugar, organic acids (AS), Vitamin C (VC), lycopene, and nitrate content were determined according to their respective methods of determination. Six matured fruits were selected from each treatment and checked for each quality parameters. Electronic handled refractor was used to measure TSS (PR-32 Co., Ltd Tokyo Japan). The Anthrone colorimetric method was used to determine the SS (Li, 2000). NaOH was titrated with 0.1 mol/L and calculated as equivalents of citric acid expressed as percentages of fresh mass (Agroindustriais, 2013). VC was measured using the extraction-molybdate blue spectrophotometric method (Association of Official Analytical Chemists, 1984). Spectrophotometric method was used to measure lycopene (Lianfu, & Xiaolin, 2001). Spectrophotometric method was used for the measurement of NC (Lianfu, & Xiaolin, 2001).

Data collection and analysis

Tomatoes data such as plant height, fruit diameter, branch number, and marketable and unmarketable yield were collected and used for analysis.

Plant height. Ten plants were selected randomly from the middle rows and measured using a measuring tape from the ground surface to the top of the tomato to determine the plant height of tomatoes at different stages of maturity.

Fruit length (mm) and fruit diameter (mm). At harvesting times, ten fruits were selected from different sizes of tomato, measured with a caliper, and the average values were used for the analysis.

Branch number. The number of tomato branches was counted during maturity stages from 10 plants, and their average was used for analysis.

Marketable yields (tons/ha). Tomato fruits were collected at maturity stages from the three middle rows in all rounds of harvesting, weighed using a sensitive balance, and then added together to determine the total weigh. The fruits attacked by diseases, pests, and the sun are in marketable tomato yield. The total weight of fresh tomatoes was collected from a 12 m^2 plot area and converted to ton/ha.

The data analysis was subjected to the ANOVA method using the SAS software program for a split-plot design over two years. The least significant difference at a .05 probability level is used to compare the means.

Results

Effect of irrigation level nitrogen rate and their interaction on growth parameter and yield of tomato

Table 2 represent the overall data for growth parameters and yield for two cropping seasons. The growth parameters and yields show significant differences for both irrigation levels and nitrogen application rate application.

Plant height. Plant varies significantly depending on the soil moisture and nitrogen levels applied. The tallest plants were observed under higher soil moisture conditions of 100% and

75% ETc, measuring 62.5 and 62.1 cm respectively, with no significant difference between them. In contrast, plants under 50% ETc irrigation were notably shorter, measuring 59.9 cm. This difference highlights tomatoes' sensitivity to increased soil moisture stress, which leads to reduced plant height.

There is also a significant difference in plant height depending on nitrogen application rate. Reducing nitrogen levels results in a reduction in plant height, as shown in Table 2. The application of 230 and 184 kg/ha of nitrogen resulted in the tallest tomato plants compared to the application of 138, 92, and 0 kg/ha, without any significant difference. These treatments yielded tomato heights of 65.0 and 64.7 cm, respectively. Applications of 138, 92, and 0 kg/ha also resulted in plant heights of 63.3, 59.4, and 55.1 cm, respectively. The result indicates that plant height increases with an increase in nitrogen rate up to a certain point, and then decreases above optimal levels. Excessive nitrogen application can negatively impact water and nutrient absorption.

Branch number. Tomato branch numbers show a significant difference when different irrigation levels and nitrogen rates are applied. The largest number of tomato branches was obtained by applying 75% ETc, yielding 9.4 tomato branches, as shown in Table 2. Soil moisture stress at 50% ETc and 100% ETc levels resulted in a lower (8.7) and moderate (9.1) number of tomato branches. Irrigating tomatoes with 75% ETc resulted in 3.19% and 7.44% more tomato branches than irrigating with 100% ETc and 50% ETc, respectively.

In this study, the largest (9.6) and lowest (8.6) tomato branches were obtained by applying 230 kg/ha and 0 nitrogen rates. The moderate tomato branch numbers 9.3 and 9.1 were achieved with applications of 184 and 138 kg/ha, respectively, showing no significant difference. This suggests that as nitrogen application rates increase, tomato branch number also increase.

Fruit diameter. As shown in Table 2 the diameter of the tomato fruit varies significantly with the application of different irrigation levels. The maximum fruit diameter of 57.9 mm was achieved with the application of 75% ETc, while the minimum fruit diameter of 51.3 mm was achieved with greater deficit irrigation (50% ETc). This indicates that soil moisture of 75% ETc is optimal to produce tomatoes with a larger fruit diameter. Application of 100% ETc results in a medium fruit diameter of 54.3 cm compared to application of 75% and 50% ETc irrigation levels.

Application of different nitrogen rates shows a significant impact on tomato fruit diameter. The larger fruit diameters of 59.5 and 57.0 mm were obtained by applying 184 and 138 kg/ha of nitrogen treatments. Increasing nitrogen rates up to 184 kg/ha of fruit diameters, but they decreased when the nitrogen rate reached 230 kg/ha. This indicate that applying a nitrogen rate above the optimal level does not increase tomato fruit diameter. The smaller fruit diameters of 53.0 and 48.4 mm were obtained by applying 92 and 0 kg/ha of nitrogen, respectively.

Tomato fruit length. Tomato fruit length varies significantly depending on the application of different soil moisture levels and nitrogen rates. The longest fruit length of 74.6 mm was achieved by applying 75% ETc irrigation level. The shortest fruit length of 70.7 mm was also observed when 50% ETc irrigation levels was applied. Irrigation of tomatoes with 100% ETc results in a tomato fruit length of 72.4 mm.

Applying different N rates had a significant effect on the length of tomato fruits. Longest fruit length was achieved by applying 184 and 138 kg/ha nitrogen, resulted 77.0 and 77.7 mm, without significant difference. Applying 230 kg/ha of nitrogen resulted in shorter fruit length compared to applying 184 and 138 kg/ha of N. A shorter fruit length of 61.9 mm was obtained at the zero-nitrogen rate. Irrigation at rates of 230 and 92 kg/ha resulted in fruit lengths of 72.2 and 72.1 mm, respectively, with no significant difference.

Tomato marketable yield. The total marketable yield of tomatoes over a two-year period varied significantly due to the application of different soil moisture and nitrogen rates in the treatments. No significant differences were observed between 100% ETc and 75% ETc, whereas a significant difference was noted when using 50% ETc irrigation levels. In this study, the highest yield of 39.8 and 38.9 tons/ha was obtained by applying 75% ETc and 100% ETc, respectively, without any significant difference. Applying an irrigation level of 50% ETc results in a yield of 35.0 tons/ha, with a statistically significant difference.

The application of nitrogen rates significantly impacts marketable tomato yields. Appling 184 and 138 kg/ha of nitrogen results in higher marketable tomato yields, with reported yields of 42.1 and 41.1 tons/ha, respectively, showing no significant differences between the two rates. In this study, the maximum nitrogen application of 230 kg/ha did not yield the highest tomato output, resulting in 38 tons/ha. Additionally, the application of 92 kg/ha of nitrogen produced a marketable yield of 34 tons/ha, while no nitrogen application led an even lower yield of 33.1 tons/ha.

The interactive effect of irrigation level and nitrogen rate on growth parameters and yield is presented in Table 3. The interaction effect of soil moisture and nitrogen content significantly influences plant height, number of branches, fruit diameter, fruit length, and marketable yields of tomato.

The combination of 75% ETc and 230 kg/ha N resulted the longest plant height of 66.2 cm, while the shortest plant height of 54.1 cm, was observed with the combination of 0 kg/ha N and 50% ETc irrigation level. Combination of 50% ETc resulted in shorter plant height across all nitrogen rates and an increase in plant height within the same

Table 3. Interactive Effect Irrigation Level and Nitrogen Rate on Growth Parameters and Yield.

	TREATMENT	CROP YIELD AND GROWTH PARAMETERS				
		PLANT HEIGHT (CM)	BRANCH NUMBER	FRUIT DIAMETER (MM)	FRUIT LENGTH (MM)	MARKETABLE YIELD (TON/HA)
1	230N × 100% ETc	64.1cd	9.6abc	54.6cdef	71.9cdefgh	39.5bcd
2	184N × 100% ETc	65.9ab	9.3abcde	57.1bc	75.5abcd	41.4abc
3	138N × 100% ETc	64.9abc	9.1abcdef	55.4cd	74.8bcdef	41.4abc
4	92N × 100% ETc	60.4e	9.2abcdef	54.0cdef	71.7defgh	35.6de
5	0N × 100% ETc	55.0gh	8.6def	50.5f	68.0h	35.6de
6	230N × 75% ETc	66.2a	9.9a	57.1bc	73.3bcdefg	38.0cd
7	184N × 75% ETc	65.5abc	9.8ab	65.9a	79.3a	45.5a
8	138N × 75% ETc	64.2bcd	9.3abcd	60.7b	77.2ab	43.6ab
9	92N × 75% ETc	60.5e	9.1abcdef	54.0cdef	73.4bcdefg	36.3de
10	0N × 75% ETc	56.2fg	8.8cdef	51.9def	70.0gh	35.5de
11	230N × 50% ETc	64.8abc	9.3abcd	52.3def	71.4efgh	36.4de
12	184N × 50% ETc	62.7d	9.0abcdef	55.4cd	76.1abc	39.2bcd
13	138N × 50% ETc	60.8e	8.9bcdef	54.9cdf	75.2abcde	38.3cd
14	92N × 50% ETc	57.2f	8.2f	51.1ef	71.2fgh	32.9e
15	0N × 50% ETc	54.1h	8.3ef	42.5g	59.7i	28.3f

Note. Letter with different letter in the same column was significant different at 5% probability level.

irrigation levels. The study found that the highest number of branches in tomatoes was achieved with a combination of 75% ETc and a nitrogen content of 230 kg/ha treatment. These were also followed by a combination of 184 kg/ha and 75% ETc as indicated in 3. Interaction of 75% ETc and 184 kg/ha of N resulted in the largest fruit diameter, followed by the interaction of 75% ETc and 138 kg/ha of N. The smallest fruit diameter was obtained from the interaction of 50% ETc and 0N.

In this study, application of 75% ETc and 184 kg/ha nitrogen (N) is also resulted in maximum fruit length. The highest marketable tomato yields were achieved through the interaction of 75% ETc and 184 kg/ha of N, followed by the combination of 75% ETc and 138 kg/ha. The lowest yields were observed with 0 kg/ha of N and 50% ETc irrigation level.

In general, height and branching of tomato plants were optimized by applying a maximum nitrogen rate of 230 kg/ha at an irrigation level of 75% ETc, while tomato fruit diameter and length were optimized by applying a nitrogen rate of 184 kg/ha and 75% ETc irrigation level. The highest marketable tomato yields were achieved through the interaction of 75% ETc and 184 kg/ha of N.

Impact of irrigation levels and nitrogen rates and their interaction on water use efficiency (WUE) and nitrogen use efficiency (NUE)

WUE was influenced by both deficit irrigation and the application of different amount of nitrogen. Lower WUE was obtained by applying full irrigation while greater deficit irrigation resulted the maximum WUE. Moderate WUE was obtained by applying 75% of the ETc irrigation levels. Application of 184 and 138 kg/ha of nitrogen results in the maximum WUE without any significant difference (Figure 4). Medium WUE, was also achieved with the application of 230 kg/ha, while lower WUE was observed with the application of 92 and 0 kg/ha, without a significant difference.

NUE, such as agronomic use efficiency (AUE) and partial factor of productivity (PFP), was significantly affected by different nitrogen rates. AUE does not show significant effects from application of soil moisture, but it is affected by the application of different nitrogen rates, as indicated in Table 4. Maximum AUE was achieved by applying a lower amount of nitrogen, neglecting 0N application. In this study, application of 92 kg/ha nitrogen followed by 138 kg/ha resulted in the maximum AUE nitrogen.

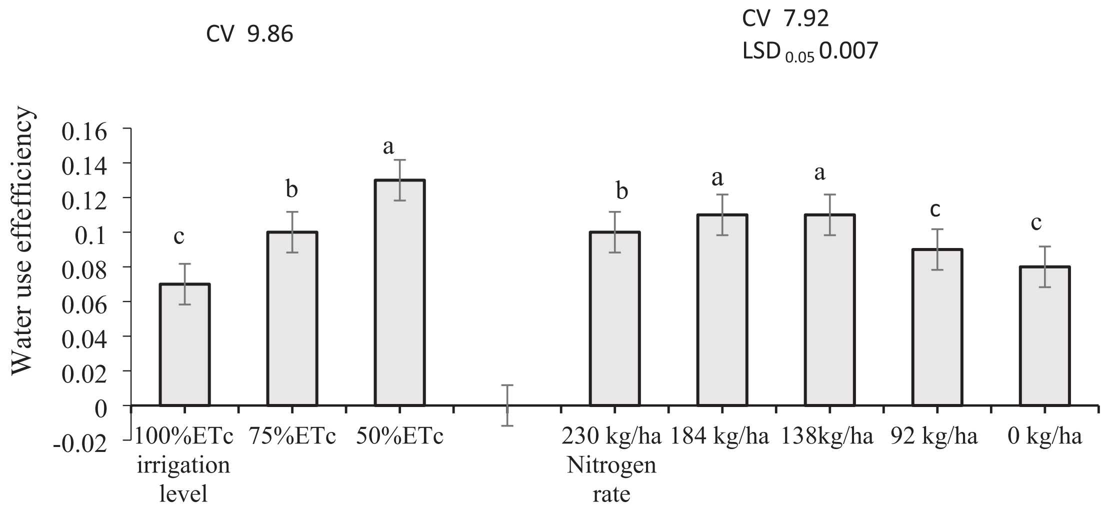

Figure 4. Effect of deficit irrigation and nitrogen rate on the irrigation water use efficiency.

Table 4. Effect of Deficit Irrigation and Nitrogen Rate on Agronomic Efficiency and Partial Factor of Productivity of Nitrogen.

TREATMENT	AGRONOMIC EFFICIENCY	PARTIAL FACTOR OF PRODUCTIVITY
100% ETc	0.22	0.047^{a}
75% ETc	0.226	0.054^{a}
50% ETc	0.22	0.03^{b}
CV	6.59	28.13
$LSD_{0.05}$	Ns	4.5×10^{-3}
N230	0.2^{c}	0.03^{d}
N184	0.22^{c}	0.06^{a}
N138	0.30^{b}	0.07^{a}
N92	0.38^{a}	0.04^{c}
N0	-1.1^{-16}	-1.39^{-17}
CV	12.55	32.57
$LSD_{0.05}$	0.01	6.7^{-3}

Note. Ns stand for non-significant, letter with different letter in column shows significant difference.

PFP shows a significant difference by applying different irrigation levels and nitrogen rates. Due to the application of 50% ETc, a lower PFP was achieved in this study. However, applying 100% ETc and 75% ETc results in a higher PFP, without a significant difference compared to the 50% ETc soil moisture level. Increasing nitrogen rates increase PFP up to certain ranges of application and then decrease PFP above the optimal range, as indicated in Table 4. The application of 138 and 184 kg/ha resulted in the maximum partial factor of productivity, without significant difference. The addition of nitrogen above 184 kg/ha does increase PFP in this study. In this study, zero nitrogen application resulted in the minimum PFP among all treatments. Both the lack of nitrogen use and excess nitrogen use result in lower PFP for nitrogen, as shown in Table 4.

The interaction effect of irrigation level and nitrogen application is statistically significant ($p < .05$) on water use efficiency as indicated in Figure 5. The combination of a 50% ETc irrigation level with all nitrogen rates resulted in maximum WUE compared to the interaction of all nitrogen rates with 100% and 75% ETc irrigation levels. Nitrogen rates of 184 and 138 kg/ha, in interaction with 50% ETc, result in higher WUE without significant different. The interaction of 100% ETc with 92 and 0 kg/ha resulted in the lowest irrigation water use efficiency, without a significant difference.

Figure 6 shows that the interactive effect of nitrogen amount and soil moisture on the nitrogen use efficiency such as AUE of N and (PFP). Interaction of nitrogen rate and soil moisture shows significant difference on AUE of nitrogen and PFP ($p < .05$). The AUE of nitrogen increased as the applied amount of nitrogen decreased. An application of 92 kg/ha nitrogen with three different irrigation levels results in the highest AUE.

Nitrogen rates and soil moisture interaction show a significant difference in PFP (Figure 6). The highest PFP was achieved with the combination of 138 kg/ha and 100%ETc; 138 kg/ha nitrogen and 75% ETc, followed by the combination of 184 kg/ha and 75% ETc of irrigation amount.

Impact of irrigation and nitrogen rate and their interaction on tomato fruit quality

Two-way ANOVA analysis indicated that tomato fruit quality was affected by irrigation water level and different nitrogen rate application. Vitamin C (VC), total soluble solids (TSS), soluble sugar (SS), Lycopene (Lyc), organic acids

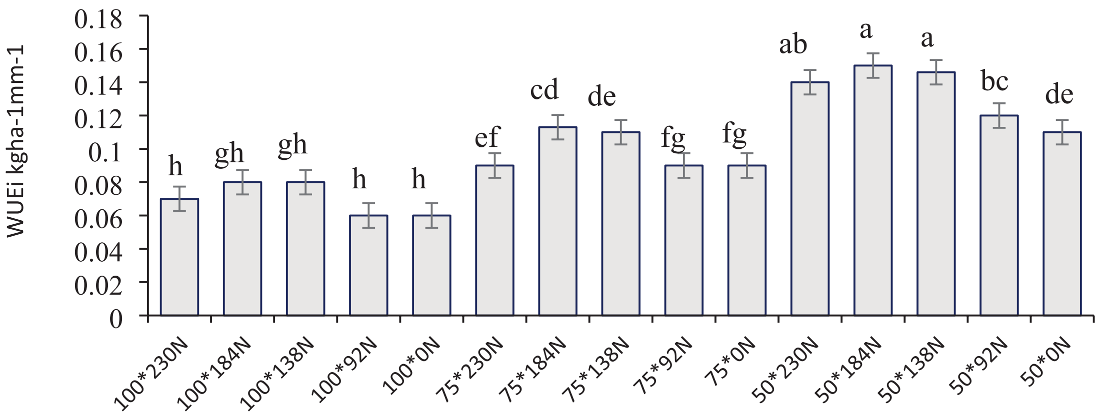

Figure 5. Interaction effect of deficit irrigation and nitrogen rate on WUE.

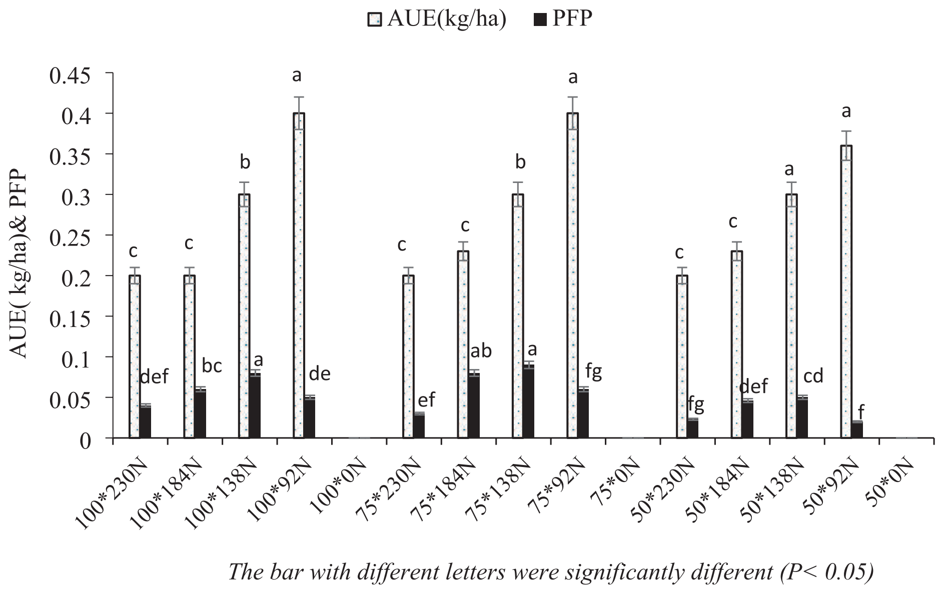

Figure 6. Agronomic use efficiency and partial factor of productivity for *N*.
Note. The bar with different letters were significantly different ($p < .05$).

(OA), and nitrogen content (NC) were parameters tested for tomato quality. VC decreases with decrease of irrigation level while TSS increases with increase of soil moisture as shown in the Table 5. Soluble sugars show significant difference among applied irrigation level. Similarly, Lycopene, OA, and NC shows significant effect by application different of irrigation level. On other hand application of different nitrogen rate affected all tested parameters. VC, TSS, SS, and Lyc. initially increase with increase of nitrogen rate with in limited rage and the decrease. OA and NC increase with increase of nitrogen rate showing significant difference among the treatment.

Interaction of irrigation and nitrogen rates affects tomato fruit quality, as shown in Table 6. The combination of 100% ETc and all nitrogen rates results in higher VC followed by the 75% ETc interaction. Total soluble solids increase due to the interaction of 50% ETc with all nitrogen rates. The interaction between irrigation levels and nitrogen rates also shows significant difference on SS, Lyc, AO, and NC.

Discussion

Effect of irrigation level and nitrogen rate on growth parameters and yields of tomato

Water and nitrogen are the main limiting factors for crop yield and quality (Sainju et al., 2019). The application of nitrogen and irrigation are critical factors for increasing crop yield (Y. Du et al., 2021; Li et al., 2021). Nitrogen is crucial nutrient for the physiological and metabolic process in a tomato, as its availability affects tomatoes growth and yields (Shewangizaw et al., 2024). The study's results revealed that the growth and yields of tomatoes were impacted by varying nitrogen rates and irrigation levels, as well as their interaction, with a significance level of 5%.

Table 5. Impact of Irrigation Level and Nitrogen Rate on Tomato Fruit Quality.

TREATMENT	VC (MG·100/G)	TSS (%)	SS (%)	LYC (μG G)	OA (%)	NC (MG·KG)
100% ETc	25.19^{a}	6.3^{c}	4.5^{a}	36.1^{a}	0.8^{a}	109.6^{a}
75% ETc	22.5^{a}	7.4^{b}	4.2^{a}	32.6^{ab}	0.67^{b}	105.49^{a}
50% ETc	16.4^{b}	8.2^{a}	3.5^{b}	30.7^{b}	0.6^{b}	83.03^{b}
CV	17.25	10.1	10.62	14.5	13.0	4.2
$LSD_{0.05}$	1.3	0.75	0.15	1.77	0.03	2.8
230	20.4^{b}	5.0^{c}	3.6^{bc}	34.1^{bc}	0.8^{a}	114.2^{a}
184	22.3^{a}	7.6^{b}	5.04^{a}	38.9^{a}	0.74^{a}	184.9^{a}
138	22.3^{a}	8.1^{a}	4.5^{a}	34.1^{bc}	0.73^{a}	102.9^{b}
92	21.2^{ab}	8.2^{a}	3.9^{b}	30.2^{cd}	0.63^{b}	91.08^{c}
0	20.6^{b}	7.6^{b}	3.19^{c}	29.4^{d}	0.57^{b}	78.7^{d}
CV	6.04	12.05	11.9	13.96	6.11	4.22
$LSD_{0.05}$	1.2	0.42	0.26	1.8	0.03	2.86

Note. VC = vitamin C; TSS = total soluble solids; SS = Soluble sugar; Lyc. = lycopene; OA = Organic acids; NC = Nitrogen Content. Different letter in the same column shows significant effect at $p < 0.05$.

Plant height. Application of different irrigation levels shows a significant effect on tomato plant height ($p < .05$). Irrigating tomatoes with 100% ETc and 75% ETc results in the tallest tomato plant height, without significant differences. The treatments exhibit a significant difference when compared to 50% ETc irrigation levels. Ullah et al. (2021) and also reported that irrigating at 100% ETc and 75% ETc resulted in the tallest plant height without any significant difference. Different studies have reported varying effects of soil moisture on tomato plant heights. Bhattarai et al. (2005) found that both deficiency and saturation of soil moisture reduced plant height. Furthermore, Sarker et al. (2020) and Sibomana et al. (2013) found a gradual decline in plant height with increasing moisture stress. An appropriate combination of soil moisture and rhizosphere aeration can improve water uptake and root vigor, potentially leading to increased plant height (Niu et al., 2012).

Applying different amount of nitrogen rates also shows a significant effect on tomato plant height. In this study, increasing nitrogen rate also increases tomato plant height indicating significant difference. The application of higher nitrogen rate of 230 and 184 kg/ha resulted in higher plant height compared to the application of 138, 92, and 0 kg/ha of N. Previous study also indicates that increasing nitrogen rate also increase plant height (Degefa et al., 2019; Etissa et al., 2013; Iqbal et al., 2011). Similarly, Ullah et al. (2021) suggested that increasing nitrogen supply improved root shoot morphology.

Branch number. Different soil moisture application significant affects tomato branch number. Application of 75% ETc results in highest number of tomato branches. Tesfay et al. (2019), also pointed out that the plots treated with moderate (75% ETc) to full (100% ETc) irrigation had significantly higher numbers of tomato branches.

On other hand, application of different nitrogen also affects tomato branch number. Increasing nitrogen application rates resulted in the maximum number of tomato branches, while the lowest number of tomato branches was achieved from treatment without any nitrogen application. Degefa et al. (2019) and Iqbal et al. (2011) indicated that an increase in nitrogen application leads to a higher number of branches on tomato plants.

Fruit diameter. Application of different soil moisture and nitrogen rates significantly affects the diameter of tomato fruits. In this study, the maximum fruit diameter of tomato was achieved with the application of 75% ETc, while the minimum fruit diameter was achieved with higher deficit irrigation. Soil moisture content significantly affects the fruit diameter of tomatoes, with both deficit and saturation leading to a reduction in fruit yield (Bhattarai et al., 2005).

Fruit diameter increased with the application of a lower nitrogen rate (0 kg/ha) until the optimal rate and then decreased when the nitrogen rate reached its maximum. The influence of nitrogen content on fruit diameter of tomatoes is a complex interaction influenced by various factors and different studies quantify different amounts of nitrogen level. Iqbal et al. (2011) found that applying a nitrogen rate of 120 kg N and 90 kg K resulted in maximum fruit diameter. Lee et al. (2007) also observed an increase in tomato yield with increasing nitrogen fertilization rates, with the highest fruit yield achieved at a N-Fertigation rate of 80. Similarly, Kirimi et al. (2011) reported that an application rate of 80 kg/ha nitrogen

Table 6. Interaction Effect of Irrigation and Nitrogen on Tomato Fruit quality.

	TREATMENT	VC	TSS	SS	LYC	OA	NC
1	230N × 100% ETc	24.7^{a}	3.8^{f}	3.8^{de}	33.1^{bc}	0.88^{a}	118.4^{a}
2	184N × 100% ETc	25.7^{a}	7.1^{cd}	6.9^{a}	37.3^{ab}	0.9^{a}	120.8^{a}
3	138N × 100% ETc	25.4^{a}	7.9^{bc}	5.1^{bc}	37.2^{ab}	0.86^{ab}	115.8^{a}
4	92N × 100% ETc	24.8^{a}	7.8^{bc}	4.1^{cde}	37.6^{ab}	0.79^{abc}	101.4^{b}
5	0N × 100% ETc	25.2^{a}	6.5^{d}	3.4^{ef}	37.2^{ab}	0.62^{de}	91.7^{bc}
6	230N × 75% ETc	21.7^{ab}	5.0^{e}	3.6^{de}	36.6^{ab}	0.79^{abc}	122.6^{e}
7	184N × 75% ETc	23.9^{a}	8.2ab	5.3^{ab}	41.7^{a}	0.71^{bcd}	117.7^{a}
8	138N × 75% ETc	24.2^{a}	8.1bc	4.5^{bcd}	31.9^{bcd}	0.68^{cde}	112.8^{a}
9	92N × 75% ETc	22.2^{ab}	7.8bc	4.0^{de}	27.4^{cd}	0.56^{ef}	97.6^{bc}
10	0N × 75% ETc	20.3^{bc}	7.9bc	$3.4d^{f}$	25.7^{cd}	0.63^{de}	76.7^{de}
11	230N × 50% ETc	14.8^{d}	6.2d	3.2^{ef}	32.2^{bc}	0.75^{abcd}	101.6^{b}
12	184N × 50% ETc	17.3^{c}	9.3a	3.2^{ef}	37.2^{ab}	0.63^{de}	91.3^{c}
13	138N × 50% ETc	17.3^{c}	8.5ab	4.1^{cde}	33.4^{bc}	0.65^{cde}	802^{d}
14	92N × 50% ETc	16.5^{cd}	8.5ab	3.6^{def}	25.6^{cd}	0.55^{ef}	74.2^{de}
15	0N × 50% ETc	16.2^{cd}	8.6ab	2.7^{f}	25.2^{d}	0.46^{f}	67.7^{e}

Note. Letter with different letter in the same column was significant different at 5% probability level.

produced the highest fruit yield. Qiang et al. (2014) further emphasized the importance of nitrogen form and emphasized that nitrate-N promotes the growth and development of plants, resulting in increased biomass accumulation and fruit yield. Overall, these studies suggest that optimal nitrogen content in combination with the appropriate form of nitrogen is crucial for achieving the maximum diameter of the tomato fruit.

Fruit length. Fruit length was significantly affected by variations in soil moisture and nitrogen application rates. The longest fruit length was achieved with an irrigation rate of 75% ETc, while the shortest fruit length was observed at higher moisture stress (50% ETc). The results coincide with those of Birhanu and Tilahun (2010), who reported that both the number and size of tomato fruits decreased as soil moisture decreased.

Application of different nitrogen rates shows significant variation in tomato fruit length. Increasing the nitrogen levels increases tomato fruit length to the same extent and then decrease to higher nitrogen rates. The longest fruit length of tomatoes was achieved by applying 184 and 138 kg/ha nitrogen, with no statistically significant difference between them. For optimal fruit length, the application of nitrogen at rates of 184 and 138 kg/ha is important in this study. Iqbal et al. (2011) found that nitrogen and potassium application significantly affected fruit length, with maximum length observed with a specific combination of these nutrients.

Marketable yields. Irrigating tomatoes with 100% ETc and 75% ETc resulted in the highest tomato yield without any significant difference, whereas a notable variance was observed when using 50% ETc irrigation levels. Previous studies have also suggested that the marketable fruit yield of tomatoes decreases as moisture stress increases from 100% ETc to 50% ETc irrigation levels (Gragn et al., 2023; Mebrahtu et al., 2020). Furthermore, Wu et al. (2021) also mentioned that both total yield and marketable tomato yield increased with higher irrigation amounts. Lu et al. (2019) suggested that the application of heavy deficit irrigation reduces tomato yield. Too high or too low soil moisture content can negatively affect tomato yield (Chen et al., 2006).

The application of nitrogen rates significantly affects the marketable yield of tomatoes. Higher marketable tomato yields were obtained from the application of 184 kg/ha N and 138 kg/ha N without a significant difference. Applying the maximum nitrogen rate of 230 kg/ha did not produce the highest tomato yield. Beyene and Mulu (2019) also mentioned that there is a gradual increase in tomato yield with nitrogen fertilization rate until reaching the optimal level.

Impact of irrigation levels, nitrogen rates, and their interaction on water use efficiency (WUE) and nitrogen use efficiency (NUE)

Water use efficiency (WUE) is defined as the amount of carbon assimilated as biomass or grain produced per unit of water used by the crop (Hatfield & Dold, 2019). In this study, full irrigation led to lower irrigation water efficiency, while greater deficit irrigation led to maximum WUE. Muroyiwa et al. (2023) also pointed out that the highest WUE was achieved at 60% without a significant difference at 80% of ETc, and the lowest was found at 100% of ETc irrigation levels.

Conversely, applying nitrogen (N) rates increases WUE within a certain range, but does not improve WUE beyond the optimal range. Cheng et al. (2021) mentioned that nitrogen application resulted in a significant increase in WUE, with an average improvement of 22.7%, 22.7%, 22.7%, 23.2%, and 17.9% compared to situations in which nitrogen was not applied at various experimental sites, average annual temperatures, soil textures, pH values, and irrigation water depths. Furthermore, it was observed that at high nitrogen application rates (>354 kg/ha), WUE responses remained consistent regardless of the different average annual temperatures (Cheng et al., 2021).

On the other hand, agronomic nitrogen use efficiency (AEU) was not affected by soil moisture, but it was influenced by the application of different nitrogen rates. The maximum AUE was achieved by applying a lower amount of nitrogen.

Both soil moisture and nitrogen rates affect significantly the partial factor productivity. Applying 100% ETc and 75% ETc irrigation levels yielded maximum PFP compared to the 50% ETc irrigation level. The result is consistent with the results of Li et al. (2021), who mentioned that PFP increased with increasing irrigation amount.

However, nitrogen application increases PFP up to the optimal range and then decreases when applied above the optimal range. The result is consistent with the findings of Li et al. (2021), who found that excess nitrogen significantly reduced PFP. The NUE value, which steadily decreases with increasing N levels, may be related to a limitation in the uptake and assimilation capacities, resulting in a saturation response.

The interaction effect of soil moisture and nitrogen rate significantly affects WUE, AUE, and PFP. X. Wang and Xing (2017) indicated that WUE and NUE were significantly affected by interaction of nitrogen and soil moisture level. The interaction 50% ETc with different nitrogen rates resulted in the maximum WUE compared to 100% ETc and 75% ETc. Specifically, applying 50% ETc with 184 and 138 kg/ha resulted in higher WUE, without significant difference between them. The interaction of maximum irrigation levels with lower nitrogen application (0 and 92 kg/ha) resulted in the lowest irrigation water use efficiency, without significant difference between them. Ullah et al. (2021) found that a slight decrease in irrigation, combined with an increase in nitrogen supply, improved WUE.

When the application of nitrogen rate was decreased, the AUE increased. AUE was strongly influenced by nitrogen fertilizer application level (Tesfay et al., 2019). An application of 92 kg/ha of nitrogen with three different irrigation levels results in the highest AUE. The highest PFP was achieved with the combination of 138 kg/ha of nitrogen and 75% ETc irrigation level.

Conclusion

In tomatoes farming, optimum use of soil moisture and nitrogen rates is crucial for achieving the highest yield of tomatoes and enhancing water use efficiency. In our study, soil moisture levels and nitrogen rates influence tomato yields, yield quality, yield components, WUE, and NUE such as AUE and PFP. Increasing nitrogen above optimum range does not increase tomato yield and WUE except for plant height and branch number. The maximum diameter and length of tomato fruits were also achieved with a combination of 75% ETc and 184 kg/ha in the study area.

The maximum marketable tomato yields were also achieved through the interaction of 75% ETc and 184 kg/ha of nitrogen. Applying 50% ETc with different nitrogen rates resulted in the maximum WUE. Applying 50% ETc with 184 and 138 kg/ha resulted in higher WUE. Interaction of 92 kg/h and soil moisture at all levels results in the maximum AUE without any significant differences. The maximum PFP obtained from 138 and 184 kg/ha with no significant difference. In general, the application of 75% ETc and 138 to 184 kg/ha of nitrogen is optimal for tomato production and it is recommended for farmer.

Declaration of Conflicting Interests

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Data Availability Statement

The corresponding author in this study is willing to pro-vide the generated and analyzed data upon reasonable request.

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REFERENCES

Agroindustriais, P. (2013). AOAC. Official methods of analysis of the Association of Official Analytical Chemists. *Caracterização, Propagação E Melhoramento Genético De Pitaya Comercial E Nativa Do Cerrado*, 26(74), Article 62.

Alaguero-Cordovilla, A., Gran-Gómez, F. J., Tormos-Moltó, S., & Pérez-Pérez, J. M. (2018). Morphological characterization of root system architecture in diverse tomato genotypes during early growth. *International Journal of Molecular Sciences*, 19(12), Article 3888.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO, Rome*, 300(9), Article D05109.

Andrade, I. (2020). Quality of Italian tomatoes grown with different forms of calcium application. *Research, Society and Development*, *9*(12), e10191210837.

Association of Official Analytical Chemists. (1984). Vitamin C (ascorbic acid) in vitamin preparations and juices, 2, 6 dichloroindophenol titrimetric method. In *Official methods of analysis of the association of official analytical chemists* (pp. 844–845).

Benzon, H. R. L., & Lee, S. C. (2016). Potential of wood vinegar in enhancing fruit yield and antioxidant capacity in tomato. *Korean Journal of Plant Resources*, 29(6), 704–711.

Beyene, N., & Mulu, T. (2019). Effect of different level of nitrogen fertilizer on growth, yield and yield component of tomato (lycopersicon esculentum mill.) at West Showa Zone, Oromia, Ethiopia. *World Journal of Agricultural Sciences*, 15(4), 249–253.

Bhattarai, S. P., Su, N., & Midmore, D. J. (2005). Oxygation unlocks yield potentials of crops in oxygen-limited soil environments. *Advances in Agronomy*, 88, 313–377.

Birhanu, K., & Tilahun, K. (2010). Fruit yield and quality of drip-irrigated tomato under deficit irrigation. *African Journal of Food, Agriculture, Nutrition and Development*, 10(2), 2139–2151.

Chen, X., Ma, Y. F., Fang, G. Z., Chu, G. X., Yang, J. R., Xue, L., Li, Y., & Wang, J. J. (2006). Preliminary study on the influence of soil moisture on yield and quality of processed tomato. *Water Saving Irrigation*, 4, 1–4.

Cheng, M., Wang, H., Fan, J., Xiang, Y., Tang, Z., Pei, S., Zeng, H., Zhang, C., Dai, Y., Li, Z., & Zhang, F. (2021). Effects of nitrogen supply on tomato yield, water use efficiency and fruit quality: A global meta-analysis. *Scientia Horticulturae*, *290*, Article 110553.

deCastro Paixão, A. C., Netto, R. A. C., & Marenco, R. A. (2022). Severity of target spot and gas-exchange in tomato cultivated under colored films. *Revista Ceres*, 69(5), 553–538.

Degefa, G., Benti, G., Jafar, M., Tadesse, F., & Berhanu, H. (2019). Effects of intra-row spacing and n fertilizer rates on yield and yield components of tomato (Lycopersicon Esculentum L.) at Harawe, Eastern Ethiopia. *Journal of Plant Sciences*, 7(1), 8–12.

Dobermann, A. (2007). Nutrient use efficiency–measurement and management.*Proceedings of the International Fertilizer Industry Association (IFA) Workshop on Fertilizer Best Management Practices*, 7–9 March 2007, Brussels, 1–28.

Drobek, M., Frąc, M., & Cybulska, J. (2019). Plant biostimulants: Importance of the quality and yield of horticultural crops and the improvement of plant tolerance to abiotic stress—A review. *Agronomy*, 9(6), Article 335.

Du, Q., Zhang, D., Jiao, X., Song, X., & Li, J. (2018). Effects of atmospheric and soil water status on photosynthesis and growth in tomato. *Plant, Soil & Environment*, 64(1), 13–19.

Du, Y., Niu, W., Zhang, Q., Cui, B., Zhang, Z., Wang, Z., & Sun, J. (2021). A synthetic analysis of the effect of water and nitrogen inputs on wheat yield and water-and nitrogen-use efficiencies in China. *Field Crops Research*, 265, Article 108105.

Etissa, E., Dechassa, N., Alamirew, T., Alemayehu, Y., & Desalegn, L. (2013). Growth and yield components of tomato as influenced by nitrogen and phosphorus fertilizer applications in different growing seasons. *Ethiopian Journal of Agricultural Sciences*, 24(1), 57–77.

Gheshm, R., & Brown, R. N. (2018). Organic mulch effects on high tunnel lettuce in southern New England. *HortTechnology*, 28(4), 485–491.

Gil-Ortiz, R., Naranjo, M. Á., Atares, S., & Vicente, O. (2023). Antioxidant responses of water-stressed cherry tomato plants to natural biostimulants. *Agronomy*, 13(9), 2314.

Gragn, T., Mamo, A., & Wolde, O. (2023). Evaluation of tomato (Solanum Lycopersicum L.) response to deficit irrigation at Adola District, Guji Zone, Southern Ethiopia. *Science Research*, 11(5), 117–122.

Hao, Q., Shang, W., Zhang, C., Chen, H., Chen, L., Yuan, S., Chen, S., Zhang, X., & Zhou, X. (2016). Identification and comparative analysis of CBS domain-containing proteins in soybean (Glycine max) and the primary function of GmCBS21 in enhanced tolerance to low nitrogen stress. *International Journal of Molecular Sciences*, 17(5), 620.

Hatfield, J. L., & Dold, C. (2019). Water-use efficiency: Advances and challenges in a changing climate. *Frontiers in Plant Science*, 10, Article 429990.

Iqbal, M., Niamatullah, M., Yousaf, I., Munir, M., & Khan, M. Z. (2011). Effect of nitrogen and potassium on growth, economical yield and yield components of tomato. *Sarhad Journal of Agriculture*, 27(4), 545–548.

Jamiolkowska, A., Thanoon, A. H., Patkowska, A., & Grzadziel, J. (2019). Impact of AMF Claroideoglomus etunicatum on the structure of fungal communities in the tomato rhizosphere. *Acta Mycologica*, 54(1), 1120. https://doi. org/10.5586/am.112.

Kenul, A. (2018). Influence of different nitrogen norms on the collection of nutrients in tomato plant in the background of organic fertilizers. *Бюллетень науки и практики*, 4(4), 109–114.

Kirimi, J. K., Itulya, F. M., & Mwaja, V. N. (2011). Effects of nitrogen and spacing on fruit yield of tomato. *African Journal of Horticultural Science*, 5, 50–60.

Lee, I. B., Lim, J. H., & Park, J. M. (2007). Effect of reduced nitrogen fertigation rates on growth and yield of tomato. *Korean Journal of Environmental Agriculture*, 26(4), 306–312.

Li, H. S. (2000). *The principle and technology of plant physiology and biochemistry experiment* (pp., 184, 192–94). Higher Education Press.

Li, H. S., Liu, H., Gong, X., Li, S., Pang, J., Chen, Z., & Sun, J. (2021). Optimizing irrigation and nitrogen management strategy to trade off yield, crop water productivity, nitrogen use efficiency and fruit quality of greenhouse grown tomato. *Agricultural Water Management*, 245, Article 106570.

Lianfu, Z., & Xiaolin, D. (2001). Establishment of a new lycopene determination method. *Food and Fermentation Industries*, 27(3; 159), 51–55.

Lu, J., Shao, G., Cui, J., Wang, X., & Keabetswe, L. (2019). Yield, fruit quality and water use efficiency of tomato for processing under regulated deficit irrigation: A meta-analysis. *Agricultural Water Management*, 222, 301–312.

Matos, R. M., da Silva, P. F., Neto, J. D., de Lima, A. S., Antunes, de, Lima, V. L., & Falle Saboya, L. M. (2021). Organic fertilization as an alternative to the chemical in cherry tomato growing under irrigation depths. *Bioscience Journal*, 37(1). e37006. https://doi.org/10.14393/BJ-v37n0a2021-48270

Mebrahtu, Y., Mohammed, A., & Tamiru, H. (2020). Response of Tomato (Solanum lycopersicum) to deficit irrigation in Raya Valley, Northern Ethiopia. *Results of Natural Resources Management Research* 6(1): 33–39.

Muhamad-Hassan, M. H., Awang, Y., Jaafar, J. N., Sayuti, Z., Othman Ghani, M. N., Mohamad Sabdin, Z. H., & Nazli, M. H. (2022). Effects of salinity sources on growth, physiological process, yield, and fruit quality of grafted rock melon (Cucumis melo L.). *Pertanika Journal of Tropical Agricultural Science* 45(4), 919–941.

Muroyiwa, G., Mashonjowa, E., Mhizha, T., & Muchuweti, M. (2023). The effects of deficit irrigation on water use efficiency, yield and quality of drip-irrigated tomatoes grown under field conditions in Zimbabwe. *Water SA*, 49(4), 363–373.

Niu, W. Q., Jia, Z. X., Zhang, X., & Shao, H. B. (2012). Effects of soil rhizosphere aeration on the root growth and water absorption of tomato. *CLEAN–Soil, Air, Water*, 40(12), 1364–1371.

Ogundare, S. K., Oloniruha, J. A., Ayodele, F. G., & Bello, I. A. (2015). Effect of different spacing and urea application rates on fruit nutrient composition, growth and yield of tomato in derived savannah vegetation of Kogi state, Nigeria. *American Journal of Plant Sciences*, 6(14), 2227-2233.

Oprea, M. I., Giosanu, D., Bratu, I. G., & Vulpe, M. (2022). Determining the amounts of nitrites and nitrates from five varieties of tomatoes grown in a classic and ecological system. University of Pitesti publishing, *Current Trends in Natural Sciences* 11(22), 220–223.

Qiang, Z., Fei, X. U., Rong-fu, W. A. N. G., Liang-zuo, S. H. U., Rui, L. I. U., & De-yu, Z. H. A. N. G. (2014). Effects of nitrogen forms on the growth, yield and fruit quality of tomato under controlled alternate partial root zone irrigation. *Yingyong Shengtai Xuebao*, 25(12), 3547–3555.

Sainju, U. M., Ghimire, R., & Pradhan, G. P. (2019). Nitrogen fertilization I: Impact on crop, soil, and environment. *Nitrogen Fixation*, 9, 1–9.

Sarker, M., Choudhury, S., Islam, N., Zeb, T., Zeb, B., & Mahmood, Q. (2020). The effects of climatic change mediated water stress on growth and yield of tomato. *The Central Asian Journal of Environmental Science and Technology Innovation*, 1(2), 85–92.

Shewangizaw, B., Kassie, K., Assefa, S., Lemma, G., Gete, Y., Getu, D., Getanh, L., Shegaw, G., & Manaze, G. (2024). Tomato yield, and water use efficiency as affected by nitrogen rate and irrigation regime in the central low lands of Ethiopia. *Scientific Reports*, 14(1), Article 13307.

Sibomana, I. C., Aguyoh, J. N., & Opiyo, A. M. (2013). Water stress affects growth and yield of container grown tomato (Lycopersicon esculentum Mill) plants. *GJBB*, 2(4), 461–466.

Singh, B., Singh, K., Talwar, D., Jindal, S. K., & Sardana, V. S. (2018). Influence of bio- fertilizers on growth and yield attributing attributes in tomato. *International Journal of Current Microbiology and Applied Sciences*, 7(4), 3686–3694.

Sitaula, H. P., Dhakal, R., Bhattarai, C., Aryal, A., & Bhandari, D. (2020). Effects of different combinations of poultry manure and urea on growth, yield and economics of garlic (Allium sativum L.). *Journal of Agriculture and Natural Resources*, 3(1), 253–264.

Sobrinho, O. P. L., dos Santos, L. N. S., Soares, F. A. L., Cunha, F. N., Vidal, V. M., & Teixeira, M. B. (2022). General aspects of tomato culture and phosphate fertilization: A systematic review. *Comunicata Scientiae*, 13, e3369.

Tesfay, T., Berhane, A., & Gebremariam, M. (2019). Optimizing irrigation water and nitrogen fertilizer levels for tomato production. *The Open Agriculture Journal*, 13(1), 13–198.

Ullah, I., Mao, H., Rasool, G., Gao, H., Javed, Q., Sarwar, A., & Khan, M. I. (2021). Effect of deficit irrigation and reduced N fertilization on plant growth, root morphology and water use efficiency of tomato grown in soilless culture. *Agronomy*, 11(2), Article 228.

Wang, J., Du, Y., Niu, W., Han, J., Li, Y., & Yang, P. (2022). Drip irrigation mode affects tomato yield by regulating root–soil–microbe interactions. *Agricultural Water Management*, 260, Article 107188.

Wang, X., & Xing, Y. (2017). Evaluation of the effects of irrigation and fertilization on tomato fruit yield and quality: A principal component analysis. *Scientific Reports*, 7(1), Article 350.

Wu, Y., Yan, S., Fan, J., Zhang, F., Xiang, Y., Zheng, J., & Guo, J. (2021). Responses of growth, fruit yield, quality and water productivity of greenhouse tomato to deficit drip irrigation. *Scientia Horticulturae*, 275, Article 109710.

Yang, H., Du, T., Qiu, R., Chen, J., Wang, F., Li, Y., Wang, C., Gao, L., & Kang, S. (2017). Improved water use efficiency and fruit quality of greenhouse crops under regulated deficit irrigation in northwest China. *Agricultural Water Management*, 179, 193–204.

Yousafi, Q., Bibi, S., Saleem, S., Hussain, A., Hasan, M. M., Tufail, M., Qandeel, A., Khan, M.S., Mazhar, S., Yousaf, M., & Kabra, A. (2022). Identification of novel and safe fungicidal molecules against fusarium oxysporum from plant essential oils: In vitro and computational approaches. *BioMed Research International*, 2022(1), Article 5347224.

Zhang, M. Z., Niu, W. Q., Bai, Q. J., Li, Y., Wang, J. W., Wang, Z. Q., & Zhang, Z. X. (2020). Improvement of quality and yield of greenhouse tomato (Solanum lycopersicum L.) plants by micro-sprinkler irrigation under plastic film. *Applied Ecology & Environmental Research*, 18(5), 6902–6926.