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Research Article

Integrating soil mulching and subsurface irrigation for optimizing deficit irrigation effectiveness as a water-rationing strategy in tomato production

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Abstract

Irrigated agriculture from now on should be implemented under water scarcity. Hence, this research was designed to determine the optimal interaction between irrigation water-rationing strategy (deficit irrigation), irrigation techniques, and soil mulching to improve water use efficiency and maintaining plant performance as well as yield productivity of tomatoes. The experiment was set up during the 2020-2021 and 2021-2022 growing seasons. Three factors were studied: two drip irrigation techniques, surface (SI) and subsurface (SSI) irrigation, and two irrigation rates, 100% ETc for full irrigation (FI) and 60% ETc for deficit-irrigation (DI) along with three treatments of soil mulching, bare soil (BS), organic mulch (OrM) and black polyethylene mulch (BPE). The results demonstrated that applying the absolute regular DI regime significantly reduced vegetative growth, fruit yield, and yield component along with water productivity. Also, it reduced the physiological function measures, and nutrient content of the tomato leaf. Meanwhile, applying the DI regime via the SSI technique and integrated with BPE soil mulching proved the best optimization of the DI negative effect followed by applying the DI regime through either SSI or SI technique combined with OrM or BPE soil mulching, respectively. As a result, it is advisable to use the integration of DI via the SSI accompanied by BPE soil mulching since this is considered a good method for conserving irrigation water from being lost by both evaporation and seepage out of the root zone improving water use efficiency without significantly reducing tomato yield.

Keywords: soil mulching; subsurface irrigation; tomato; water use efficiency; water saving; yield

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Introduction

Tomato (*Solanum lycopersicum* L) is a popular vegetable and widely consumed throughout the world due to its higher nutritional value, particularly its content of lycopene, vitamin C, and vitamin B (Hedges and Lister, 2005). According to FAO statistics, 186.82 million metric tons of fresh tomatoes were produced worldwide in 2020. Egypt ranks fifth in tomato production after China, India, Turkey, and the United States (MALR, 2018; FAO, 2022). Water is an essential component for agricultural production and a requirement for ensuring food security. Improving water efficiency is an ongoing objective in agricultural production. Howell (2001) provided several strategies for improving irrigation water use efficiency in irrigated agriculture, including the management of engineering and agronomic aspects: demand-based irrigation scheduling, uniform irrigation water distribution, reducing water loss, limiting the movement of water away from the root zone, and using a slight to moderate deficit irrigation to encourage deeper soil water extraction along with agronomic and botanical factors that raise crop productivity.

The subsurface drip irrigation approach (SSI) is becoming more common among agronomists since it enables the crop to be "spoon-fed" for water and nutrients, which are added directly to the plant's root zone (Wang *et al*., 2022; Yang *et al*., 2022). The SSI technique also greatly improves water use efficiency by reducing water waste from runoff, deep percolation, wind drift, and soil evaporation (Camp *et al*., 2000; Mati, 2011; Sheta and Fayed, 2021; Abdelbaset *et al*., 2023). According to Abdelhady *et al*. (2017) and Ragab *et al*. (2018), applying the SSI technique via drip irrigation improved tomato growth, yield, fruit quality, and water use efficiency when compared to the SI technique, whether using full or deficit irrigation. Furthermore, tomato plants used N, P, and K fertilizers more effectively under the SSI drip irrigation technique than under the SI drip irrigation technique. In line with this, Al-Mansor *et al*. (2015) showed that using SSI on tomatoes increased water use efficiency and decreased the adverse effects of either severe or moderate deficit irrigation compared to SI, which utilized the same watering amount. Irrigation and soil moisture levels have a substantial impact on the growth and productivity of tomato plants (Dawa *et al*., 2019). According to Yang *et al*. (2022), regulated deficit irrigation is one of the most successful approaches for reducing water waste and increasing water use efficiency while maintaining the quality of agricultural products. Deficit irrigation, a strategy for conserving irrigation water, uses less water than is needed to irrigate the crop, improving quality while slightly reducing yield (El-Labad *et al*., 2019). According to Bogale *et al*. (2016), when tomatoes received 50% of the full irrigation, the yield dropped by 24-38%. While Wang and Xing (2017) showed that deficit irrigation of tomatoes at a rate of 75% ETo (the reference crop evapotranspiration) increased water use efficiency, lycopene, and vitamin C by approximately 7.25%, 26.87%, and 17.68%, respectively when compared to irrigation by a 100% ETo rate. Furthermore, tomato yield, water productivity, and various nutritional quality indices of the fruit can be significantly improved by increasing watering frequency while using the same amount of irrigation water (Liu *et al*., 2019).

Water evaporation from the soil surface and transpiration from the crop canopy are the main ways of losing water from the soil. So, Allen *et al*. (1998) developed the widely used method for estimating reference crop evapotranspiration (ETo) by which irrigation water requirements are calculated. Most of the soil surface is not covered by the crop canopy for the majority of the growing season. Thus, applying agronomic practices that cover the soil surface to minimize or prevent soil water evaporation will conserve water, and this will have a notable impact on the soil water budget, which is crucial for agriculture. Many techniques were tested to increase crop productivity and the efficiency of water use by reducing soil moisture loss or maintaining moisture in the soil (Mahadeen, 2014). These techniques include mulching the soil, adding organic matter to the soil, and designing irrigation systems. Soil mulch is considered a more efficient and common treatment for preventing water evaporation. Implementing soil mulching involves covering the soil's surface with polyethylene sheets and/or organic material. According to Singh and Kamal (2012), compared to bare soil, using black plastic sheets as soil mulch increased tomato yield from 20.7 to 29.8%. Additionally, He *et al*. (2023)

reported that, compared to the conventional cultivation system using bare soil, the water use efficiency of pepper and eggplant was 54.9-59.7% higher under the cultivation system involving plastic mulch on the soil.

Tomato production is a vital component of global agriculture, providing a nutritious and versatile fruit. However, the cultivation of tomatoes requires substantial amounts of water, making it imperative to explore innovative techniques to optimize water use efficiency. This article delves to determine the most effective combination of irrigation water-rationing strategy, deficit irrigation, with agronomic practices for conserving water and maximizing water use efficiency without significantly affecting tomato productivity. This was accomplished by combining surface or subsurface drip irrigation techniques and soil mulching in conjunction with a deficit irrigation approach.

Materials and Methods

Plant material, experimental methods, and design

The experiment was performed in Shoubra El-Khima region, Qalyoubia Governorate (30° 5' 10" N latitude, 31° 12' 44" E longitude, and 70 m altitude) at the experimental and training farm of the Hort. Department, Faculty of Agriculture, Ain Shams University in the 2020-2021 and 2021-2022 growing seasons. Before implementing the experiment, soil properties were determined by collecting soil samples and analysing them. Table 1 displays the in-situ measurements of soil-water field capacity (FC) and wilting point (WP) at the soil. The USDA textural triangle, for soil taxonomy, classified the soil as clay loam. The extract of saturated soil paste has an electrical conductivity of 0.42 dS/m and a pH of 7.7.

Tomato seedlings (*Solanum lycopersicum* L) of the 'Salimia 65010' cultivar, imported by the Egyptian company G.S.I. Technogreen Corporation were transplanted on September 1 and September 6, respectively, for the 2020-2021 and 2021-2022 growing seasons. Three factors were utilized throughout the experiment: the first was an irrigation schedule based on crop evapotranspiration (ETc), which included deficit irrigation applied by irrigation at 60% of ETc and full irrigation applied by irrigation at 100% of ETc. All the irrigation rates were applied through all stages of the crop cycle. The second factor was irrigation methods like surface and subsurface irrigation using the drip irrigation technique. The drip irrigation system was installed using built-in dripper hoses (GR), which have drippers spaced 30 cm apart and discharge 4 liters of water every hour. In the surface irrigation method, the hoses were placed on the soil surface, while in the subsurface irrigation method, the hoses were buried 0.2 meters deep in the center of the row. The third factor was soil mulching with two types of soil mulch materials: organic mulch material (shredded waste paper) and black polyethylene film, along with the control, which was soil with no mulch (bare soil).

The FAO Penman-Monteith approach (Allen et al., 1998) was used to estimate the daily reference evapotranspiration (ETo) using the "ETo Calculator" software (FAO, 2022). Although the applied crop coefficient (Kc) values were the same as those specified for tomato crops by Allen *et al.* (1998), the lengths of the tomato growth stages varied based on the actual data obtained from the experiment (Table 2). The soil water content was monitored daily for each plot at a depth of 30 cm under the soil surface using a PMS-714 Lutron soil moisture meter (Lutron Electronic). The watering schedule for each day was determined using this data. So, the amount of irrigation water per feddan (4200 m^2) consumed for the growing seasons of 2020-2021 and 2021-2022, respectively, was 3200 m^3 and 3000 m^3. The experiment was established using a split-plot experimental design, it included 12 treatments: two watering schedules, two irrigation techniques, and three soil mulching treatments. The two watering schedules were placed in the main plots however, the combination of irrigation techniques and soil mulch treatments was placed in the sub-main plots. All treatments were replicated three times. Each subplot included three 5-meter-long cultivation rows.

Table 1. Soil characteristics of the experimental site

Element	Quantity
Sand (%)	36.25
Clay (%)	37.5
Silt (%)	36.2
Class of Texture	clay loam
Field Capacity (%)	37.3
Wilting Point (%)	23.2
Organic matter (%)	1.5
ECe (dS m^{-1})	0.42
pH	7.7

The soil was plowed twice, then the beds were raised. After establishing the irrigation system, soil mulching was installed. For seedling transplantation, irrigation was carried out to the point of soil saturation, and the seedlings were then planted on top of the beds, above the buried irrigation hoses in subsurface-irrigated plots, and beside the hoses in surface-irrigated plots. Plants in a row were placed 0.5 meters apart, and rows were separated by 1.2 meters. There are three 5-meter-long rows on each experimental plot. For the seasons of 2020-2021 and 2021-2022, the harvest began on December 20 and 25, respectively. Except for irrigation, all agronomic practices were followed as recommended by the Egyptian Ministry of Agriculture.

Table 2. Tomato growth stages in days with and without soil mulching

Growth stage	Length of stage (day)	Crop coefficients
Establishment	15	0.45
Flowering	15	0.45
Fruit set	40	0.75
Maturity	30	1.15
Harvesting	30	0.9
Total	130	

Measurement of plant growth

Shoot and root

A sample of five plants was collected randomly from the middle row of each experimental plot after 40 days of planting at the flowering onset stage, to measure the vegetative parameters. These plants were uprooted and then subjected to measuring the plant length and the number of branches per plant. The plants from the collected samples were divided into shoots and roots, which were then dried separately at 70 °C in an aerated oven until the weight became constant. The dry weight of the plant shoot and root, and consequently the root-to-shoot ratio, were recorded.

Leaf physiology and nutrient content

Chlorophyll content

The fourth leaf from the tip of the plant's main stem that was still attached was used to measure the relative chlorophyll content (leaf greenness). The values shown were the average of five leaves from various plants for each experimental plot. The Konica Minolta SPAD-502 Plus device, Tokyo, Japan was used to measure this element as SPAD reading.

Leaf Relative Water Content (LRWC)

In assessing the relative water content (RWC) of the leaves, 10 leaf discs with a diameter of 2 cm were weighed to measure the fresh weight (FW). The leaves were then placed in distilled water for 24 hours inside a covered petri dish to determine the turgid weight (TW). Following this, the samples underwent oven-drying at 70°C for a period of 48 to 72 hours to establish their dry weight (DW). Consistent with the methodology outlined by Smart and Bingham (1974), the obtained values were employed in the calculation of RWC using the provided equation:

RWC (%) = (FW–DW)/(TW–DW)×100.

<u>Leaf stomatal conductance (LSC)</u>

According to Kim *et al*. (2004), the portable leaf porometer device was used to measure the leaf stomatal conductance (LSC) on five fully grown leaves recently for each experimental plot at 30 and 40 days from planting. The average of the two LSC readings formed the displayed LSC values in mmol/m^2s units.

Determination of nitrogen, phosphorus, and potassium (NPK)

Nitrogen, phosphorus, and potassium (NPK) content were measured in leaves digested solution. In each experimental plot, ten leaves from various plants, the 4^{th} leaf from the main stem tip, were selected for the N, P, and K elements analysis. The leaf samples were dried at 70 °C until they reached a constant weight, and then they were ground into a fine powder that could pass through a 1 mm sieve. The powder was then wet digested, according to Thomas *et al*. (1967), using 0.1 g of sulfuric acid (98%) and 30% hydrogen peroxide. In the digested solution, the mineral content of the leaves was measured. The Kjeldahl method, as described by Fixen and Grove (1990), was used to calculate the total nitrogen. According to AOAC (2005), the ascorbic acid method was used to calorimetrically measure the amount of phosphorus in the sample using a spectrophotometer. According to Knudsen et al. (1982), potassium was measured using a flame photometer.

Yield, fruit quality and water productivity

At the end of the growing season, ripe fruits had been picked five times in four weeks. Based on the fruits produced by five plants per experimental plot, data on fruit count, average fruit weight, and yield per plant were estimated. Only consumable fruit was used to estimate this fruit data.

Yield per feddan was estimated by multiplying the number of plants per feddan by the average fruit yield per plant.

Yield reduction percent was calculated by comparing the yield of each treatment to the yield of the control treatment which was planted in bare soil and received a full rate through the surface irrigation method.

Water productivity was determined by dividing the fruit yield per feddan by the amount of irrigation water consumption (m^3) in the same area over the growing season.

Experimental data statistical analysis

The test of analysis of variance (ANOVA) was used for statistical assessment of the significance of applied treatments' effect on tomato plant growth, leaf physiology and nutrient content, yield, fruit quality, and water productivity variables. The least significant difference (LSD) was used to compare means. The computer package program, Co Stat software for Windows, was used to analyze the collected data using analysis of variance. The significance of applied treatments' effect on variables means was assessed using Duncan's Multiple Range tests. To compare the treatment means, the least significant difference (LSD) test was run at a 5% level of probability (Gomez and Gomez, 1984).

Results

Effect of irrigation scheduling, irrigation technique, and soil mulching on tomato plants vegetative measurements

The data in Tables 3 and 4 display how tomato plants respond to the main effect and first-order interaction effects of the experimental factors, irrigation scheduling (rate) based on ETc (deficit irrigation (DI) and full irrigation (FI)), irrigation method (surface drip irrigation (SI) and subsurface drip irrigation (SSI)), and soil mulching treatments (bare soil (BS), organic mulched soil (OrMS) and black polyethylene mulched soil, (BPMS)). The irrigation rate has a significant impact on the vegetative growth of the tomato plants. Therefore, according to the ANOVA test, the plant length, number of branches, shoot fresh and dry weight, and root dry weight, but not the root-to-shoot ratio, all recorded higher values with FI rate than with DI rate. Regarding the impact of irrigation techniques SI and SSI on the behavior of tomato plants during vegetative growth, the SSI technique resulted in more vigorous plants that appeared longer owned more branches, and held heavier shoots and roots compared to the SI technique. The root-to-shoot ratio did not differ between the SI and SSI methods. These vegetative measurements recorded significantly different values with the three soil mulching treatments. The BPMS treatment, followed by the OrMS treatment, produced the plants with the highest length, number of branches, fresh and dry shoot weight, dry root weight, and root-to-shoot ratio measurements. By planting the tomato in the BS, the lowest values of all plant variables were recorded. Data on the interaction between irrigation rate and method demonstrate that except for the root-to-shoot ratio, plants that received FI rate or DI rate via the SSI method outperformed those that received the same irrigation rates via the SI method. However, the plants that received the FI rate via the SSI method had better vegetative status, whereas the plants that received the DI rate via the SI method had the least vegetative status. Higher root-to-shoot ratio values appeared to be more closely associated with the irrigation rate, DI, than the irrigation methods, SI and SSI. As for the first-order interaction, the interaction between irrigation rates FI and DI, and soil mulching treatments, BS, OrMS, and BPMS, the data proved that the values of vegetative variables except root-to-shoot ratio were better in all soil mulching treatments with FI rate than their counterparts under DI rate. The OrMS or BPMS when each was combined with the FI rate recorded the lowest root-to-shoot ratio, whereas the BPMS combined with DI rate recorded the highest root-to-shoot ratio. The collected data on the earlier plant vegetative variables documented significant changes due to the first-order effects of irrigation methods, SI and SSI, integrated with soil mulching treatments, BS, OrMS, and BPMS. The lower values of these parameters were noted to be coupled with the SI method in BS, while the higher values were recorded with the SSI method plus BPMS treatment. However, the root-to-shoot ratio was higher in the BS plants that were irrigated via surface irrigation (SI). The data was consistent between the two growing seasons.

Table 3. Effect of irrigation scheduling (full and deficit), irrigation method (surface and subsurface), and soil mulching on tomato vegetative growth during the 2020-2021 growing season

Treatments		Plant length (cm)	No. of branches	Shoot fresh weight (gm.)	Shoot dry weight (gm.)	Root dry weight (gm.)	Root to shoot ratio
Irrigation rate							
Full irrigation		79.03 a	7.90 a	1288.9 a	136.49 a	26.43 a	19.42 b
Deficit irrigation		55.49 b	6.02 b	820.6 b	74.72 b	21.56 b	29.09 a
Irrigation method (type)							
Surface irrigation		63.03 b	6.39 b	965.8 b	97.12 b	22.79 b	25.29 a
Subsurface irrigation		71.49 a	7.52 a	1043.6 a	114.09 a	25.23 a	23.22 b
Soil mulching							
Non-mulched soil		61.01 c	6.43 c	966.3 c	99.22 c	23.06 c	24.69 a
Organic-mulched soil		67.89 b	6.93 b	1059.6 b	105.66 b	23.79 b	24.08 b
Black PE-mulched soil		72.89 a	7.51 a	1138.3 a	111.94 a	25.14 a	23.99 b
Irrigation rate × irrigation method (type)							
Full irrigation	Surface irrigation	76.07 b	7.61 b	1211. 7 b	130.38 b	25.99 b	19.96 c
	Subsurface	81.99 a	8.19 a	1366.1 a	142.59 a	26.88 a	18.88 d
Deficit irrigation	Surface irrigation	50.00 d	5.18 d	720.0 d	63.86 d	19.53 d	30.62 a
	Subsurface	60.99 c	6.86 c	921.1 c	85.59 c	23.59 c	27.56 b
Irrigation rate × Soil mulching							
Full irrigation	Non-mulched soil	74.49 c	7.25 c	1187.5 c	128.19 c	25.85 c	20.19 b
	Organic-mulched	79.27 b	7.98 b	1296.7 b	137.53 b	26.42 b	19.22 c
	Black PE-mulched	83.34 a	8.47 a	1382.5 a	143.75 a	27.03 a	18.84 c
Deficit irrigation	Non-mulched soil	47.54 f	5.62 e	745.0 f	70.25 f	20.28 f	29.19 a
	Organic-mulched	56.52 e	5.88 e	822.5 e	73.78 e	21.16 e	28.93 a
	Black PE-mulched	62.44 d	6.55 d	894.2 d	80.14 d	23.25 d	29.14 a
Irrigation method (type) × Soil mulching							
Surface irrigation	Non-mulched soil	57.64 e	5.23 e	863.4 e	89.73 f	21.59 e	25.89 a
	Organic-mulched	63.70 d	5.77 d	980.0 d	97.13 e	22.36 d	25.00 b
	Black PE-mulched	67.77 c	6.52 c	1054.2 c	104.49 d	24.33 c	24.97 b
Subsurface irrigation	Non-mulched soil	64.39 d	6.89 b	1069.2 c	108.70 c	24.54 c	23.49 c
	Organic-mulched	72.09 b	7.14 b	1139.2 b	114.18 b	25.22 b	23.16 c
	Black PE-mulched soil	78.00 a	7.62 a	1222.5 a	119.40 a	25.94 a	23.01 c

All means in the column followed by the same letter are not significantly different at P≥5 %

Table 4. Effect of irrigation scheduling (full and deficit), irrigation method (surface and subsurface), and soil mulching on tomato vegetative growth during the 2021-2022 growing season

Treatments		Plant length (cm)	No. of branches	Shoot fresh weight (gm.)	Shoot dry weight (gm.)	Root dry weight (gm.)	Root to shoot ratio
Irrigation rate							
Full irrigation		75.63 a	7.16 a	1204.51 a	134.91 a	25.06 a	18.65 b
Deficit irrigation		54.45 b	6.11 b	825.63 b	74.79 b	20.60 b	27.83 a
Irrigation method (type)							
Surface irrigation		61.23 b	6.32 b	943.16 b	95.96 b	21.71 b	24.38 a
Subsurface irrigation		68.84 a	6.95 a	1086.98 a	113.74 a	23.95 a	22.10 b
Soil mulching							
Non-mulched soil		59.41 c	6.35 c	943.50 c	98.00 c	21.96 c	23.85 a
Organic-mulched soil		65.60 b	6.62 b	1019.00 b	104.56 b	22.65 b	23.22 b
Black PE-mulched soil		70.10 a	6.94 a	1082.71 a	112.00 a	23.88 a	22.64 c
Irrigation rate × irrigation method (type)							
Full irrigation	Surface	72.96 b	7.00 b	1142.04 b	128.31 b	24.81 b	19.37 c
	Subsurface	78.29 a	7.32 a	1266.98 a	141.52 a	25.31 a	17.92 d
Deficit irrigation	Surface	49.50 d	5.65 d	744.28 d	63.62 d	18.61 d	29.39 a
	Subsurface	59.39 c	6.58 c	906.98 c	85.96 c	22.59 c	26.28 b
Irrigation rate × Soil mulching							
Full irrigation	Non-	71.54 c	6.80 c	1122.49 c	126.22 c	24.52 c	19.48 c
	Organic-	75.84 b	7.21 b	1210.80 b	136.07 b	25.15 b	18.52 d
	Black PE-	79.50 a	7.47 a	1280.24 a	142.46 a	25.51 a	17.96 e
Deficit irrigation	Non-	47.28 f	5.89 e	764.51 f	69.77 f	19.40 f	28.23 a
	Organic-	55.37 e	6.04 e	827.21 e	73.04 e	20.15 e	27.93 a
	Black PE-	60.69 d	6.41 d	885.18 d	81.55 d	22.24 d	27.33 b
Irrigation method (type) × Soil mulching							
Surface irrigation	Non-	56.37 e	5.96 e	860.24 e	87.69 f	20.56 e	25.28 a
	Organic-	61.83 d	6.32 d	954.62 d	95.17 e	21.38 d	24.47 b
	Black PE-	65.49 c	6.70 c	1014.62 c	105.03 d	23.19 c	23.39 c
Subsurface irrigation	Non-	62.45 d	6.73 c	1026.76 c	108.30 c	23.36 c	22.42 d
	Organic-	69.38 b	6.93 b	1083.39 b	113.94 b	23.92 b	21.98 de
	Black PE-	74.70 a	7.19 a	1150.80 a	118.97 a	24.57 a	21.89 e

All means in the column followed by the same letter are not significantly different at P≥5 %

Data in Tables 5, and 6 show the behavior of tomato plants in two successive growing seasons, 2020-2021 and 2021-2022, is significantly influenced by the second-order interaction of irrigation scheduling based on ETc (DI) and (FI), irrigation method (SI) and s (SSI) and soil mulching treatments (BS), (OrMS) and (BPMS). The plants irrigated by FI rate using the SSI method in the BPMS treatment showed the highest values for plant length, number of branches, shoot fresh and dry weight, and root dry weight, but not for the root-to-shoot ratio. Otherwise, plants irrigated with DI rate using the SI method in the BS treatment induced the lowest values of these variables. The plants that were irrigated by DI rate using the SI method had the highest root-to-shoot ratio, regardless of the soil mulching treatment.

Table 5. Effect of second order interaction of irrigation scheduling (full and deficit), irrigation method (surface and subsurface), and soil mulching on tomato vegetative growth during the 2020-2021 growing seasons

Treatments			Plant length (cm)	No. of branches	Shoot fresh weight (gm.)	Shoot dry weight (gm.)	Root dry weight (gm.)	Root to shoot ratio
Full irrigation	Surface irrigation	Non-mulched soil	72.60 e	6.83 de	1100.0 e	121.93 f	25.33 d	20.78 c
		Organic-mulched soil	76.43 d	7.73 b	1226.7 d	132.38 e	25.89 cd	19.56 d
		Black PE-mulched soil	79.17 c	8.27 a	1308.3 c	136.82 c	26.73 ab	19.54 d
	Subsurface irrigation	Non-mulched soil	76.37 d	7.67 bc	1275.0 cd	134.44 d	26.37 bc	19.61 d
		Organic-mulched soil	82.10 b	8.23 a	1366.7 b	142.67 b	26.95 ab	18.89 de
		Black PE-mulched soil	87.50 a	8.67 a	1456.7 a	150.68 a	27.32 a	18.14 e
Deficit irrigation	Surface irrigation	Non-mulched soil	42.67 j	4.63 g	626.7 j	57.53 l	17.84 j	31.00 a
		Organic-mulched soil	50.97 i	5.03 g	733.3 i	61.88 k	18.82 i	30.44 a
		Black PE-mulched soil	56.37 h	5.87 f	800.0 h	72.16 j	21.93 h	30.40 a
	Subsurface irrigation	Non-mulched soil	52.40 i	6.60 e	863.3 g	82.97 i	22.71 g	27.38 b
		Organic-mulched soil	62.07 g	6.73 e	911.7 g	85.69 h	23.49 f	27.42 b
		Black PE-mulched soil	68.50 f	7.23 cd	988.3 f	88.11 g	24.56 e	27.88 b

All means in the column followed by the same letter are not significantly different at P≥5 %

Table 6. Effect of second-order interaction of irrigation scheduling (full and deficit), irrigation method (surface and subsurface), and soil mulching on tomato vegetative growth during the 2021-2022 growing season

Treatments			Plant length (cm)	No. of branches	Shoot fresh weight (gm.)	Shoot dry weight (gm.)	Root dry weight (gm.)	Root-to-shoot ratio
Full irrigation	Surface irrigation	Non-mulched soil	69.84 e	6.57 de	1051.70 e	119.14 e	24.04 c	20.19 e
		Organic-mulched soil	73.29 d	7.07 b	1154.17 d	130.56 d	24.94 b	19.10 f
		Black PE-mulched soil	75.75 c	7.36 a	1220.24 c	135.23 c	25.46 a	18.83 f
	Subsurface irrigation	Non-mulched soil	73.23 d	7.03 bc	1193.28 cd	133.30 cd	25.01 b	18.76 f
		Organic-mulched soil	78.39 b	7.34 a	1267.43 b	141.58 b	25.37 a	17.93 g
		Black PE-mulched soil	83.25 a	7.59 a	1340.24 a	149.68 a	25.55 a	17.08h
Deficit irrigation	Surface irrigation	Non-mulched soil	42.9 j	5.35 g	668.77 j	56.25 i	17.09 i	30.38 a
		Organic-mulched soil	50.37 i	5.57 g	755.07 i	59.77 i	17.83 h	29.83 a
		Black PE-mulched soil	55.23 h	6.03 f	809.00 h	74.83 h	20.91 g	27.96 b
	Subsurface irrigation	Non-mulched soil	51.66 i	6.44 e	860.24 g	83.30 g	21.72 f	26.08 cd
		Organic-mulched soil	60.36 g	6.51 e	899.34 g	86.31 fg	22.47 e	26.04 d
		Black PE-mulched soil	66.15 f	6.79 cd	961.36 f	88.27 f	23.58 d	26.71 c

All means in the column followed by the same letter are not significantly different at P≥5 %

Effect of irrigation scheduling, irrigation technique, and soil mulching on tomato leaf physiological indicators and N, P and K nutrients content

Data in Tables 7, and 8 exhibit how the primary and first-order interactions of irrigation scheduling based on ETc (DI and FI) and irrigation method (SI and SSI), as well as soil mulching treatments (BS, OrMS and BPMS), affect tomato plant leaf health status in terms of greenness (SPAD reading), leaf relative water content (LRWC), stomatal conductance, and leaf content of nitrogen, phosphorus, and potassium. These characteristics were significantly higher with the FI rate than with the DI rate. It should be noted that irrigation using the SSI method was better at demonstrating a significant improvement in the plant leaf health criteria than irrigation using the SI method. In comparison to the BS treatment, planting the tomato in mulched soil significantly improves the plant's leaf health criteria. Moreover, mulching the soil with BPMS is superior to

OrMS treatment. The interaction of irrigation rate (FI and DI) and irrigation method (SI and SSI) had a significant effect on the tomato leaf health indicators. As a result, higher indicators were noted when applying the FI rate, usually via the SSI method and occasionally via the SI method. Meanwhile, when the DI rate was applied using the SI method, the lowest indicators were documented. As for the effect of a combination of irrigation rate and soil mulching treatments on tomato leaf health indicators, they were significantly affected. Better indicators were consequently seen when the FI rate was applied to soil mulched by BPMS. The lowest level of indicators was produced when using the DI rate in BS soil. The effect of the interaction of irrigation methods (SI and SSI) and soil mulching treatments on tomato leaf health indicators was found to have a crucial effect on these indicators. These indicators were enhanced well with the SSI method combined with BPMS mulched soil. The poor leaf health indicators were registered when the SI method was implemented in BS soil.

Table 7. Effect of irrigation scheduling (full and deficit), irrigation method (surface and subsurface), and soil mulching on tomato leaf greenness, relative water content (LRWC) and stomatal conductance as well as N, P and K content during the 2020-2021 growing season

Treatments		Greenness (SPAD)	LRWC	Stomatal conductance	N percent	P percent	K percent
Irrigation rate							
Full irrigation		46.68 a	92.61 a	103.90 a	0.396 a	0.197 a	0.662 a
Deficit irrigation		43.62 b	68.49 b	55.70 b	0.298 b	0.153 b	0.475 b
Irrigation method (type)							
Surface irrigation		44.62 b	78.38 b	77.17 b	0.338 b	0.169 b	0.539 b
Subsurface irrigation		45.68 a	82.72 a	82.43 a	0.356 a	0.181 a	0.598 a
Soil mulching							
Non-mulched soil		44.75 c	78.07 c	75.64 c	0.340 c	0.170 c	0.537 c
Organic-mulched soil		45.08 b	80.08 b	80.46 b	0.345 b	0.175 b	0.573 b
Black PE-mulched soil		45.64 a	83.50 a	83.31 a	0.357 a	0.180 a	0.597 a
Irrigation rate X irrigation method (type)							
Full irrigation	Surface irrigation	46.52 a	92.10 b	102.90 b	0.395 a	0.195 b	0.657 a
	Subsurface irrigation	46.85 a	93.11 a	104.91 a	0.398 a	0.199 a	0.668 a
Deficit irrigation	Surface irrigation	42.72 c	64.66 d	51.44 d	0.282 c	0.143 d	0.421 c
	Subsurface irrigation	44.52 b	72.33 c	59.96 c	0.315 b	0.163 c	0.528 b
Irrigation rate X Soil mulching							
Full irrigation	Non-mulched soil	46.52 a	91.65 c	101.92 c	0.395 a	0.196 b	0.655 b
	Organic-mulched soil	46.74 a	92.58 b	103.77 b	0.396 a	0.197 ab	0.663 ab
	Black PE-mulched soil	46.80 a	93.59 a	106.02 a	0.398 a	0.198 a	0.669 a
Deficit irrigation	Non-mulched soil	42.97 d	64.49 f	49.36 f	0.286 d	0.144 e	0.419 e
	Organic-mulched soil	43.43 c	67.58 e	57.14 e	0.294 c	0.154 d	0.482 d
	Black PE-mulched soil	44.47 b	73.42 d	60.61 d	0.316 b	0.161 c	0.524 c
Irrigation method (type) X Soil mulching							
Surface irrigation	Non-mulched soil	44.12 e	76.27 e	72.15 d	0.334 d	0.165 f	0.515 d
	Organic-mulched soil	44.62 d	78.53 d	78.14 c	0.339 c	0.169 e	0.548 c
	Black PE-mulched soil	45.14 c	80.34 c	81.23 b	0.342 c	0.173 d	0.554 c
Subsurface irrigation	Non-mulched soil	45.37 bc	79.87 c	79.13 c	0.347 b	0.175 c	0.559 c
	Organic-mulched soil	45.55 b	81.63 b	82.78 b	0.350 b	0.182 b	0.597 b
	Black PE-mulched soil	46.14 a	86.67 a	85.40 a	0.372 a	0.187 a	0.639 a

All means in the column followed by the same letter are not significantly different at P≥5 %

Table 8. Effect of irrigation scheduling (full and deficit), irrigation systems (surface and subsurface), and soil mulching on tomato leaf greenness, relative water content (LRWC) and stomatal conductance as well as N, P and K content during the 2021-2022 growing season

Treatments		Greenness (SPAD)	L RWC	Stomatal conductance	N percent	P percent	K percent
Irrigation rate							
Full irrigation		44.67 a	89.75 a	101.17 a	0.392 a	0.195 a	0.655 a
Deficit irrigation		42.65 b	70.70 b	54.03 b	0.295 b	0.151 b	0.470 b
Irrigation system (type)							
Surface irrigation		43.31 b	78.51 b	74.46 b	0.335 b	0.167 b	0.533 b
Subsurface irrigation		44.01 a	81.94 a	80.74 a	0.352 a	0.179 a	0.591 a
Soil mulching							
Non-mulched soil		43.39 c	78.26 c	74.02 c	0.336 c	0.168 c	0.531 c
Organic-mulched soil		43.62 b	79.86 b	78.33 b	0.341 b	0.173 b	0.566 b
Black PE-mulched soil		43.98 a	82.56 a	80.46 a	0.353 a	0.178 a	0.590 a
Irrigation rate X irrigation method (type)							
Full irrigation	Surface irrigation	44.56 a	89.35 b	100.36 b	0.390 a	0.193 b	0.650 a
	Subsurface	44.78 a	90.15 a	101.98 a	0.393 a	0.197 a	0.660 a
Deficit irrigation	Surface irrigation	42.06 c	67.67 d	48.57 d	0.279 c	0.141 d	0.417 c
	Subsurface	43.24 b	73.73 c	59.49 c	0.311 b	0.161 c	0.523 b
Irrigation rate X Soil mulching							
Full irrigation	Non-mulched soil	44.56 a	88.99 c	99.56 c	0.390 a	0.194 b	0.648 b
	Organic-mulched	44.70 a	89.73 b	101.06 b	0.391 a	0.195 ab	0.656 ab
	Black PE-mulched	44.75 a	90.52 a	102.89 a	0.393 a	0.196 a	0.662 a
Deficit irrigation	Non-mulched soil	42.22 d	67.53 f	48.48 f	0.282 d	0.142 e	0.414 e
	Organic-mulched	42.53 c	69.98 e	55.59 e	0.291 c	0.152 d	0.477 d
	Black PE-mulched	43.21 b	74.59 d	58.03 d	0.312 b	0.159 c	0.518 c
Irrigation method (type) X Soil mulching							
Surface irrigation	Non-mulched soil	42.98 e	76.84 e	70.01 e	0.330 d	0.163 f	0.510 d
	Organic-mulched	43.31 d	78.63 d	75.70 d	0.336 c	0.167 e	0.542 c
	Black PE-mulched	43.65 c	80.06 c	77.68 c	0.338 c	0.171 d	0.548 c
Subsurface irrigation	Non-mulched soil	43.80 bc	79.69 c	78.03 c	0.343 b	0.173 c	0.552 c
	Organic-mulched	43.92 b	81.09 b	80.95 b	0.346 b	0.179 b	0.590 b
	Black PE-mulched	44.31 a	85.06 a	83.23 a	0.368 a	0.184 a	0.632 a

All means in the column followed by the same letter are not significantly different at P≥5 %

The second-order interaction between the tested factors, irrigation rates, irrigation methods, and soil mulching material types (Tables 9, 10), shows pivotal changes in the tomato plant health indicators. When using the FI rate, tomato plants grown in BPMS, ORMS, or BS soil show no statistically significant difference from those grown in the same covered soil using both the SI and SSI methods for all parameters except leaf phosphorus content. However, it was best for planting tomato in BPMS-mulched soil, particularly when using the SI method. Otherwise, it is noted that using the SSI method to implement the DI rate is superior to doing so using the SI method. Also, soil mulching treatments under the SI method were effective compared to those under the SSI method. The non-ignored thing is that integration between the SSI method and mulching soil by BPMS is generally crucial in improving the leaf health criteria, especially when applying the DI rate. These outcomes were held true for both growing seasons, 2020-2021 and 2021-2022.

Table 9. Effect of second-order interaction of irrigation scheduling (full and deficit), irrigation method (surface and subsurface), and soil mulching on tomato leaf greenness, relative water content (LRWC) and stomatal conductance as well as N, P and K content during the 2020-2021 growing season

Treatments			Greenness (SPAD)	L RWC	Stomatal conductance	N percent	P percent	K percent
Full irrigation	Surface irrigation	Non-mulched soil	46.27 b	91.27 d	101.33 c	0.394 a	0.194 d	0.648 b
		Organic-mulched soil	46.60 ab	92.03 cd	102.62 bc	0.394 a	0.195 d	0.659 ab
		Black PE-mulched soil	46.70 ab	93.00 bc	104.74 b	0.396 a	0.196 cd	0.665 ab
	Subsurface irrigation	Non-mulched soil	46.77 ab	92.03 cd	102.50 bc	0.396 a	0.198 bc	0.663 ab
		Organic-mulched soil	46.87 a	93.13 b	104.92 ab	0.397 a	0.199 ab	0.667 ab
		Black PE-mulched soil	46.90 a	94.17 a	107.30 a	0.400 a	0.200 a	0.674 a
Deficit irrigation	Surface irrigation	Non-mulched soil	41.97 g	61.27 i	42.97 h	0.274 e	0.136 j	0.383 f
		Organic-mulched soil	42.63 f	65.03 h	53.65 g	0.284 d	0.143 i	0.437 e
		Black PE-mulched soil	43.57 e	67.67 g	57.71 f	0.288 d	0.149 h	0.444 e
	Subsurface irrigation	Non-mulched soil	43.97 de	67.70 g	55.75 fg	0.297 c	0.152 g	0.454 e
		Organic-mulched soil	44.23 d	70.13 f	60.63 e	0.303 c	0.164 f	0.527 d
		Black PE-mulched soil	45.37 c	79.17 e	63.50 d	0.343 b	0.173 e	0.604 c

All means in the column followed by the same letter are not significantly different at P≥5 %

Table 10. Effect of second order interaction of irrigation scheduling (full and deficit), irrigation method (surface and subsurface), and soil mulching on tomato leaf greenness, relative water content (LRWC) and stomatal conductance as well as N, P and K content during the 2021-2022 growing season

Treatments			Greenness (SPAD)	L RWC	Stomatal conductance	N percent	P percent	K percent
Full irrigation	Surface irrigation	Non-mulched soil	44.40 b	88.69 d	99.08 c	0.389 a	0.192 d	0.640 b
		Organic-mulched soil	44.62 ab	89.30 cd	100.13 bc	0.390 a	0.193 d	0.652 ab
		Black PE-mulched soil	44.68 ab	90.06 bc	101.85 b	0.391 a	0.194 cd	0.657 ab
	Subsurface irrigation	Non-mulched soil	44.73 ab	89.30 cd	100.04 bc	0.392 a	0.195 bc	0.655 ab
		Organic-mulched soil	44.79 a	90.17 b	101.99 ab	0.393 a	0.196 ab	0.659 ab
		Black PE-mulched soil	44.81 a	90.98 a	103.93 a	0.396 a	0.198 a	0.666 a
Deficit irrigation	Surface irrigation	Non-mulched soil	41.56 g	64.99 i	40.94 i	0.271 e	0.134 j	0.379 f
		Organic-mulched soil	42.00 f	67.97 h	51.26 h	0.281 d	0.142 i	0.432 e
		Black PE-mulched soil	42.61 e	70.05 g	53.52 g	0.285 d	0.147 h	0.439 e
	Subsurface irrigation	Non-mulched soil	42.88 de	70.07 g	56.03 f	0.294 c	0.150 g	0.449 e
		Organic-mulched soil	43.05 d	72.00 f	59.92 e	0.300 c	0.162 f	0.521 d
		Black PE-mulched soil	43.80 c	79.13 e	62.53 d	0.340 b	0.171 e	0.597 c

All means in the column followed by the same letter are not significantly different at P≥5 %

Effect of irrigation scheduling, irrigation technique, and soil mulching on tomato fruit yield and its components, and water use efficiency

Data in Tables 11, and 12 illustrates how the main tested factors, irrigation scheduling, irrigation method, and soil mulching treatments, as well as their first-order interactions, affect tomato fruit yield and yield components, yield reduction percent, and water use efficiency. In comparison to a deficit irrigation rate, irrigation at a full rate significantly boosted water use efficiency, fruit weight, fruit number per plant, yield per plant, and yield per feddan. In line with this, for the first and second growing seasons, respectively, deficit irrigation decreased fruit yield per feddan by 44.68% and 45.92% when compared to full irrigation. The surface and subsurface irrigation methods used by drip irrigation also had an impact on the tomato fruit yield variables and water use efficiency. The subsurface irrigation method produces higher-weighed fruits, more fruit number and yield per plant, and then more estimated fruit yield per feddan than the surface irrigation method, also resulting in higher water use efficiency. When irrigation was done through the subsurface method as opposed to the surface method, the fruit yield rose by 22.7% and 18.47% for the first and second growing seasons, respectively. Among the factors tested, soil mulching with OrMS and BPMS against BS has an impact on the gathered data regarding yield, yield components, and water use efficiency. The BPMS treatment outperformed the OrSM and BS treatments in terms of yield parameters and water use efficiency. Soil mulching with OrMS and BPMS, respectively, increased the yield per feddan in comparison to cultivation in the BS by 9.54% and 19.47% in the first season and 5.96% and 12.38% in the second season. The interaction of the investigated factors in terms of irrigation rate, irrigation methods, and soil mulching all had a significant impact on water use efficiency, fruit yield, and yield components of tomato. It appears that applying irrigation via the subsurface method exceeded the surface method either at a full or deficit irrigation rate. The combined full irrigation and subsurface method treatment yielded higher values for all yield measurements. Despite the variation in yield per feddan got by the use of subsurface irrigation in addition to either full or deficit irrigation, the water use efficiency of each was the highest and not noticeably different from the other, especially in the first season. When comparing tomato yield data and water use efficiency to non-mulched soil, whether with full or deficit irrigation, mulching the soil with organic material or black polyethylene film had a better impact. The highest WUE was correlated to combined DI and BPMS treatment, but the best yield component values were recorded with combined full irrigation and BPMS. Tomato yield and yield components as well as WUE are significantly impacted by the interaction of soil mulching practices and irrigation methods, surface and subsurface. With subsurface irrigation, all soil mulching practices outperformed their surface irrigation counterparts. Applying BPMS with subsurface irrigation resulted in the highest yield and WUE values. These data held actual over the experimented seasons.

Table 11. Effect of irrigation scheduling (full and deficit), irrigation method (surface and subsurface), and soil mulching on tomato fruit weight, fruit number per plant, yield per plant, yield per feddan, yield reduction and water use efficiency during the 2020-2021 growing season

Treatments		Fruit weight (gm.)	Fruit number/ plant	Yield/plant (kg)	Yield/ feddan (kg)	Yield reduction percent	Water use efficiency
Irrigation rate							
Full irrigation		142.41 a	34.52 a	4.92 a	34434.66 a	0 a	10.77 a
Deficit irrigation		100.17 b	26.87 b	2.72 b	19050.63 b	-44.68 b	9.94 b
Irrigation method (type)							
Surface irrigation		116.49 b	28.55 b	3.43 b	24016.71 b	0 b	9.16 b
Subsurface irrigation		126.08 a	32.83 a	4.21 a	29468.58 a	+22.70 a	11.55 a
Soil mulching							
Non-mulched soil		117.26 c	28.72 c	3.49 c	24385.1 c	0 c	9.30 c
Organic-mulched soil		120.84 b	30.81b	3.82 b	26710.5 b	+9.54 b	10.32 b
Black PE-mulched soil		125.77 a	32.55 a	4.16 a	29132.3 a	+19.47 a	11.46 a
Irrigation rate X irrigation method (type)							
Full irrigation	Surface	141.02 b	32.56 b	4.59 b	32142.4 b	0.00 b	10.05 b
	Subsurface	143.80 a	36.48 a	5.25 a	36726.9 a	+14.26 a	11.50 a
Deficit irrigation	Surface	91.97 d	24.54 d	2.27 d	15891.0 d	-50.56 d	8.27 c
	Subsurface	108.37 c	29.19 c	3.17 c	22210.3 c	-30.90 c	11.61 a
Irrigation rate X Soil mulching							
Full irrigation	Non-	141.10 c	33.12 c	4.68 c	32719.8 c	0.00 c	10.23 d
	Organic-	142.30 b	34.62 b	4.93 b	34503.2 b	+5.45 b	10.79 c
	Black PE-	143.83 a	35.82 a	5.16 a	36081.0 a	+10.27 a	11.31 b
	Non-	93.42 f	24.32 f	2.30 f	16050.5 f	-50.95 f	8.37 f

Deficit irrigation	Organic-	99.39 e	27.00 e	2.71 e	18917.8 e	-42.18 e	9.86 e
	Black PE-	107.70 d	29.29 d	3.17 d	22183.7 d	-32.20 d	11.61 a
Irrigation method (type) X Soil mulching							
Surface irrigation	Non-	113.32 f	26.15 e	3.09 f	21654.75 f	0.00 e	8.11 f
	Organic-	115.97 e	28.52 d	3.41 e	23815.60 e	+9.98 d	9.08 e
	Black PE-	120.20 d	30.99 c	3.80 d	26579.75 d	+22.74 c	10.30 d
Subsurface irrigation	Non-	121.20 c	31.29 c	3.88 c	27115.45 c	+25.22 c	10.49 c
	Organic-	125.72 b	33.10 b	4.23 b	29605.40 b	+36.72 b	11.56 b
	Black PE-	131.33 a	34.12 a	4.53 a	31684.90 a	+46.32 a	12.62 a

All means in the column followed by the same letter are not significantly different at P≥5 %

Table 12. Effect of irrigation scheduling (full and deficit), irrigation method (surface and subsurface), and soil mulching on tomato fruit weight, fruit number per plant, yield per plant, yield per feddan, yield reduction and water use efficiency during the 2021-2022 growing season

Treatments		Fruit weight (gm.)	Fruit number/ plant	Yield/plant (kg)	Yield/fed dan (kg)	Yield reduction percent	Water use efficiency
Irrigation rate							
Full irrigation		138.90 a	34.42 a	4.78 a	33480.3 a	0.00 a	11.16 a
Deficit irrigation		101.88 b	25.19 b	2.59 b	18107.8 b	-45.92 b	10.06 b
Irrigation method (type)							
Surface irrigation		116.48 b	27.99 b	3.37 b	23615.0 b	0.00 b	9.56 b
Subsurface irrigation		124.30 a	31.62 a	4.00 a	27973.2 a	+18.47 a	11.65 a
Soil mulching							
Non-mulched soil		117.22 c	28.71 c	3.47 c	24308.0 c	0.00 c	9.91 c
Organic-mulched soil		119.96 b	29.90 b	3.68 b	25756.3 b	+5.96 b	10.59 b
Black PE-mulched soil		123.99 a	30.83 a	3.90 a	27317.9 a	+12.38 a	11.34 a
Irrigation rate X irrigation method (type)							
Full irrigation	Surface irrigation	137.72 b	33.20 b	4.57 b	32012.8 b	0.00 b	10.67 b
	Subsurface	140.08 a	35.64 a	4.99 a	34947.9 a	+9.17 a	11.65 a
Deficit irrigation	Surface irrigation	95.25 d	22.77 d	2.17 d	15217.1 d	-52.47 d	8.45 c
	Subsurface	108.51 c	27.60 c	3.00 c	20998.5 c	-34.41 c	11.67 a
Irrigation rate X Soil mulching							
Full irrigation	Non-mulched soil	137.79 c	33.55 c	4.62 c	32366.5 c	0.00 c	10.79 d
	Organic-mulched	138.81 b	34.48 b	4.79 b	33515.6 b	+3.55 b	11.17 c
	Black PE-mulched	140.11 a	35.23 a	4.94 a	34558.9 a	+6.77 a	11.52 b
Deficit irrigation	Non-mulched soil	96.65 f	23.87 f	2.32 f	16249.4 f	-49.80 f	9.03 f
	Organic-mulched	101.12 e	25.26 e	2.57 e	17997.0 e	-44.40 e	9.99 e
	Black PE-mulched	107.88 d	28.44 d	3.07 d	21478.1 d	-33.64 d	12.30 a
Irrigation method (type) X Soil mulching							
Surface irrigation	Non-mulched soil	114.17 f	26.69 f	3.18 f	22222.7 f	0.00 f	8.91 f
	Organic-mulched	115.86 e	27.96 e	3.35 e	23453.8 e	+5.54 e	10.49 e
	Black PE-mulched	119.42 d	29.31 d	3.60 d	25168.3 d	+13.25 d	10.29 d
Subsurface irrigation	Non-mulched soil	120.26 c	30.73 c	3.77 c	26393.2 c	+18.77 c	10.91 c
	Organic-mulched	124.07 b	31.80 b	4.01 b	28058.8 b	+26.26 b	11.86 b
	Black PE-mulched	128.56 a	32.35 a	4.21 a	29467.4 a	+32.60 a	12.83 a

All means in the column followed by the same letter are not significantly different at P≥5 %

Over the two tested seasons, there was a significant impact on tomato yield variables, yield per feddan, yield per plant, and average fruit weight and number per plant, as well as water use efficiency by the main effect and interaction of the three tested factors, irrigation rates, irrigation methods, and soil mulching practices (Tables, 13, 14). Generally, the combination of irrigation methods (surface and subsurface) and soil mulching practices (BS, OrMS, and BPMS) showed better performance with full than deficit irrigation. The best yield component outcomes were obtained by BPMS practice combined with irrigation at the full rate by the subsurface method. However, using the DI rate via the SSI method along with BPMS practice resulted in a higher WUE.

Table 13. Effect of second order interaction of irrigation scheduling (full and deficit), irrigation method (surface and subsurface), and soil mulching on tomato fruit weight, fruit number per plant, yield per plant, yield per feddan, yield reduction and water use efficiency during the 2020-2021 and growing season

Treatments			Fruit weight (gm.)	Fruit number/ plant	Yield/ plant (kg)	Yield/ feddan (kg)	Yield reduction percent	Water use efficiency
Full irrigation	Surface irrigation	Non-mulched soil	140.40 d	30.97 e	4.35 f	30433.9 f	0.00 f	9.52 g
		Organic-mulched soil	140.93 cd	32.33 d	4.56 e	31897.2 e	+4.81 e	9.97 f
		Black PE-mulched soil	141.73 c	34.37 c	4.87 d	34096.2 d	+7.05 d	10.67 e
	Subsurface irrigation	Non-mulched soil	141.80 c	35.27 b	5.00 c	35005.6 c	+15.02c c	10.94 d
		Organic-mulched soil	143.67 b	36.90 a	5.30 b	37109.2 b	+21.93b b	11.60 c
		Black PE-mulched soil	145.93 a	37.27 a	5.44 a	38065.8 a	+25.08a	11.95 b
Deficit irrigation	Surface irrigation	Non-mulched soil	86.23 j	21.33 i	1.84 k	12875.6 k	-57.69 k	6.70 i
		Organic-mulched soil	91.00 i	24.70 h	2.25 j	15734.0 j	-48.30 j	8.19 h
		Black PE-mulched soil	98.67 h	27.60 g	2.72 i	19063.3 i	-37.36 i	9.93 f
	Subsurface irrigation	Non-mulched soil	100.60 g	27.30 g	2.75 i	19225.3 i	-36.83 i	10.04 f
		Organic-mulched soil	107.77 f	29.30 f	3.16 h	22101.6 h	-27.38 h	11.52 c
		Black PE-mulched soil	116.73 e	30.97 a	3.61 g	25304.0 g	-16.86 g	13.28 a

All means in the column followed by the same letter are not significantly different at P≥5 %

Table 14. Effect of second order interaction of irrigation scheduling (full and deficit), irrigation method (surface and subsurface), and soil mulching on tomato fruit weight, fruit number per plant, yield per plant, yield per feddan, yield reduction and water use efficiency during the 2021-2022 growing season

Treatments			Fruit weight (gm)	Fruit number/ plant	Yield/ plant (kg)	Yield/ feddan (kg)	Yield reduction percent	Water use efficiency
Full irrigation	Surface irrigation	Non-mulched soil	137.19 d	32.22 e	4.42 f	30941.1 f	0.00 f	10.31 g
		Organic-mulched soil	137.64 cd	33.07 d	4.55 e	31859.5 e	+2.96 e	10.62 f
		Black PE-mulched soil	138.32 c	34.33 c	4.75 d	33237.8 d	+7.42 d	11.08 e
	Subsurface irrigation	Non-mulched soil	138.38 c	34.89 b	4.83 c	33791.9 c	+9.21 c	11.26 d
		Organic-mulched soil	139.97 b	35.90 a	5.02 b	35171.7 b	+13.67 b	11.72 c
		Black PE-mulched	141.89 a	36.13 a	5.13 a	35879.8 a	+15.96 a	11.96 b
Deficit irrigation	Surface irrigation	Non-mulched soil	91.15 j	21.17 k	1.93 l	13504.3 l	-56.35 l	7.50 j
		Organic-mulched soil	94.08 i	22.85 j	2.15 k	15048.2 k	-51.37 k	8.36 i
		Black PE-mulched	100.52 h	24.30 i	2.44 j	17098.8 j	-44.74 j	9.50 h
	Subsurface irrigation	Non-mulched soil	102.14 g	26.57 h	2.71 i	18994.5 i	-38.61 i	10.55 f
		Organic-mulched soil	108.16 f	27.67 g	2.99 h	20945.9 h	-32.30 h	11.64 c
		Black PE-mulched	115.23 e	28.58 f	3.29 g	23055.0 g	-25.49 g	12.81 a

All means in the column followed by the same letter are not significantly different at P≥5 %

Discussion

Water availability is a crucial condition for promoting and extending irrigated agriculture. From now on, conducting irrigated agriculture under conditions of freshwater scarcity is inevitable (Ingrao *et al*., 2023). To cope with these challenges and sustain irrigated agriculture, requires increasing water use efficiency via conscious irrigation techniques and optimizing soil conditions, as well as keeping irrigation water from being lost during crop irrigation steps. Deficit irrigation (DI) was applied as an effective irrigation water-saving technique adopted by earlier researchers (Alkhasha *et al*., 2019; Yang, 2022; Asres, 2023; Khedr *et al*., 2023). Within the range of 40% to 80% of the crop evapotranspiration (ETc), DI irrigation was applied experimentally in tomato production in earlier studies (Zhang *et al*., 2017; Alordzinu *et al*., 2022, Alghamdi *et al*., 2023; Khalifa, 2023). In this study, DI irrigation was applied at 60% ETc, which was rather moderate, not severe, and not close to the full watering level. As a result, the saved irrigation water in this experiment was not little. However, applying the DI regime via surface irrigation (SI) technique in bare soil derived clear drought stress on tomato plants. This adverse effect of the absolute DI could be mitigated by combining it with a sub-surface irrigation method and polyethylene mulching soil. The saved irrigation water was 1220 m^3 and 1200 m^3 in the two tested growing seasons, respectively by applying 60% ETc deficit irrigation. The discussion will focus on the synergistic effects of combining subsurface (SSI) or surface (SI) drip irrigation techniques with soil mulching materials, organic material (OrM), or black polyethylene (BPE) or bare soil in conjunction with the DI irrigation approach. Subsurface irrigation provides water and nutrients directly to the plant root zone so, it stops water and nutrients from moving deeply and outside of the plant root zone. A further benefit of using the SSI irrigation technique is a reduction in the wetted soil area, which concentrates the water in the root zone and lowers water evaporation from the soil surface and runoff as well. These all minimize water loss and enable the root zone to receive the proper moisture level, allowing the plant to get the water it needs. The SSI system also helps prevent the accumulation of salinization in the soil, thus allowing plants to grow stronger and deeper roots (Siyal and Skaggs, 2009; Rasheed, 2020).

Mulching the soil refers to covering the soil's surface with certain organic or synthetic materials to provide the soil and plants with many benefits. Soil mulching reduces evapotranspiration by preventing the evaporation of water from the soil surface and inhibiting the growth of weed plants that diminish total water transpiration. All of these prevent irrigation water from being lost, so it helps the plant grow healthy without experiencing drought stress. Additionally, soil mulching prevents salt buildup, preserves an appropriate soil moisture level, and modifies the hydrothermal regime in the root zone, based on the mulch material's insulation of water and heat transmission in or out of the soil (Tswanya *et al*., 2017). Thus, mulching the soil can prevent water evaporation from the soil surface, maintain soil moisture balance, which supports plant health and growth, and maintain soil temperature with less variation from the air temperature. Together, these improve crop productivity and water use efficiency.

The results of this study indicate that the tested factors, irrigation rates (DI and FI), irrigation technique (SI and SSI drip irrigation), and soil mulching materials (Or, BPE, and no mulch), have an impact on soil moisture content along the growing season (un-displayed data). This outcome is consistent with that of El-Mansor *et al*. (2015) and Aliabadi *et al*. (2019). On the other hand, when comparing the SSI and SI drip irrigation techniques during the growing season, it was found that soil moisture content was higher with utilizing the SSI technique. This suggests that SSI drip irrigation is more effective in maintaining soil moisture levels. Furthermore, the type of soil mulching material used also influenced soil moisture content. The study found that when BPE soil mulch was used, soil moisture content was higher compared to when or soil mulch or no mulch was applied. This indicates that BPE soil mulch helps in retaining soil moisture, leading to improved soil moisture levels. In the case of the DI regime, the applied irrigation water was insufficient for the water requirements of the plants. However, when the SSI irrigation technique was combined with BPE soil mulch under the DI regime, it was found to be the most effective in conserving irrigation water. This combination not only mitigated the negative effects of the DI regime but also promoted plant health and improved water productivity (Abdelhady *et al*., 2017; Chen *et al*., 2018; Abd El-Wahed *et al*., 2020; Sang *et al*., 2020).

Tomato plants' vegetative measurements

Appling deficit irrigation rate at 60% ETc, in the current experiment stimulates drought stress as mentioned by Al-Ghobari and Dewidar (2017), and Hu (2020), thus leading to lower tomato plant vegetative measurements in terms of plant length, number of branches per plant, shoot fresh and dry weight, and root dry weight. The root-to-shoot ratio is higher with deficit irrigation than with full irrigation since the root system is more adapted to water shortage than shoots (Tables, 3 and 4). Subsurface irrigation delivers water and nutrients directly to the root zone, thereby protecting the water from being lost by evaporation, but the opposite is true with surface irrigation, so all measured vegetative parameters were strengthened with subsurface compared to surface irrigation. Mulching soil with either organic materials or black polyethylene sheets, even though the black polyethylene sheets are more effective than organic materials, reduces evaporation, retains soil moisture, decreases the effect of ambient temperature on soil temperature, and suppresses weed growth. These all can support better vegetative growth and overall plant health (Abdelhady *et al*., 2017; Chen *et al*., 2018; Abd El-Wahed *et al*., 2020; Sang *et al*., 2020).

The interaction of the tested factors (Tables 5 and 6), including irrigation rate (DI and FI), irrigation technique (surface and subsurface drip irrigation, SI, SSI), and soil mulching materials (organic material and black polyethylene), significantly affected the vegetative measurements of tomato plants, including plant length, number of branches, shoot fresh weight, shoot dry weight, root dry weight, and root to shoot ratio. The integration of the SSI technique and soil mulching by either of the two mulch materials can ameliorate the restricted effect of the DI regime compared to the SSI technique implemented in bare soil and SI technique, even when synchronized with soil mulching. SSI and soil mulch, especially by BPE, each alone or together with FI rate or DI rate, confer more length, branch number, shoot number, shoot fresh and dry weight, and root dry weight than the same treatments with SI and/or bare soil. From these data, combining the practices that conserve irrigation water from being lost via evapotranspiration and percolation out of the root zone and deliver water and nutrients directly to the roots, like the SSI technique and soil mulching, sustains the vegetative growth of tomato plants when subjected to insufficient watering. The root-to-shoot ratio exhibits a different trend because of the negative correlation between root growth and soil moisture level up to a certain point, after which all plant parts, including shoots and roots, fall apart. These findings are in line with those of Chai *et al*. (2016); Singh and Kamal (2012); Ayankojo *et al*. (2020); Al-Selwey *et al*. (2021); Alhashimi *et al*. (2023).

Tomato leaf physiological measurements

Stomatal conductance (SC) is a measurement that quantifies the opening and closing of stomata. Stomata movements play a crucial role in regulating water loss through transpiration and the efflux of carbon dioxide for the photosynthesis process. When plants undergo drought stress like that irrigated deficiently, they tend to close their stomata consequently reducing SC and then reducing water loss through transpiration and securing their chances of survival. Moreover, the closure of the stomata hurts photosynthesis. Since CO_2 which is an essential component in the photosynthesis process, enters the leaves primarily through stomata, a decrease in stomatal conductance results in a reduced influx of CO_2 into the leaf, and as a consequence, the rate of photosynthesis decreases (Al Kahtani *et al*., 2021; Wei *et al*., 2018). Other physiological effects of deficit irrigation applied to tomato plants were tracked related to a reduction in the water status of the plants, like lower leaf relative water content (LRWC), indicating that the plant is also undergoing water stress. The deficit irrigation effect extended to leaf greenness which is measured in SPAD units and indicates the chlorophyll pigment concentration in the leaf and its physiological activities which is crucial for photosynthesis as it captures the light energy necessary for the process. Deficit irrigation and associated water stress can affect the chlorophyll content of the leaf, potentially leading to a decrease in leaf greenness (Gathungu *et al*., 2016; Khapte *et al*., 2019). Also, deficit irrigation negatively affects most of physiological characters like the photosynthesis process (Abdelaal *et al*., 2018; Abdelaal *et al*., 2021a and b; Hafez *et al*., 2020), leaf relative water content (AlKahtani *et al*., 2021; Arafa *et al*., 2021) and disrupts various plant metabolic processes, including the absorption of water and nutrient elements such as NPK. These disruptions can have unfavorable consequences on the plant's physiological activities, growth, and the production of organic mass (Khapte *et al*., 2019).

Subsurface irrigation and/or soil mulching deliver water directly to the root zone, eliminate water loss due to evaporation, and suppress weed growth. So, it promotes efficient uptake of water and absorption of nutrients by plants. Additionally, it enhances plant physiological activities in terms of increasing SC and relevant activities like LRWC and photosynthesis. Combining deficit irrigation with subsurface irrigation and soil mulching can have synergistic effects on reducing the negative effects of water stress through water conservation, ensuring stable and sufficient soil moisture for plant growth, and then enhancing plant physiological activity indicators like SC, LRWC leaf greenness, and NPK content of the leaf (Badr et al. 2018; Khapte *et al*., 2019: Rehema *et al*., 2019; Parkash and Singh, 2020; Salem *et al*., 2021).

Tomato fruit yield and its components and water use efficiency

Deficit irrigation refers to a watering strategy in which plants are intentionally provided with less water than they require for optimal growth. It can have various effects on the plant, like weak vegetative growth and poor fruit yield. On the other hand, when plants are subjected to water stress, they prioritize the allocation of limited resources towards essential functions such as maintaining water balance rather than investing in vegetative growth or bearing fruits. As a result, the growth of plant organs such as stems, leaves, and branches may be limited. These vegetative structures play a crucial role in the generation and bearing of fruits and serve as conduits for nutrient transport. Additionally, water is a critical component of photosynthesis. When water availability is limited, photosynthesis can be impaired, leading to reduced production of carbohydrates, which are essential for plant growth. Consequently, the overall dry matter production of the plant, including the growth of plant organs and fruits, may be decreased.

The effects of deficit irrigation on tomato plants are complex but they could be alleviated with a proper irrigation technique as subsurface irrigation as well as optimizing soil conditions through mulching practices. Management of these practices is crucial to optimize the use of deficit irrigation techniques and minimize any potential negative impacts on plant growth and productivity. Overall, combining deficit irrigation, subsurface irrigation, and soil mulching can significantly improve water use efficiency and contribute to sustainable agricultural practices by conserving water resources and enhancing crop productivity (Abdelhady *et al*., 2017; Chen *et al*., 2018; Aliabadil *et al*., 2019; Sang *et al*., 2020).

Conclusions

Regular deficit irrigation is an effective irrigation water-rationing strategy used in tomato production, but when it is applied at a rate below moderate, the tomato's performance may be harmed. When adopting the deficit irrigation approach, it is critical to minimize or stop water loss through evaporation from the soil surface and percolation out of the root zone to provide the plant with the water it needs. Subsurface irrigation reduces irrigation water loss through percolation, while soil mulch reduces irrigation water loss through evaporation. So, integrating these practices (subsurface irrigation and soil mulching) with the deficit irrigation approach in tomato production maximizes water productivity and prevents a significant decline in plant growth, yield, and fruit quality. It also maintains the physiological functions and nutritional status.

Authors' Contributions

Conceptualization: NIA, MA; Data curation: NIA, MA; Formal analysis NIA, MA; Funding acquisition AA, OA; Methodology NIA, MA; Project administration NIA, MA, KA; Resources; Software NIA, MA; Validation KA; Writing - original draft: NIA, MA, KA; Writing - review and editing: NIA, MA, KA, AA, OA. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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