



# Effect of using reclaimed water via furrow and subsurface drip systems under alternate partial root-zone irrigation mechanism on crops growth and soil properties

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## Abstract

The growing population in the face of water scarcity inevitably necessitates the quest for alternative sources of irrigation water, which integrates them with irrigation strategies for improved agricultural productivity to meet the Sustainable Development Goals. A three-year field experiment was conducted in 2017, 2018, and 2019 to investigate the effect of water quality (reclaimed water (RW) and clean water (CW)), irrigation techniques (subsurface drip irrigation (SDI) and furrow irrigation (FUI)), irrigation methods (full irrigation (FI) and alternate partial root-zone irrigation (APRI) (70% ET<sub>c</sub>)), and their interactions on the fresh fruit yield (FY), irrigation water use efficiency (IWUE), and nitrogen use efficiency (NUE) of tomatoes. Further, electrical conductivity (EC), pH, and organic matter (OM) of soil were evaluated. The experiments were undertaken over three growing spring seasons in a greenhouse at the Chinese Academy of Agricultural Sciences in Henan Province, China. Throughout the three years of this study, the yield, the IWUE, and the NUE values of all treatments under RW were higher than those corresponding values under CW. The trend was the same under SDI as it was under FUI. Statistical analyses revealed that there was no significant effect ( $P > 0.05$ ) of water quality, irrigation technique, and irrigation methods on the soil EC, pH, and OM over the three years. In addition, the interaction between the different experimental factors over the three years of the study was not significant. In conclusion, the application of RW under SDI can result in saving CW and increasing productivity without any negative effect on the investigated soil properties. Furthermore, when RW-SDI is used in conjunction with APRI, it can result in increasing IWUE.

## Introduction

The scarcity of water is a fundamental factor limiting crop cultivation, and it is expected to become worse in the coming years due to climate change, which would result in posing a significant challenge to food security worldwide. With the population steadily increasing and the demanding for water surpassing its supply, the need for innovative techniques to improve water efficiency in agriculture is crucial. Reclaimed water (RW) has become a viable solution to address water scarcity in many countries (Gheraout et al. 2019; Hashem and Qi 2021). RW is a reliable and steady source of water, and provides a massive amount of nutrients to crops, which enhances crop productivity (Gu et al. 2019; De Carlo et al. 2020). Besides reducing the use of clean water, the reuse of wastewater has contributed to the enhancement of soil quality by enriching it with organic matter (OM) and nutrients, which improves its ability to hold water and consequently affects the compaction resistance and drainage properties (Ganjegunte et al. 2018; Abd-Elwahed 2018).

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Several studies have investigated the impact of RW irrigation on soil chemical characteristics including salinity, sodicity, pH, etc. (Hashem and Qi 2021). Salinity is evaluated by measuring EC and sodium adsorption ratio (SAR), which are indicators of the level of soil saturation with sodium and infiltration problems (Gharaibeh et al. 2016). A study by Farhadkhani et al. (2018) found that secondary RW had no significant impact on soil physicochemical characteristics, except for slight increase in EC and SAR in the soil. There is no consensus among scientists regarding the effects of irrigation with wastewater on soil physical properties, with some researchers reporting similar soil EC under RW and clean water (CW) treatments (Virga et al. 2020; Wang et al. 2021; Du et al. 2022), while other studies have found that irrigation with RW increased the soil EC compared to CW (Liang et al. 2022; Licata et al. 2022). Soil pH is a crucial parameter that affects the nutrient charge and the availability of nutrients to crops (Urbano et al. 2017). Some studies have reported no significant effect of water quality on soil pH (Virga et al. 2020; Du et al. 2022), while other studies have found that prolonged wastewater irrigation caused a decline in soil pH (Rattan et al. 2005; Meena et al. 2016).

Tomato (*Lycopersicon esculentum* M.) is one of the most water-demanding vegetable crops (Kiyamaz and Ertek 2015), and the farmers often use more water than necessary to maximize yield, which reduces water use efficiency (DU et al. 2017). Tomatoes irrigated with RW produced higher fruit yields than those irrigated with clean water, possibly due to the abundance of nutrients found in RW (Wu et al. 2010; Li et al. 2019). Nevertheless, improper treatment of wastewater can lead to salinity build-up, toxicity hazards, and could pose public health risk (Al Arni et al. 2019; Ghernaout et al. 2019). Therefore, selecting an appropriate irrigation system and cropping pattern with effective irrigation management practices is crucial to reducing the negative impact of RW irrigation. Drip irrigation is generally the most appropriate method when using reclaimed water due to its safety and efficiency. (Hashem and Qi 2021). Low irrigation water use efficiency (IWUE) is a significant challenge for sustainable agriculture worldwide, particularly in drought-prone areas (Wang et al. 2010), and therefore, it is important to use irrigation techniques that increase the IWUE. Alternate partial root-zone irrigation (APRI) is a water-saving technique that creates simultaneous dry and wet areas within the root zone, which results in minimal yield losses and increased IWUE (El-Sadek 2014; S Hashem et al. 2018; Cheng et al. 2021). Mahmoudi et al. (2020) found that subsurface drip irrigation (SDI) offered better growth and yield than surface drip irrigation. Using alternate furrow irrigation (FUI) combined with reducing applied water is considered a water-saving approach that enhances water productivity (Sepaskhah and Hosseini 2008; El-Sayed et al. (2020); . In comparison with FUI, drip irrigation increased tomato yield by almost

one and a half times while using 30% less irrigation water (Kahlon et al. 2007).

Najafi (2006) investigated the effects of using RW with various irrigation systems on tomatoes, and maximum yield was recorded under drip irrigation compared to other irrigation systems. This is likely due to the improved soil moisture and increased availability of nitrogen (N) in the root zone. N is an essential nutrient for plant growth and yield (Wen et al. 2020), and proper rates and timing of N fertilizer application are crucial for attaining optimum yield and nutrient use efficiency (Yoseftabar 2013; Zhang et al. 2021). Split applications of fertilizer can help growers avoid excessive fertilization during the early growth stage of the crop and provide sufficient nutrient supply during later stages (Lu et al. 2021). Mehmood et al. (2019) found that the IWUE of drip irrigation treatment was higher than that of surface irrigation treatment under the same nitrogen application rate.

Greenhouses are known to provide better management of growth conditions for crops compared to open fields. Sun et al. (2013) stated that tomato cultivation in greenhouses requires significantly less water and N than conventional management in field conditions. Drip irrigation was found to greatly decrease nitrate leaching and increase nitrogen use efficiencies (NUE) and IWUE compared to FUI (Aujla et al. 2007; Sun et al. 2013).

The main hypothesis of this study is that utilizing RW with certain irrigation techniques can reduce the use of clean water without affecting yield and soil properties including soil EC, soil pH, and OM concentrations. Therefore, this study aims to investigate the effect of water quality (RW and CW) on tomato yield, WUE, NUE, and some soil properties under two irrigation methods (SDI and FUI) with two irrigation techniques (FI and APRI).

## Materials and methods

### Experimental site

The experiment was conducted over three years (2017, 2018, and 2019) in greenhouses at the Chinese Academy of Agricultural Sciences, Henan Province, China (35°19'0" N, 113°53'0" E, and elevation of 73.2 m), in the continental monsoon climate area of the temperate zone. The annual mean air temperature of the site is 14.1 °C. The site has 2398.8 h of sunlight per year, 588.8 mm of precipitation annually, and a 210-day frost-free period.

### Specifications of the soil at the experimental site

Soil properties, including extractable phosphorus (amount of plant-available phosphorus in the soil), organic matter, and total nitrogen were 0.02467, 19.90, and 0.85 g kg<sup>-1</sup>,

respectively. The soil texture was silty clay loam, soil pH was 8.00, and bulk density was 1.40 g cm<sup>-3</sup>.

### Water characteristics

The plots employed tap water irrigation and reclaimed water. In this study, the experimental area received the irrigation RW from Luotuo Wan Reclamation Plant, located in Xinxiang city (35°15'09" N, 113°55'05" E, and elevation of 73.2 m), undergoing an anaerobic–anoxic–oxic denitrification biofilter and ozone oxidation process. The quality of the RW met the National Standard for Farmland Irrigation Water Quality (GB5084–(2005) (2006)). Quality of tap water and RW are shown in Table 1.

### Irrigation treatments

The experimental factors of this study included two types of water quality (reclaimed wastewater (RW) and clean water (CW)), two types of irrigation methods (full irrigation (FI) and alternate partial root-zone irrigation (APRI)), and two types of irrigation techniques (furrow irrigation (FUI) and subsurface drip irrigation (SDI)).

The irrigation treatments were: (1) SDI with APRI; (2) SDI with FI; (3) FUI with APRI; and (4) FUI with FI, and these treatments were conducted with RW and CW, so the experiment consisted of eight treatments. Each treatment was replicated three times. The APRI treatments received 70% of the irrigation water volume of FI (Table 2).

### Experimental layout

This experiment had 8 plots, and each plot was divided into three rows. The irrigation water was applied from one side in FI treatments and both sides in APRI treatments. The statistical design used in this study was a Completely Random Block Design.

In the plots of SDI-FI treatments, the drip irrigation lines were laid at the centers of crop rows and separated by a 0.7 m distance. In the APRI treatment plots, each row of tomatoes had two lateral lines with a nested shape for the emitters and a distance of 0.4 m between the two lines. The distance between the treatments was 0.75 m, as illustrated in Fig. 1. Irrigation with the treatment of APRI was shifted from one side of the plants to the other to achieve a long-term APRI effect on ABA signaling and leaf gas exchange in the tomato crop.

### Water requirement

Based on the climatic data received from the weather station inside the greenhouse, the water irrigation requirement was determined as potential crop evapotranspiration using the FAO Penman–Monteith equation (Allen et al. 1998) (Eq. 1), and Kc, as shown in Eq. 2. Then, the daily crop water requirement (CWRd) was calculated using Eq. 3 (Von Zabeltitz 2010):

$$ET_O = \frac{0.408\Delta(R_n - G + y \frac{900}{t_{mean} + 273} u_2 (e_s - e_a))}{\Delta + y(1 + 0.3u_2)} \tag{1}$$

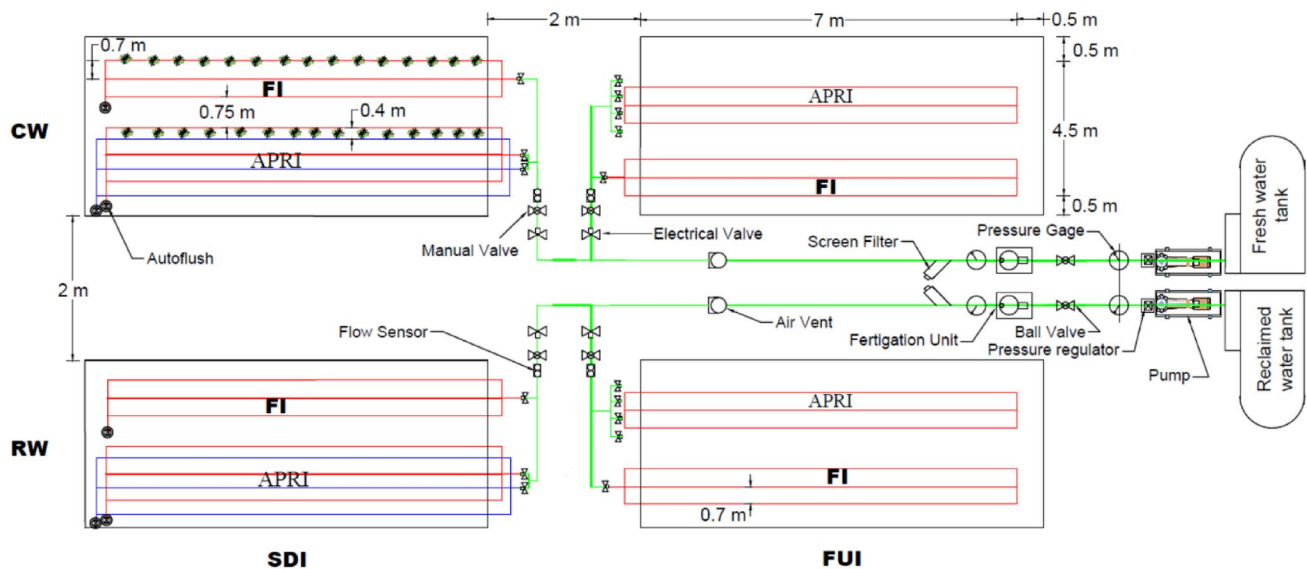
where ET<sub>O</sub> is the reference evapotranspiration (mm day<sup>-1</sup>); Δ is the slope of saturation vapor pressure curve (kPa °C<sup>-1</sup>);

**Table 1** RW and tap water Quality

Index	pH	Cd (mg·L <sup>-1</sup> )	Cu (mg·L <sup>-1</sup> )	Pb (mg·L <sup>-1</sup> )	Zn (mg·L <sup>-1</sup> )	TN (mg·L <sup>-1</sup> )	TP (mg·L <sup>-1</sup> )	EC (dS·m <sup>-1</sup> )	COD <sub>Mn</sub> (mg·L <sup>-1</sup> )
Reclaimed water	7.84	0.0021	0.035	0.026	0.772	29.57	1.95	2.06	17.6
Clean water	7.32	0.0004	0.006	0.005	0.016	4.63	0.23	1.62	7.2

**Table 2** Summary of field treatments

Water type	Irrigation treatments	ETc (%)
Reclaimed wastewater (RW)	Subsurface drip irrigation (SDI) + Alternate partial root-zone irrigation (APRI)	70
	Subsurface drip irrigation (SDI) + Full irrigation (FI)	100
	Furrow irrigation (FUI) + Alternate partial root-zone irrigation (APRI)	70
	Furrow irrigation (FUI) + Full irrigation (FI)	100
Clean water (CW)	Subsurface drip irrigation (SDI) + Alternate partial root-zone irrigation (APRI)	70
	Subsurface drip irrigation (SDI) + Full Irrigation (FI)	100
	Furrow irrigation (FUI) + Alternate partial root-zone irrigation (APRI)	70
	Furrow irrigation (FUI) + Full Irrigation (FI)	100



**Fig. 1** Experiment layout. CW and RW are clean water and reclaimed water. SDI and FUI are subsurface drip irrigation and furrow irrigation. FI and APRI are full irrigation and alternate partial root-zone irrigation

**Table 3** FAO 56 tomato crop coefficient (Allen et al. 1998)

Crop	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Tomato	0.6	1.15	0.70–0.90

$R_n$  is the net radiation at the crop surface ( $\text{MJ m}^{-2} \text{day}^{-1}$ );  $G$  is the soil heat flux density ( $\text{MJ m}^{-2} \text{day}^{-1}$ );  $\gamma$  is the psychrometric constant ( $\text{kPa } ^\circ\text{C}^{-1}$ );  $U_2$  is the wind speed at 2 m height ( $\text{m s}^{-1}$ );  $T$  is the mean daily air temperature at 2 m height ( $^\circ\text{C}$ );  $e_s$  is the mean saturation vapor pressure ( $\text{kPa}$ );  $e_a$  is the actual vapor pressure ( $\text{kPa}$ ).

$$ET_C = K_C \times ET_o \quad (2)$$

where  $ET_C$  is crop evapotranspiration ( $\text{mm day}^{-1}$ ), and  $K_C$  is crop coefficient. The  $K_c$  for all growth stages of the tomato was taken from FAO-56 (Table 3)

$$CWR_d = ET_C(1 + l_i) A_{Crop}/A_G \quad (3)$$

where  $l_i$  is the loss factor for irrigation (0.03–0.1 for drip irrigation systems) and  $A_{Crop}/A_G$  is the ratio of the crop-covered area to the greenhouse floor area (0.9 for vegetables).

### Cultivated crops

The experiment was carried out in the experimental field during the spring seasons of the years 2017, 2018, and 2019. The crop was tomato (*Lycopersicon esculentum* L.). Tomato is a herbaceous plant that grows above the soil surface.

Tomato seeds were germinated in Jiffy 7 pellets in a controlled greenhouse. The seed was planted four weeks before being transferred to the land. The pellets were observed every day to maintain moisture and to check for any problems. After four weeks, the seedlings were transferred to the sustainable land of the experiment field in the greenhouse. The distance of planting was 0.5 m within the line, and 0.7 m between lines.

### Planting and harvesting dates

The actual date of planting in the first year was on 1 March 2017, and the harvesting was on 5 July 2017. In the second year, the actual date of planting was 1 March 2018 and the harvesting was on 3 July 2018. In the third year, the actual date of planting was 8 March 2019 and the harvesting was on 15 July 2019.

### Agricultural practices

Fertilizer, disease, pest, and insect control, as well as other common practices, were implemented. All treatment plots received the same amount of total fertilizer. A compound NPK fertilizer was applied based on the appropriate application time schedules.

We manually collected the fruits from each line and weighed them to find the fresh weight of fruit per plant.

## Data recorded

### Soil analyses

Electrical conductivity (EC), pH, and organic matter (OM) concentration were the main soil parameters analyzed in the study. Sampling was carried out in a soil layer ranging from 0 to 0.5 m, with tomato plants that have an average root depth of 0.5 m. Every year, three soil samples were collected per plot with a standard 0.035 m Ø soil auger at tomato transplanting and harvest stages. The soil samples were subsequently air-dried, sieved through a 2 mm sieve screen, and then analyzed for the main soil parameters (EC, pH, and OM). The soil pH was determined in distilled water at a soil-to-solution mass ratio of 1:5 by the Leici-Shanghai PHS-1 pH meter. The electrical conductivity of the soil extracts at a soil and water ratio of 1:5 (EC 1:5) was measured by a Leici-Shanghai DDB-303A conductivity meter. The soil organic matter was determined using the oxidation volumetric method for the determination of potassium dichromate, as described by Bao (2000). All the analyses were carried out at the Farmland irrigation research institute.

### Total fresh fruit yield (Mg hectare<sup>-1</sup>)

Tomato crop was harvested manually every year. We manually collected the fruits from each line and weighed them to find the fresh weight of fruit (Mg hectare<sup>-1</sup>) per treatment.

### Irrigation water use efficiency (IWUE, kg m<sup>-3</sup>)

The most important indicator to show the benefit of any treatment is the irrigation water use efficiency (IWUE). IWUE for each treatment was calculated as the ratio between the marketable yields harvested as weight (kg) and the total volume of water consumed for the tomato production applied as volume (m<sup>3</sup>) as shown in Eq. 4 (Agbna et al. 2017).

$$IWUE = \frac{Y}{I} \quad (4)$$

where  $Y$  is the total marketable tomato fruit yield (kg);  $I$  is the total irrigation water applied (m<sup>3</sup>).

### Nitrogen use efficiency (NUE, kg kg<sup>-1</sup>)

The contribution of  $N$  application to the tomato yield was calculated as Aujla et al. (2007):

$$NUE = \frac{Y}{N} \quad (5)$$

where NUE is measured in kg kg<sup>-1</sup>,  $Y$  is the total marketable tomato fruit yield (kg), and  $N$  is the amount of N applied (kg).

### Data analysis

The statistical analysis of the data collected in this study was conducted using the SPSS software (IBM, Armonk, New York, NY, USA). The data were subjected to a multivariate analysis of variance (MNOVA). The MNOVA was conducted to compare the main effects of irrigation water qualities (CW and RW), irrigation methods (FI and APRI), and irrigation techniques (FUR and SDI), as well as their interaction effects, on tomato and soil properties. The significance of all statistical analyses was accepted at  $P=0.05$ . The Tukey's test was used to find any significant differences between the means of the different irrigation treatments at a significance level of  $P<0.05$ . The figures were prepared using Microsoft Excel ver. 2016 software.

## Results and discussion

### Soil properties

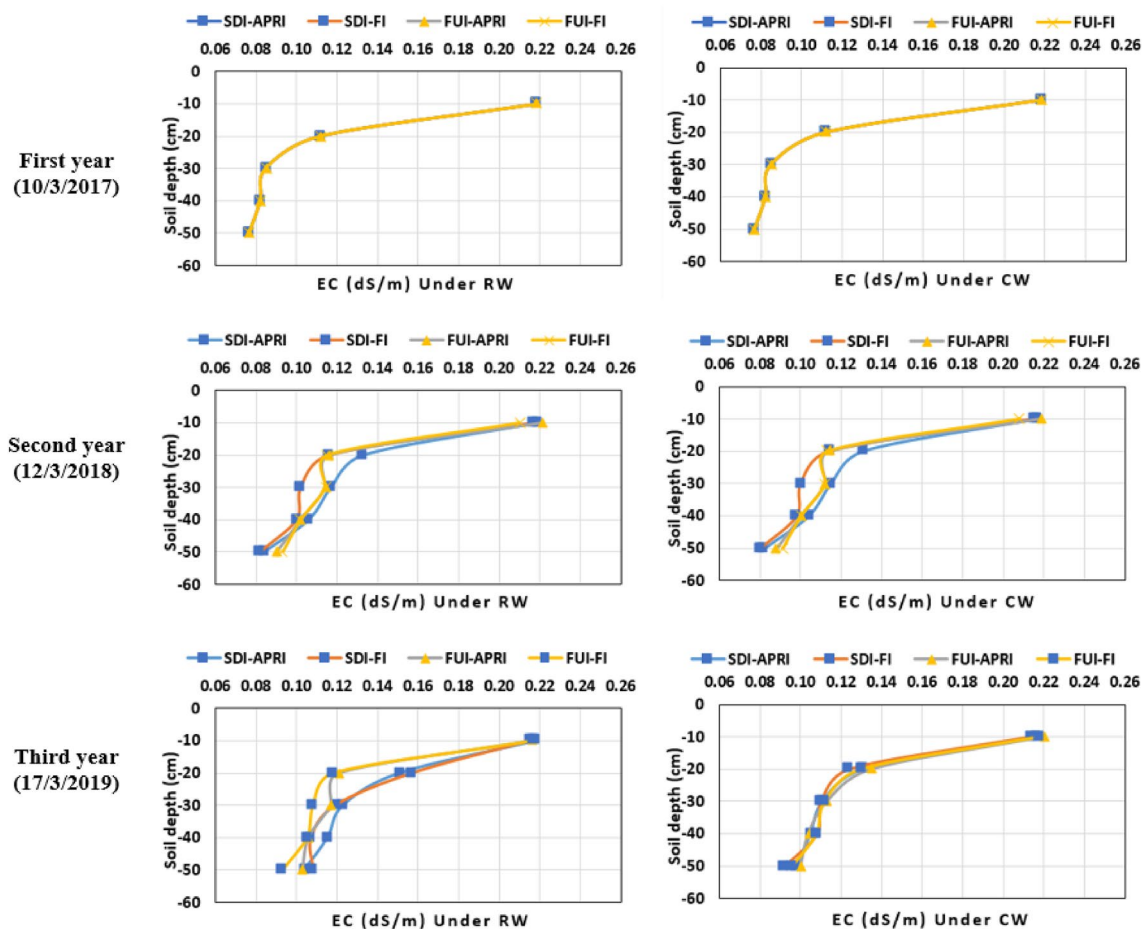
The study found that during the first year, EC, PH, and OM values at the beginning of the season were the same across all treatments, where the effect of the treatments had not yet begun. However, in subsequent years, differences in EC and pH values were observed at the beginning of the season, likely due to the previous year's treatments.

The analysis of variance showed that there was no significant effect ( $P>0.05$ ) of water quality, irrigation technique, and irrigation methods on soil EC, PH, and OM over the three-year study period. Moreover, there was no significant effect ( $P>0.05$ ) on the interaction between the experimental factors over the three years.

### Soil electrical conductivity (EC)

Typically, soil electrical conductivity (EC) is used to indicate the concentration of soluble salts present in the soil. Crops only remove a small quantity of salt. Hence, salt distribution and its movement in soil are closely related to water movement (Heidarpour et al. 2007). Figures 2 and 7 present the EC values at different depths under all treatments throughout the three years.

Throughout the three-year study period, the EC values were always higher under the APRI treatments than those under the FI treatments, for both RW and CW treatments. In the first year, after harvesting, the results revealed that water-saving treatment APRI under FUI and SDI increased the EC values by 21.61% and 19.87% under RW and CW,



**Fig. 2** Soil EC (dS/m) for the different irrigation treatments at the beginning of the planting throughout the three years. RW reclaimed water, CW clean water, SDI subsurface drip irrigation, APRI alternate partial root zone irrigation, FI full irrigation, FUI furrow irrigation

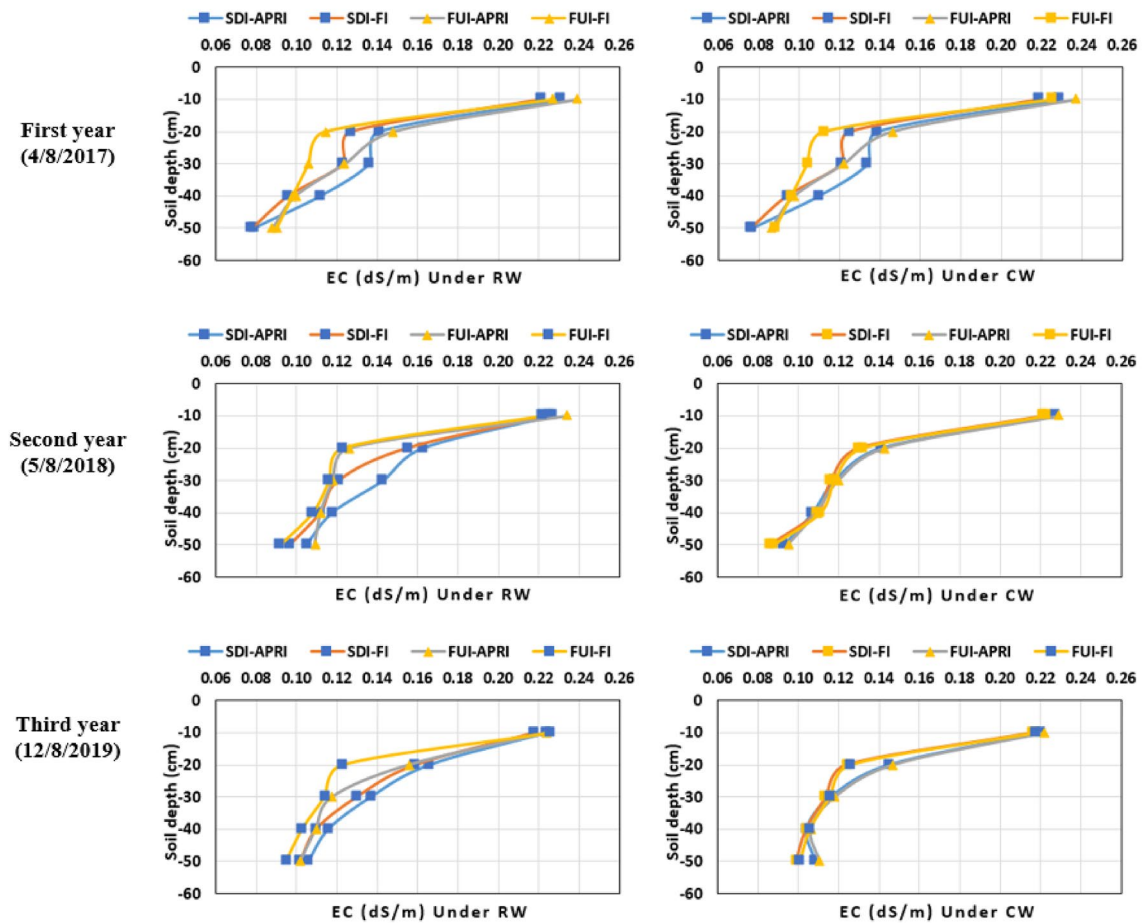
respectively, compared to the values at the beginning of the season (Fig. 2 and 3). At the end of the season of the first year, the average value of the EC of SDI-APRI under both RW and CW was increased by 8.36% and 8.49% compared with SDI-FI under RW and CW, respectively. A similar pattern was observed in the second and third year, with increase of 6.48% and 3.64% in the second year, and 4.17% and 5.63% in the third.

Also, when comparing the average of EC values under FUI-APRI and FUI-FI for both RW and CW, it was noticed to increase by 9.83% and 9.99%, respectively, in the first year, by 5.74% and 3.59% respectively, in the second year, and by 7.24% and 5.55% in the third year, respectively. This increase in EC under deficit irrigation is expected, as a higher amount of irrigation water can lead to increased leaching of soil salts compared to situations with less irrigation water.

When comparing the soil EC values at the end of the season with the beginning of the season in all three years, it turns out that there is an increase in the EC values regardless

of water quality. This increase ranged from 8.9% to 21.61%, 4.25% to 15.07%, and 1.84% to 6.91% in the first, second, and third years, respectively, across all treatments. This increase in EC values was expected, as irrigation water and fertilizers are major sources of soil salts.

Figures 2 and 3 showed that the EC values under all treatments were the highest at a depth of 0.01 m and gradually decreased until reaching their lowest value at a depth of 0.5 m. This trend was consistent throughout the three-year study period. The high EC value in the upper layer under all treatments is due to water evaporation from the surface, whether under FUI treatments or SDI, where the irrigation pipes were placed at a depth of 0.015 m. Hence, there was an upward movement of water by evaporation and capillary rise, resulting in salt accumulation at the soil surface. This finding is consistent with previous studies by Assadian et al. (2005), Choi and Rey (2004), and Heidarpour et al. (2007). Many researchers, such as Du et al. (2022), Virga et al. (2020), and Wang et al. (2021), illustrated that the EC of the soil under RW treatments was not significantly different



**Fig. 3** Soil EC (dS/m) for the different irrigation treatments after harvesting, throughout the three years. RW reclaimed water, CW clean water, SDI subsurface drip irrigation, APRI alternate partial root zone irrigation, FI full irrigation, FUI furrow irrigation

from the EC of the soil under CW, which is consistent with the findings of this study.

Although there were no significant differences between the treatments, we noted that throughout the three years, the EC values under the RW treatments were higher than the EC values under the corresponding treatments that were irrigated with CW.

For example, the EC under SDI-APRI irrigated with RW was higher than in the corresponding treatment that was irrigated with CW by 1.45%, 10.17%, and 7.94% at the end of the season of the first year, second year, and third year, respectively. The percentages of increase when comparing the FUI-APRI under RW with the FUI-APRI under CW were also close to these percentages, as they were 1.57%, 7.23%, and 9.46% at the end of the season of the first year, second year, and the third year, respectively. Irrigation water is considered the primary source of salts in the soil (Heidarpour et al. 2007). In this study, the EC value of RW was greater than that of CW. Therefore, the application of RW causes greater EC than CW in the soil layers (Table 1).

These findings are in agreement with previous studies (Guo et al. 2017; Licata et al. 2022), who stated that irrigation with RW increased the EC of the soil compared to the CW. Similarly, Liang et al. (2022) stated that the content of soil total salinity was higher after RW irrigation than those with CW irrigation.

Numerous variables, such as the quality of irrigation water, the irrigation techniques, the soil properties, and the plant absorption characteristics, can all affect the build-up of salts in the soil. Additionally, the accumulation of salts increased as the number of irrigation cycles increased, which resulted in more ions being added to the soil (Guo et al. 2017).

### Soil pH

Soil pH is a crucial parameter because it can affect the nutrient charge and how readily available nutrients are to crops (Urbano et al. 2017).

In the present study, over the three years, the values of soil pH in all treatments were between 8.06 and 9.05 with only a small variation among treatments (Figs. 4 and 5). This may be due to high soil buffering capacity (Guo et al. 2017).

These results were in accordance with findings by Licata et al. (2022) who stated that the soil pH varied very little throughout a three-year period. The soil pH was found to be lower at the upper layer and gradually increased until reaching its highest value at a depth of 0.4–0.5 m.

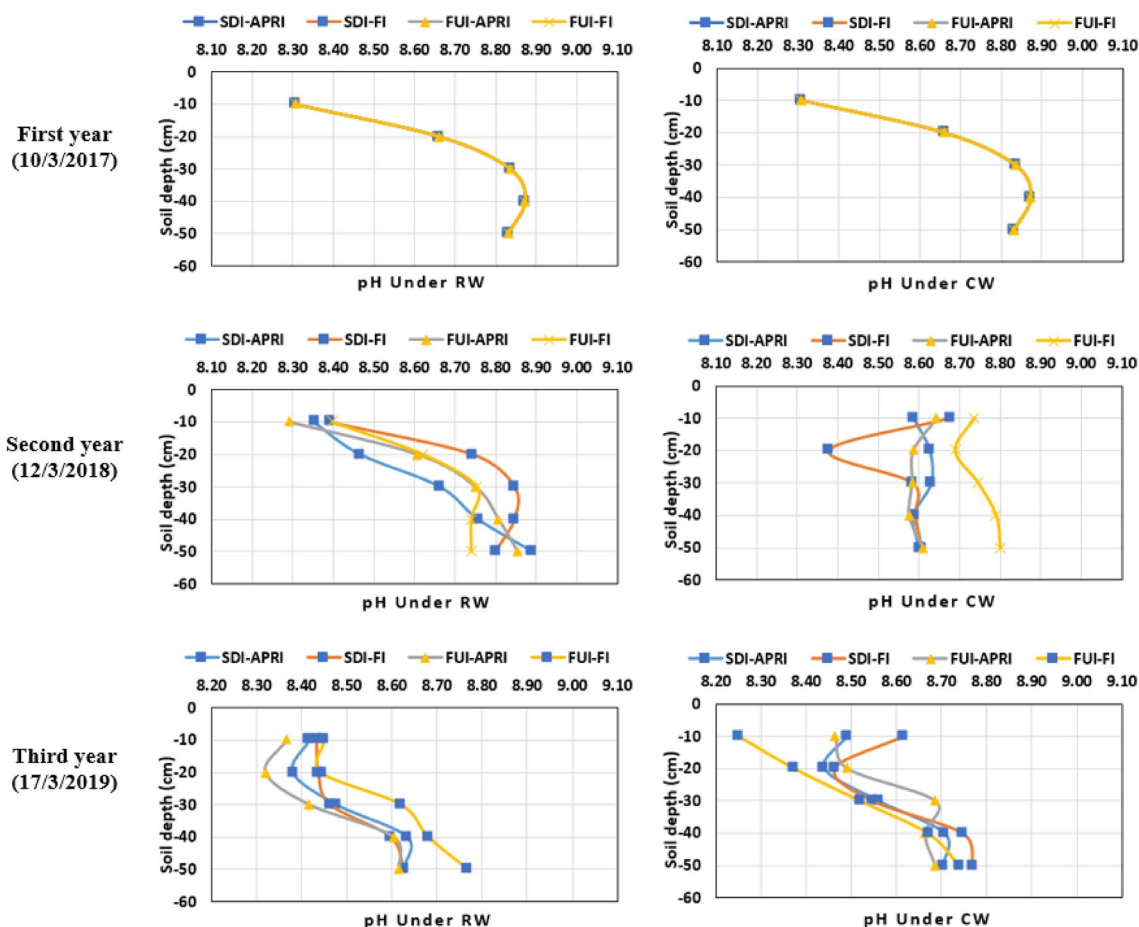
The average soil pH in the first year at the end of the season ranged from 8.78 to 9.01, while in the second year at the beginning of planting, it ranged from 8.32 to 8.77, and then ranged from 8.46 to 8.63 at the end of the season. The pH value in the third year at the beginning of planting ranged from 8.63 to 8.46, while it ranged from 8.62 to 8.79 after harvesting. This same trend was also reported by Urbano et al. (2015, 2017). There were no significant effects ( $P > 0.05$ ) on soil pH due to the treatments. These results were similar to those of other researchers, such as Du et al.

(2022) and Virga et al. (2020), who reported that there were no significant effects on the pH of soil due to water quality.

In a three years study, Bernstein et al. (2009) found that there was no significant difference in soil pH between RW and CW treatments. Liang et al. (2022) reported that under RW irrigation, the soil pH (ranging from 7.76 to 8.73) after 5 years had no significant difference in different soils compared with the contrast treatment under CW. This is similar to the previous results, which also revealed no significant difference in soil pH after years of RW irrigation (Liu and Chang, 2011). However, Qian and Mecham (2005) reported that irrigation with RW can increase soil pH due to its high concentration of  $\text{HCO}_3^-$ , salt, and plant nutrients.

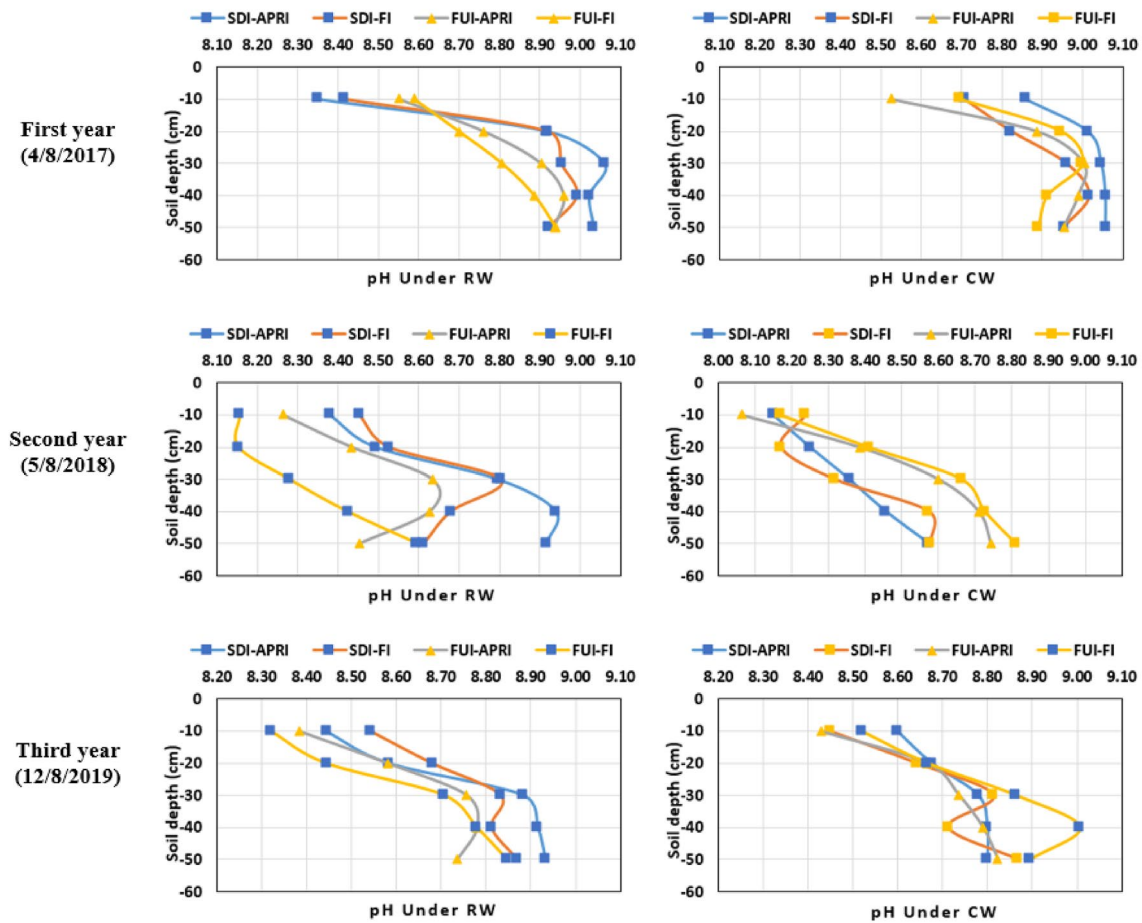
### Soil organic matter (OM)

Soil organic matter (OM) is a vital nutrient for the growth and development of plants and thus is considered one of the main indicators to determine soil fertility levels.



**Fig. 4** Soil pH for the different irrigation treatments at the beginning of the planting throughout the three years. RW reclaimed water, CW clean water, SDI subsurface drip irrigation, APRI alternate partial root zone irrigation, FI full irrigation, FUI furrow irrigation





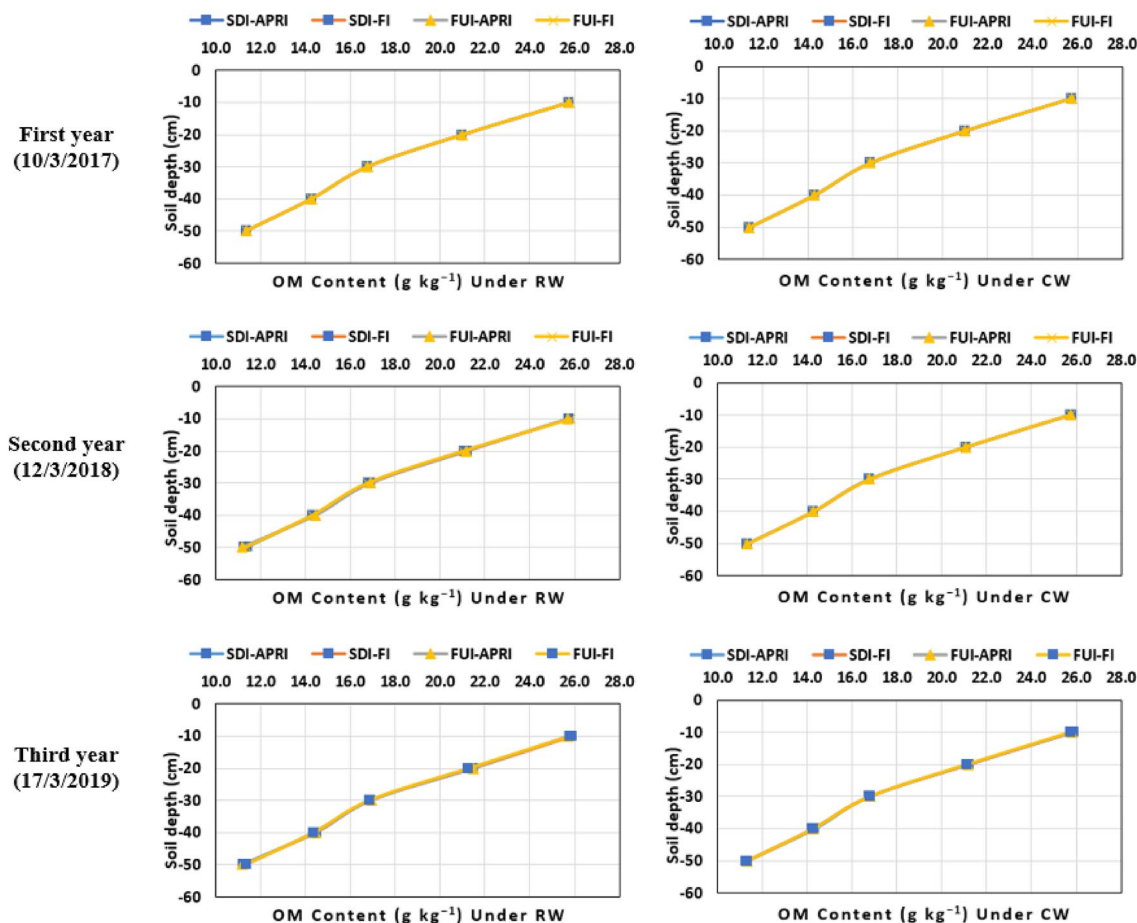
**Fig. 5** Soil pH for the different irrigation treatments after harvesting, throughout the three years. *RW* reclaimed water, *CW* clean water, *SDI* sub-surface drip irrigation, *APRI* alternate partial root zone irrigation, *FI* full irrigation, *FUI* furrow irrigation

In the present study, the soil OM remained relatively constant under the different treatments throughout the three years. The results showed that the experimental factors had very little influence on soil OM across all treatments (Figs. 6 and 7). Organic matter values in the first year ranged from 17.821 to 17.836 g kg<sup>-1</sup>, while these values ranged from 17.833 to 17.927 g kg<sup>-1</sup> in the second year and from 17.837 to 18.050 in the third year. There was no significant difference ( $P > 0.05$ ) in soil OM between all the experimental factors, and the same behavior was found in their interaction. The results showed that there was no notable tendency for the effect of irrigation techniques and irrigation methods on the values of soil OM.

The values of soil OM under RW treatments increased very slightly compared with the corresponding treatments under CW throughout the three years. Although this increase is very small, it increased every year compared to the year before, and this is consistent with the finding that long-term reclaimed water irrigation can increase soil OM (Urbano et al. 2017).

Compared to the soil OM under CW, the soil OM values under RW increased by only 0.05% to 0.07%, 0.16% to 0.43%, and 0.36% to 0.96% in the first year, the second year, and the third year, respectively. This increase is very small, although the RW has a higher concentration of OM than CW (Table 1). This result may be due to the presence of actinomycetes in RW, which can accelerate the decomposition of OM and reduce soil OM concentration, resulting in little change in soil OM under different treatments.

Our results are consistent with the findings of Virga et al. (2020). They reported that the level of organic constituents in the RW plots was not significantly higher than that of the CW plots. Also, Liang et al. (2022) reported that the soil OM concentration did not change significantly after RW irrigation in most plants. However, Du et al. (2022) reported that the soil OM significantly increased under unconventional water irrigation in the top layer. There is no consensus in the literature on the effects of RW on soil's physical properties (Hashem and Qi 2021).



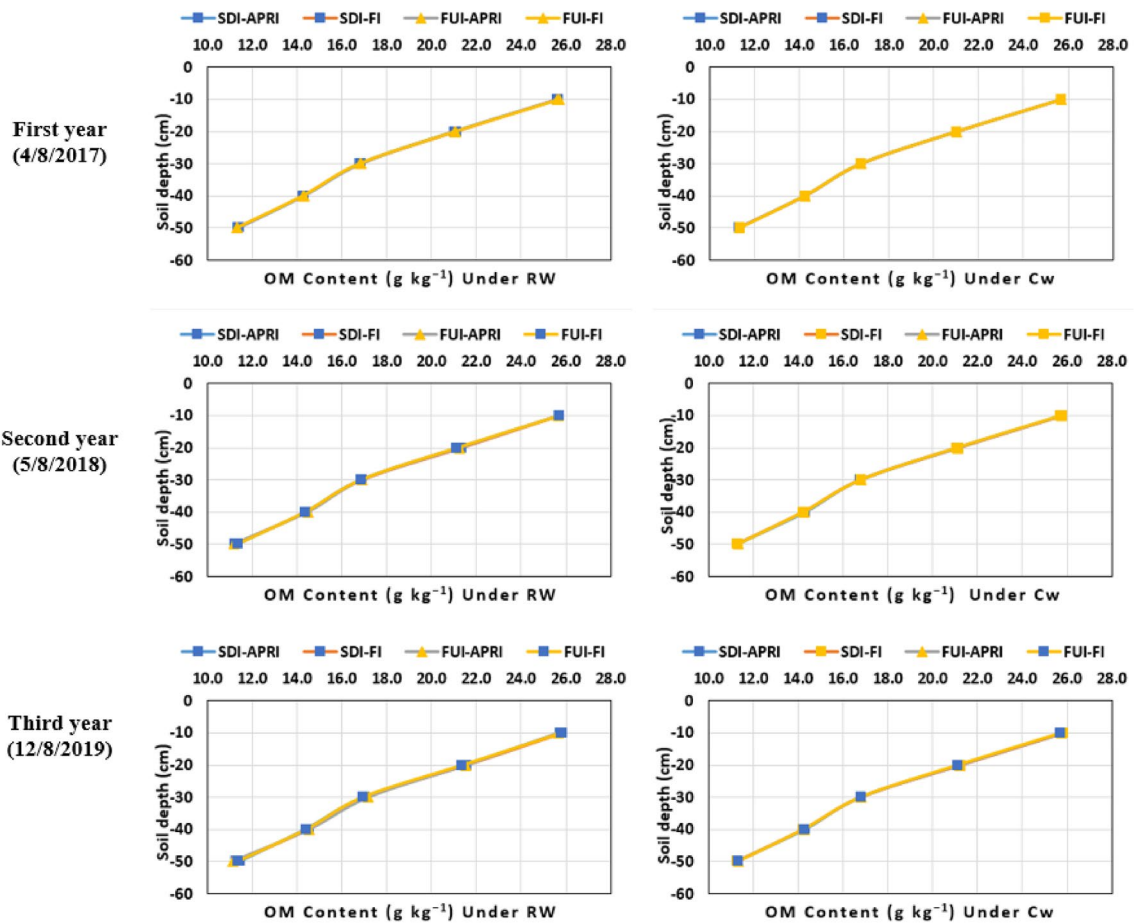
**Fig. 6** Soil OM ( $\text{g kg}^{-1}$ ) for the different irrigation treatments at the beginning of the planting throughout the three years. RW reclaimed water, CW clean water, SDI subsurface drip irrigation, APRI alternate partial root zone irrigation, FI full irrigation, FUI furrow irrigation

This discrepancy in OM may be due to the nature of the water sources, irrigation amount, and irrigation frequency.

### Tomato fresh fruit yield (FY)

The fresh fruit yield per hectare (FY) was calculated for each treatment as  $\text{Mg ha}^{-1}$ . FY for all different irrigation treatments through the three years of the experiment was shown in Table 4. In general, Table 4 showed that through the three years of the experiment, the highest yield was obtained under RW. As we can see from Table 4, the highest yield values were obtained under SDI-FI, SDI-APRI, FUI-FI, and FUI-APRI, respectively, whether under RW or CW. The results showed that under RW, the values of FY under SDI-FI increased more than FY with SDI-APRI through the years of the experiment, but this rise was not significant ( $P > 0.05$ ) in the first and third year. Also, through the three years of the experiment, the FY with FUI-FI increased more than the values under FUI-APRI, but this increase was not significant ( $P > 0.05$ ).

Analysis of variance over the years of the experiment showed that there was a significant effect ( $P < 0.05$ ) for the irrigation water qualities, irrigation techniques, and irrigation methods on the tomato yield. The interaction between the experimental factors also had a significant effect ( $P < 0.05$ ) on the tomato yield except for the third year. Table 4 showed that the mean of tomato yields under RW was higher than those under CW in each of the three years. Similarly, the means of the tomato yield under FI were high compared to those under APRI. The finding of the present study that the tomato yield increased under RW was consistent with previous research by Xu et al. (2010) and Gu et al. (2019), who also reported increased crop production under RW. This increase in productivity may be due to the high levels of nutrients that RW can supply (Guo et al. 2017; Teklehaimanot et al. 2015). Jamjoum and Khattari (1986) attributed the increase in the yield production of corn under RW to the improvement in soil physical characteristics and the increase in nutrient uptake. The results of the present study are consistent with those of Najafi, (2006), who



**Fig. 7** Soil OM (g kg<sup>-1</sup>) for the different irrigation treatments after harvesting throughout the three years. RW reclaimed water, CW clean water, SDI subsurface drip irrigation, APRI alternate partial root zone irrigation, FI full irrigation, FUI furrow irrigation

**Table 4** Tomato fresh fruit yield (FY) Mg ha<sup>-1</sup> under all treatments throughout the three years

Years	Yield (Mg ha <sup>-1</sup> )/SE							
	R-SDI-APRI	R-SDI-FI	R-FUI-APRI	R-FUI-FI	C-SDI-APRI	C-SDI-FI	C-FUI-APRI	C-FUI-FI
2017	137.82/83	145.94/1.09	114.39/2.65	116.48/2.41	109.39/0.87	118.27/1.27	103.29/1.52	108.46/0.63
2018	120.01/1.51	128.92/1.35	105.25/1.15	109.31/2.24	98.51/0.95	110.96/1.27	95.4/0.36	97.98/1.26
2019	116.68/2.54	121.96/1.38	103.28/1.25	107.16/0.46	91.66/1.04	98.72/0.77	79.61/0.16	88.65/1.06

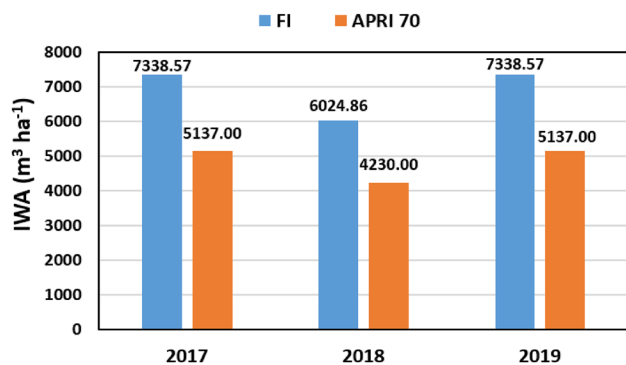
reported that the tomato maximum yield was obtained under drip irrigation in comparison to the other irrigation systems. This may be due to improved soil moisture and an increase in the amount of accessible nitrogen in the root zone. Furthermore, compared with surface irrigation, the SDI reduces the growth of grass and weeds and limits the plant nutrients’ leaching (Khawla et al. 2019; Singh et al. 2000).

The results of the present study were consistent with the findings of Zegbe et al. (2004), who observed that the regime treatments did not affect the FY of fruit. Also, the present results agree with the findings of Al-Hadidi and Sweity (2022), who stated that compared with APRI and

deficit irrigation, the treatments of FI gave the highest yield, and they attributed these results to the fact that the soil water content was higher under full irrigation than that under deficit irrigation.

### Irrigation water use efficiency (IWUE)

The IWUE is an important indicator that reflects the effective use of water resources in crop production (Kuscu et al. 2014). The improvement in the IWUE is essential for maintaining crop yields while mitigating water shortages (Ma et al. 2015; Xu et al. 2018).



**Fig. 8** Amount of irrigation water applied per hectare (IWA ( $\text{m}^3 \text{ha}^{-1}$ )) at the FI and APRI throughout the three years

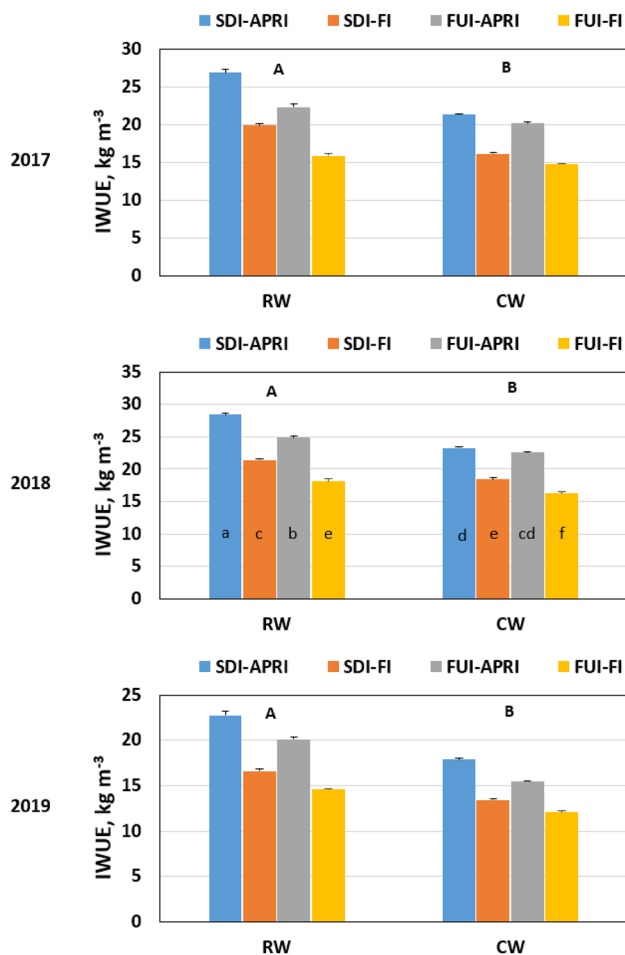
One of the goals of deficit irrigation is to raise IWUE by reducing the amount of water applied or by decreasing the number of irrigation events (Mohawesh and Karajeh 2015; Serhat 2017). So the amount of irrigation water applied (IWA) was recorded for the tomato crop under all treatments during the three years of the experiment as presented in Fig. 8.

During the three years of the experiment, the highest IWUE values were found in SDI-APRI, FUI-APRI, SDI-FI, and FUI-FI treatments, respectively, both under RW and CW.

The values of IWUE for all irrigation treatments were shown in Fig. 9. Generally, the IWUE was consistently higher under APRI compared to FI in all three years, for both RW and CW. Also, SDI showed higher IWUE values compared to FUI. Throughout all three years, the IWUE values were consistently higher under RW compared to CW for all treatments.

The results illustrated that the IWUE values under SDI-APRI were greater under RW than the values under SDI-FI by 34.91%, 32.58%, and 36.68% in the first year, second year, and third year, respectively. The same trend was obtained under CW, where the values under SDI-APRI were greater than the SDI-FI values in the first year, second year, and third year by 32.12%, 26.45%, and 32.63%, respectively. When comparing the IWUE values of SDI-APRI under RW and CW, it was found that the values were raised by 25.99%, 21.82%, and 27.29% in the first year, second year, and third year, respectively.

Statistical analyses through the three years showed a significant effect ( $P < 0.05$ ) of water types, irrigation methods, and irrigation techniques on the IWUE. However, there was no significant interaction ( $P > 0.05$ ) between the experimental factors on IWUE over the first and second years (Table 5). Table 5 shows that the mean IWUE values were higher under RW than those under CW, and higher under APRI than under FI, as well as higher under the SDI than under FUI for all the three years.



**Fig. 9** IWUE ( $\text{kg m}^{-3}$ ) for the different irrigation treatments in tomatoes over the three years. The different capital letters on the top of the figure represented significant differences between water types at  $P < 0.05$ . Different letters inside columns showed significant differences between irrigation treatments at  $P < 0.05$ . Bars give the means  $\pm$  standard error of the mean ( $n = 3$ ). RW reclaimed water, CW clean water, SDI subsurface drip irrigation, APRI alternate partial root zone irrigation, FI full irrigation, FUI furrow irrigation

The current results are consistent with previous studies that found deficit irrigation and APRI strategies to be more effective on improving IWUE than FI (Cheng et al. 2021; Tabatabaei et al. 2017; S Hashem et al. 2018).

Increases in IWUE in tomatoes under water deficit treatments have been reported in most studies (Chen et al. 2013; Patanè et al. 2011; S Hashem et al. 2018). APRI improved IWUE by 11.5%, according to Kirda et al. (2004). According to Nangare et al. (2016), the use of deficit irrigation increased water productivity to its highest level. The findings of the present study are consistent with those of Topçu et al. (2007) and Yang et al. (2012), who also found that IWUE can be increased under APRI and deficit irrigation.

The increase in IWUE values under deficit irrigation practices could be attributed to the partial stomatal closure

**Table 5** Analysis of variances on the effect of water qualities, irrigation methods, irrigation techniques, and their interaction on tomato yield IWUF, and NUE in the three years

Factor	Yield (Mg ha <sup>-1</sup> )			IWUE (kg m <sup>-3</sup> )			NUE (kg kg <sup>-1</sup> )		
	1st year	2nd year	3rd year	1st year	2nd year	3rd year	1st year	2nd year	3rd year
Water type									
RW (reclaimed wastewater)	128.66 a	115.87 a	112.27 a	21.21 a	23.20 a	18.51 a	221.68 a	199.64 a	213.28 a
CW (clean water)	109.86 b	100.71 b	89.66 b	18.07 b	20.13 b	14.72 b	189.27 b	173.52 b	154.48 b
<i>p</i> -value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Irrigation methods									
FI (full irrigation)	122.29 a	111.79 a	104.12 a	16.66 b	18.56 b	14.19 b	210.70 a	192.61 a	189.52 a
APRI (alternate partial root-zone irrigation)	116.23 b	104.79 b	97.81 b	22.63 a	24.77 a	19.04 a	200.25 b	180.55 b	178.24 b
<i>p</i> -value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Irrigation techniques									
FUI (furrow irrigation)	110.66 b	101.98 b	94.68 b	18.26 b	20.46 b	15.57 b	190.65 b	175.71 b	172.42 b
SDI (subsurface drip irrigation)	127.86 a	114.60 a	107.26 a	21.03 a	22.87 a	17.66 a	220.29 a	197.44 a	195.34 a
<i>p</i> -value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Water type × Irrigation methods × Irrigation techniques									
<i>p</i> -value	0.000	0.000	0.166	0.464	0.037	0.557	0.661	0.208	0.380

Mean values followed by the same letter within each factor are not significantly different ( $P < 0.05$ )

that occurred under PRD treatments and which caused a decrease in transpiration rate without any detectable changes in plant water status, and consequently, an increase in irrigation water use efficiency (Hashem et al. 2019). According to Cheng et al. (2021), the yield changes under APRI were not dramatically different from FI for tomatoes and potatoes, whereas the corresponding IWUE was significantly higher. APRI technique increases IWUE through a stress-related chemical produced by the drying roots (abscisic acid), which is delivered to the leaves and leads to physiological changes that reduce water loss from leaves (El-Sadek 2014).

Pazzagli et al. (2016) indicated that the enhancement of IWUE was closely linked to stomatal function. Liu et al. (2013) proposed that higher IWUE with reduced irrigation depth might be due to efficient utilization of available soil water in the root zone. Under FI conditions, some irrigation water might not be utilized and may accumulate in the soil profile, resulting in decreased IWUE. Over-irrigation can also lead to deep percolation beyond the root zone, further reducing IWUE.

Drip irrigation is the most effective irrigation method for vegetables because it limits water drainage and evaporation with frequent small water supplies, leading to higher IWUE (Zhang et al. 2017). Mehmood et al. (2019) revealed that IWUE was higher under drip irrigation compared to surface irrigation for the same nitrogen application rate. Similarly, Hassanli et al. (2016) and Jha et al. (2016) stated that IWUE was higher for drip irrigation than for FUI. Bai et al. (2020) reported that flood irrigation results in a low IWUE, which can threaten the sustainability of agriculture. Yuan et al. (2022) reported that drip irrigation increased

average IWUE by 8.8% compared to flood irrigation during two winter wheat seasons. Jha et al. (2019), stated that under deficit irrigation, the IWUE of the drip system was higher than surface irrigation systems. The increased IWUE in the SDI could be due to lower evaporation, uniform distribution of water and nutrients, lower deep water percolation, and easy nutrient and water availability in the root zone. Khawla et al. (2019) stated that compared to surface irrigation, SDI resulted in the largest amounts of nutrient elements.

Alkhamisi et al. (2011) found that plants irrigated with RW were more effective than those irrigated with CW for all water quantities. Hassanli et al. (2009) also reported that a higher IWUE was achieved with effluent irrigation than those with clean water. Similarly, Demir and Sahin (2017) observed higher IWUE under treated wastewater than under clean water irrigation. According to Hassanli et al. (2010), RW can result in higher yield and IWUE than CW irrigation due to its high nutrient content and organic matter. Al-Hadidi and Sweity (2022), demonstrated that 60% ET<sub>c</sub> under RW improved IWUE by 20% and saved 40% water. Soltani-Gerdefaramarzi et al. (2021) stated that integrating RW with deficit irrigation techniques can mitigate water scarcity and improve IWUE. Overall, APRI practices with RW in dry and semi-dry areas with limited water resources could be a practical and effective strategy to increase IWUE.

### Nitrogen use efficiency (NUE)

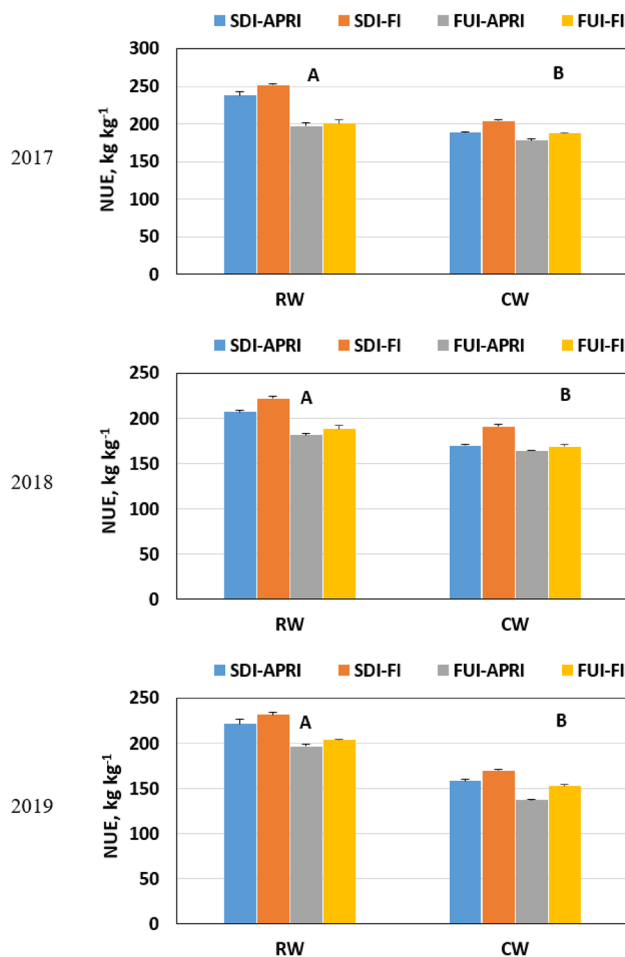
This study consisted of eight treatments, with the same total nitrogen amount of 580.4 kg ha<sup>-1</sup> and the same nitrogen

application schedules (53% base and 47% topdressing), as shown in Fig. 10.

Nitrogen is an extremely important nutrient element, and it is the main index of the quality of agricultural soils (Chen et al. 2021). Split nitrogen application during crop growth can help satisfy the plant nitrogen demand and improve NUE. Du et al. (2019) and Zhang et al. (2021) found that split nitrogen application at a reduced rate improved nitrogen uptake, nitrogen harvest index, NUE, and sweet potato yield. Split fertilizers application can also prevent excessive fertilization in the early growth period and ensure sufficient nutrient supply at the later stages (Lu et al. 2021). Figure 11 showed NUE values for all treatments throughout the three years of the experiment. Under both irrigation techniques, NUE was consistently higher under RW compared to those under CW during the three years.

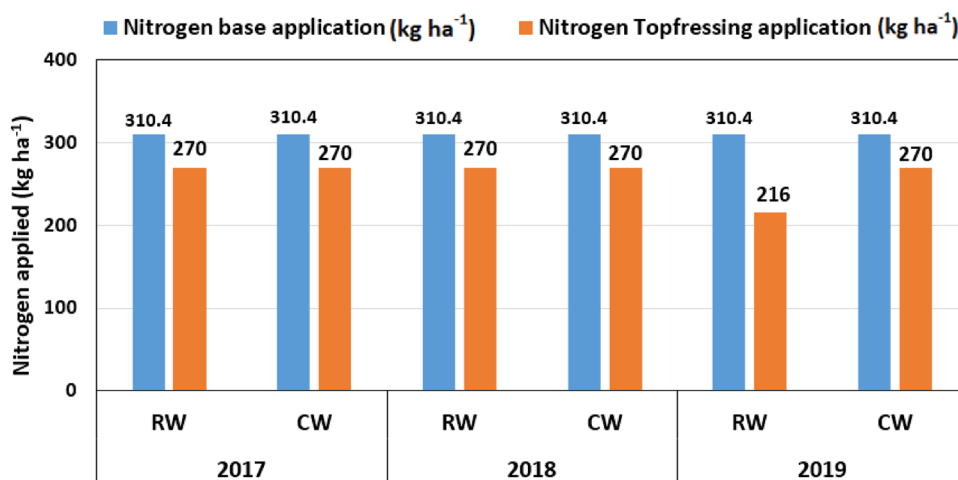
In the first year, NUE values ranged from 197.10 to 251.45 kg kg<sup>-1</sup> under RW and from 177.96 to 203.78 kg kg<sup>-1</sup> under CW. In the second year, NUE values ranged from 181.33 to 222.12 kg kg<sup>-1</sup> under RW and from 164.38 to 191.17 kg kg<sup>-1</sup> under CW. The values of NUE in the third year ranged from 196.21 to 231.68 kg kg<sup>-1</sup> under RW and from 137.16 to 170.10 kg kg<sup>-1</sup> under CW (Fig. 11). These data clearly showed that under the same irrigation technique, the higher water input leads to greater NUE, consistent with Wang and Xing, (2016). Statistical analyses indicate a significant effect ( $P < 0.05$ ) for water types, irrigation methods, and irrigation techniques on the NUE throughout the three years. However, there was no significant effect ( $P > 0.05$ ) for the interaction between the experimental factors on NUE over the three years (Table 5). Higher values of NUE were observed under the RW than CW. Similarly, the mean values of NUE under the FI were higher than those under APRI, and were higher under the SDI than under FUI throughout the three years.

The result illustrated that under the RW treatments, the NUE values were higher under SDI-FI compared to



**Fig. 11** NUE (kg kg<sup>-1</sup>) for the different irrigation treatments through the three years. The different capital letters on the top of the figure represented significant differences between water types at  $P < 0.05$ . Bars give the means  $\pm$  standard error of the mean ( $n=3$ ). RW reclaimed water, CW clean water, SDI subsurface drip irrigation, APRI alternate partial root zone irrigation, FI full irrigation, FUI furrow irrigation

**Fig. 10** Amount of nitrogen applied per hectare (kg ha<sup>-1</sup>) with the RW (reclaimed water) and CW (clean water) through the three years



SDI-APRI in all three years, with increases of 5.89%, 7.42%, and 4.52% in the first, second, and third years, respectively (Fig. 11). However, this increase was not significant ( $P > 0.05$ ). The same trend was observed under CW, where NUE values increased by 8.12%, 12.63%, and 7.70% under SDI-FI compared to SDI-APRI in the first, second, and third years, respectively. Similarly, NUE values were higher under FUI-FI compared to FUI-APRI throughout the three years under both RW and CW, However, this increase was also not significant ( $P > 0.05$ ).

These findings were consistent with DU et al. (2017), who found that NUE increased with the amount of water applied for the same level of N application. The NUE values under RW were higher compared to those under CW. This is because RW led to an increase in yield, as RW is a rich source of N, P, and K, which helped to enhance biomass production (Leonel and Tonetti 2021; Nagi et al. 2020). Several studies have reported a considerable increase in total N, effective P, and total K content in soil irrigated with RW compared to clean water (Guo et al. 2017; Li et al. 2014).

The NUE under SSD was higher compared with FUI due to the fruit yield improvement and timely scheduled fertigation that may have reduced N losses through several pathways. This finding is consistent with those obtained by other researchers, such as Li et al. (2014), who demonstrated that drip irrigation reduced water input and nitrate leaching while increasing NUE. Limiting the wetted volume in the root zone through techniques like SSD can enhance NUE (Singandhupe et al. 2003), as nitrate tends to accumulate toward the boundary of the wetted volume (Li et al. 2003).

## Conclusion

Overall, the experiment results throughout the three years showed that the fresh fruit yield was significantly affected by experimental factors. The highest yield was obtained under reclaimed wastewater. Moreover, subsurface drip irrigation resulted in a higher mean fresh fruit yield than those with furrow irrigation. The highest values of irrigation water use efficiency were obtained under alternate partial root-zone irrigation compared to full irrigation throughout the three years. This was true for both reclaimed wastewater and clean water. For all three years, the fresh fruit yield, the irrigation water use efficiency, and the nitrogen use efficiency values under reclaimed wastewater were higher than those under clean water, as well as under subsurface drip irrigation compared to furrow irrigation. Analysis of variances showed that the experimental factors and their interaction had no significant effect on the soil electrical conductivity, PH, and organic matter over the three years.

In conclusion, the application of reclaimed wastewater under subsurface drip irrigation can result in saving clean

water and increasing productivity without any negative effect on the investigated soil properties. Furthermore, combining reclaimed wastewater under subsurface drip irrigation with alternate partial root-zone irrigation can result in increase in irrigation water use efficiency, demonstrating the potential for sustainable agricultural practices that benefit both crop productivity and the environment.

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**Data availability** The authors confirm that the data supporting the findings of this study are available within the article and its supplementary material. Raw data that support the findings of this study are available from the corresponding author, upon reasonable request.

## Declarations

**Conflict of interest** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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