Agricultural Water Management 297 (2024) 108832

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

A novel smart fertigation system for irrigation with treated wastewater: Effects on nutrient recovery, crop and soil

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ARTICLE INFO

Editor: Dr Z Xiying

Keywords:
Water scarcity
Tertiary treated wastewater
Wastewater reuse
Fertilizer saving
Plant nutritional status
Plant physiological performances

ABSTRACT

Both southern and northern regions of Italy are experiencing reduced precipitation and increased heat waves due to climate change, negatively affecting agricultural sector. Urban wastewater could be a solution to this problem, providing a constant source for irrigation and reducing synthetic fertilizer use. This research presents a two-year field study on using tertiary treated wastewater for processing tomato crop irrigation through an innovative smart fertigation system, designed to supply the exact doses of NPK nutrients considering those already delivered to the plants via the irrigation water. With the aim of studying the effects of irrigation with treated wastewater, three water sources were compared: fresh water added with chemical fertilizer, tertiary treated wastewater added with chemical fertilizer and tertiary treated wastewater without addition of fertilizer. The proposed system was efficient and consistent with the design, it saved considerable amounts of fertilizers, handling nutrient fluctuations in wastewater. Of the three irrigation water types that have been tested, only the one that used tertiary treated wastewater alone without additional fertilizers was not capable of meeting tomato nutritional needs, despite the fact that significant macronutrient savings were achieved. No negative effects on soil or plant physiological performances were observed. Plants irrigated with wastewater showed similar growth and productivity to those irrigated with fresh water and no significant differences in fruit quality were found, highlighting the benefits of wastewater reuse for crop irrigation.

1. Introduction

In Italy, as in most part of the world, agriculture is affected by increasing water scarcity, which is compromising crop cultivation and, thus, food safety, especially in the southern regions (Pollice et al., 2004). In recent years, however, even the northern regions, historically less prone to drought, are experiencing a significant reduction in winter precipitation and snowfall and an increase in summer heat waves. This trend is particularly evident for those regions belonging to the Po Valley, which is one of the most important agricultural area not only in Italy, but also in Europe (Toreti et al., 2022a, 2022b, 2023). In these regions, extended droughts have primarily resulted from climate change (Faranda et al., 2023). Future projections indicate that droughts will worsen due to reduced rainfall, with longer periods without rain, and higher average temperatures (Seneviratne et al., 2021).

Reclaimed water represents one of the most readily available alternative water sources in contexts where natural water sources are depleted or suffering (Cirelli et al., 2012). Wastewater is produced continuously, and its production is not heavily impacted by climate change (Fernandes et al., 2023). Therefore, reclaimed water might provide a constant water source for crop irrigation (Mancuso et al., 2022), also during the expected periods with a lack of precipitation (Libutti et al., 2018a). Different studies have proved that the use of reclaimed water in agricultural irrigation, increases the endowment of organic matter in the soil (Aiello et al., 2007) and vehiculates plant macronutrients (e.g., N, P, K) in bioavailable forms (nitrates, ammonium, phosphates, potassium ion), that can partially satisfy crop needs (Aiello et al., 2007). As advantage, the use of reclaimed water might allow the reduction of synthetic fertilizers (Mancuso et al., 2023), helping farmers to increase the economic sustainability of irrigated productions (Al-Lahham et al., 2003; Christou et al., 2017; Cirelli et al., 2012; Hewa et al., 2020; Licata et al., 2019). However, reclaimed water in agricultural irrigation is still poorly used. A recent study showed that in Italy reclaimed water might cover up to 27.7% of crop water needs (Mancuso et al., 2020) while currently it is only 5% (Utilitalia, 2022); also, in Europe the percentage was very low, indeed, only 2.4% of the water used in agricultural irrigation was the effluent of wastewater treatment plants (WWTP) (Bonetta et al., 2022).

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https://doi.org/10.1016/j.agwat.2024.108832
Received 2 February 2024; Received in revised form 12 April 2024; Accepted 15 April 2024

The reuse of wastewater can also have negative impacts such as soil salinization and contamination of agricultural products with microbial pathogenic agents, heavy metals, and other hazardous organic compounds (Perulli et al., 2021). For example, salinity is a major factor that reduces crop productivity all over the world (Krasensky and Jonak, 2012), while the excessive accumulation of trace metals like Cd, Cu, Fe, Mn, Pb, and Zn in soils due to irrigation causes problems for agricultural production (Singh et al., 2004) and affects food quality and safety by leading to metal uptake by crops (Khan et al., 2008). Moreover, one of the significant challenges in using treated wastewater for crop irrigation is the presence of residual pathogenic microorganisms, which pose a potential health risk to consumers when they enter the food chain (Perulli et al., 2024; Toze, 2006). The importance of a wider use of reclaimed water in agricultural irrigation has been prompted by the European Union with the introduction of the new Regulation (EU) 2020/741, which came into force from June 2023 (Berti Suman et al., 2023; European Parliament, 2020). As indicated by the (EU) 2020/741, wastewater needs to be treated properly before being used in agricultural irrigation, in order to avoid risks to human, animal and environmental health (Aiello et al., 2013; Mancuso et al., 2021). In Italy, the European legislation will be transposed by a Presidential Decree, which is currently about to be approved (DPR, 2023).

Nutrient concentrations in reclaimed water depend on the type of treatment and they can vary during the irrigation season. To avoid imbalance in macronutrient supply, it is important to monitor nutrient content in reclaimed water in real time. In fact, fluctuations in macronutrient concentrations as well as the supply of macronutrients when they are not necessary to satisfy plant needs can lead to excessive vegetative growth, uneven fruit maturity, reduced quality and quantity of yields (Pedrero et al., 2010a). On the other hand, their concentration can sometimes be very low and therefore the use of additional fertilizers is necessary in order to meet crop needs (Christou et al., 2017; Chojnacka et al., 2020; Oubelkacem et al., 2020; Yalin et al., 2023).

In this context, processing tomato crop is one of the main cultivated crops in Italy (Istat, 2023) and it is likely to be most impacted by climate change in the next years (Ventrella et al., 2012). Since the reclaimed water might be used to satisfy water needs of this particular crop during the drought periods, it would be important to estimate any negative effects or benefits that this practice might have. However, at the best of the authors' knowledge, there are not major studies testing the effects of reclaimed water when irrigating processing tomato, particularly on its capability to ensure food safety as well as to meet crop nutrient needs.

Therefore, the present research aimed at testing a novel system for the processing tomato smart fertigation. The study was mainly focused to verify the attainment of the nutrient requirements of the different treatments, to evaluate the possible savings of fertilizer inputs and to assess the physiological state of the plants, their fruit quality and productivity. With this aim, an algorithm was developed and implemented to supply macronutrients (e.g. N, P, K) in addition to those already found in reclaimed water, in order to meet plant nutrient needs according to their phenological stage. To be able to do the full assessment of positive and negative sides of irrigation with reclaimed water, three different irrigation water sources were compared: i) tertiary treated wastewater without additional mineral fertilising solution (TW); ii) fresh water with additional fertilising solution (FW+F); iii) tertiary treated wastewater with additional mineral fertilising solution (TW+F).

2. Materials and methods

2.1. Experimental set up

The experimental activity was performed at the Cesena WWTP (44°10' N, 12°16' E; altitude, 15 m.a.s.l.) in Northern Italy. The novel system was tested for the processing tomato (*Solanum lycopersicum L.*; cv. 'Big Rio') smart fertigation using tertiary treated urban wastewater, aiming at investigating the effects of treated wastewater on tomato plants as well as at evaluating the capability of treated wastewater to meet plant nutrient needs. The experimental activity was performed during the irrigation season (from April to July) for the two successive years (2021 and 2022). During the experimental period, the daily meteorological parameters, such as the average daily air temperature, the daily average relative air humidity and daily cumulative precipitation were obtained from a nearby meteorological station.

Fig. 1 reports the fertigation scheme that has been implemented. Tomato plants were individually grown in nine 700 L bins (a) filled with an alkaline (pH 7.9) and clay loam (23% sand, 48% silt, 29% clay) soil (United States Department of Agriculture classification) (Fig. 2). Each of the bins contained six tomato plants (b). In order to prevent damage due to atmospheric agents and insect intrusion, tomato plants were protected by an exclusion hail net (20% shading) (Fig. 2).

Bins were divided into three rows with three irrigation treatments: (A) fresh water chemical fertilizer (FW+F), (B) tertiary treated wastewater added with chemical fertilizer (TW+F) and (C) tertiary treated wastewater without addition of fertilizer (TW). Two solenoid valves (c) allowed alternating input of fresh water (for the irrigation treatment A) and TW (for the irrigation treatments B and C) into the irrigation system (Fig. 1). Other three solenoid valves (d) allowed water to be conveyed individually to each row.

A dedicated pipeline system conveyed effluent from a tertiary treatment unit to the bins (e), previously being filtered by a disk filter (f) in order to avoid the clogging of the irrigation system. Both FW and TW volumes were monitored using a volumetric meter (g). In irrigation treatments A and B, chemical fertilizers (N, P, K) were supplemented to irrigation water by means of three peristaltic pumps (h) that collected nutrient solutions from three separate tanks (i). To prepare the mineral fertilizer solutions the following fertilizers were used: Calcium Nitrate [$Ca(NO_3)_2$], Monoammonium Phosphate [$(NH_4)H_2PO_4$], Potassium Sulphate [K_2SO_4]. Concentrations used to prepare the solutions were 40 g L^{-1}, 17 g L^{-1} and 12 g L^{-1}, respectively. Macronutrients (N, P, K) were balanced between the two fertigated treatments (FW+F, TW+F) through the smart fertigation system based on the constant monitoring of water quality and volume (Perulli et al., 2022) and the implementation of a specific algorithm that has been better discussed below (Fig. 3).

To calculate plant water needs, the indications of the Integrated Production Regulations of the Emilia-Romagna region were followed (Emilia-Romagna, 2021, 2022). These regulations contain indications on daily water restitutions for processing tomato crop, specified according to different phenological stages, such as post-transplanting, flowering-blossoming-fruit reddening, fruit ripening. Daily water restitutions, originally expressed in mm ha^{-1}, were followed and then converted in mm m^{-2}. Each bin was equipped with ten 1.1 L h^{-1} drippers (j) and received the following irrigation volumes: 454.7 L (TW), 486.1 L (TW+F), 495.2 L (FW+F) during 2021; 248 L (TW), 203.3 L (TW+F), 256.7 L (FW+F) in 2022 irrigation season. The differences between the volumes supplied in 2021 and 2022 can be attributed to the different weather-climate trends in the two seasons.

A closed piping system with three pressure gauges (k) installed in the three rows was used to regulate the flow rate.

The novel automation and control unit was designed especially for this experimental platform. The unit consisted of a system with a SCADA platform for data management and processing equipped with specially programmed and implemented control logics for the analysis of the data acquired by the experimental system. This analysis started from the evaluation of irrigation water quality (through the use of $N\text{-}NH_4$, $N\text{-}NO_3$, $P\text{-}PO_4^{3-}$, K probes placed within the tertiary treatment compartment), and based on those concentrations the fertigation of tomato plants was regulated. Amtax, Nitratax, Phosphax probes (Hach, Germany) were used to monitor $N\text{-}NH_4$, $N\text{-}NO_3$, $P\text{-}PO_4^{3-}$ content in wastewater, respectively.

In order to consider the amount of nutrients supplied to plants due to the irrigation with TW, and with the aim of integrating only the missing quantities of chemical fertilizers to reach plant nutrient requirements,

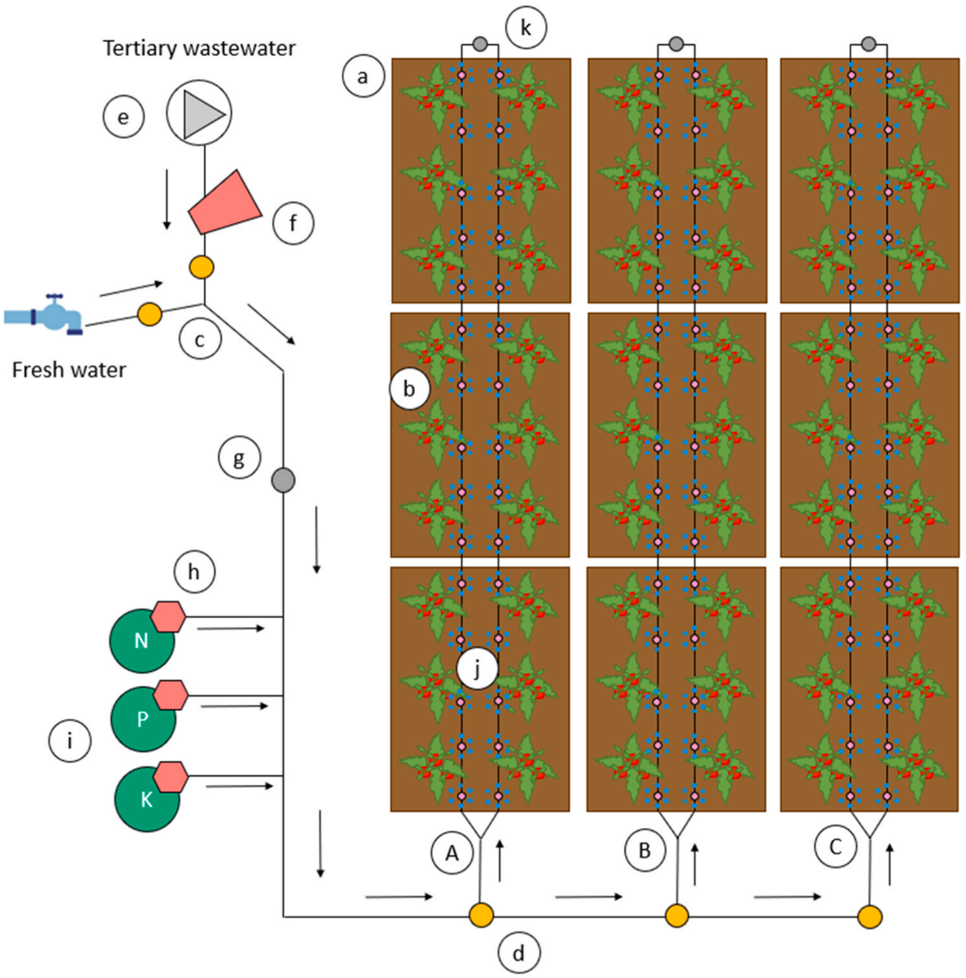

Fig. 1. Fertigation scheme: (a) 700 L bins; (b) tomato plants; (c, d) solenoid valves; (e) pump for TW collection; (f) disk filter; (g) volumetric meter; (i) fertigation station tanks (N, P, K); (h) peristaltic pumps); (j) drippers; (k) pressure gauge; (A) FW+F line; (B) TW+F line; (C) TW line.

Fig. 2. Nine 700 L bins filled with clay loam soil and divided into three rows, one per treatment.

an algorithm was implemented in the irrigation management software, by means of Eq. (1).

$$minutesON = \frac{PNN - \sum_{i=lastfert}^{today-1} Ndel * Vdel}{ST * PC} * 60 \tag{1}$$

where *minutesON* (min) is the dosing pump switch-on time, *PNN* (mg) is the plants nutrients needs, $\sum_{i=lastfert}^{today-1} Ndel$ (mg L^{-1}) is the sum of the weighted average of nutrient values (nutrient delivered) read by tertiary treated wastewater quality probes in the time interval between the last fertigation event and the day preceding the calculation, *Vdel* (L) is the water volume delivered between the start and the end of irrigation, *ST* (mg L^{-1}) is the nutrient solution title stored in the fertigation tanks, *PC* (L h^{-1}) is the pump flow rate, 60 is the coefficient to express the result in (min).

The system was also connected to an online platform for remote control, data analysis and download, and the creation of reports on a time basis chosen by the user. The objective of the implemented algorithm was to automate and optimise the tomato crop fertigation, taking all the relevant factors into account. It analyses the volumes of water distributed and the concentrations of nutrients present in them (nitrates, ammonium, phosphates and potassium) in order to calculate the administration of additional fertilizer based both on the pre-set needs of the plants, and on the quantities of nutrients actually conveyed through the tertiary treated wastewater during normal irrigation cycle.

In addition, the algorithm calculates the turn-on times of the three

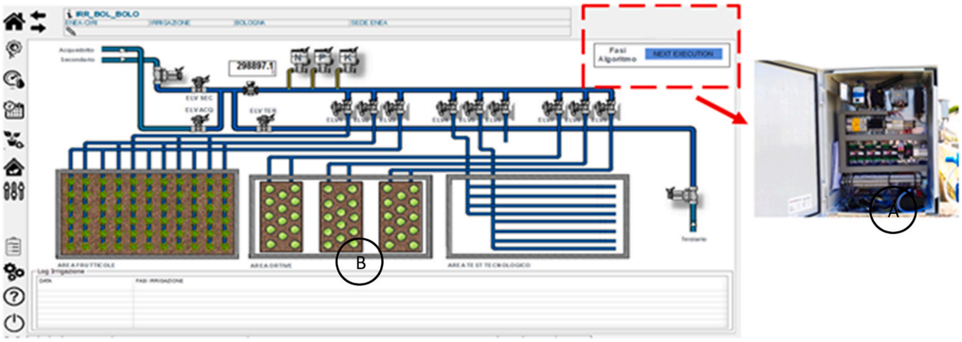

Fig. 3. (A) Control unit and (B) synoptic panel of the fertigation system.

metering pumps installed in the tanks containing the macro-nutrient mother solutions (N, P, K) and regulates the irrigation of the different sectors (corresponding to the different treatments). Following the scheme of this automated fertigation system, during the season, plants of the TW+F treatment, received doses of fertilisers solutions corresponding to the difference between plants nutritional need and the macronutrients supplied with the tertiary treated water, while the whole doses of macronutrients corresponding to plants nutritional need were supplied to FW+F plants. This permitted to compare the doses of N, P, K that were given through the three different treatments.

Nutrient needs were 2.3, 2.0 and 0.8 g plant^{-1} (respectively for N, P and K) for a period of 85 days after transplanting (DAT) for the both seasons. These nutrient needs were calculated on the basis of the indications reported on the Integrated Production Regulations of the Emilia-Romagna region (Emilia-Romagna, 2021, 2022) and converted from ha to m^2 and on a plant basis. These values refer to nutrients amounts added to freshwater (taking into account the low contents of N, P, K already present almost constantly in FW). On the contrary, in the case of TW+F, wastewater already contained a significant level of nutrients, continuously monitored by means of N, P and K sensors, and the smart fertigation system supplied only the missing content up to the overall tomato nutrient needs.

2.2. Water analysis

For each treatment, irrigation water samples were collected every two weeks in order to characterize the water quality (8 samples per irrigation season) to investigate a series of parameters different from the concentrations of N, P, K and their forms that were measured through sensors. Samples were collected in glass bottles, transported by 2 hours, in an ice chest to the lab and stored at 4 °C. The concentration of macronutrients, micronutrients and heavy metals were determined by Inductively Coupled Plasma (ICP-OES, England). Nitrate (NO_3)-N and nitrite (NO_2)-N determination were done using an auto analyser (Auto Analyzer AA-3; Bran+Luebbe, Norderstadt, Germany).

pH was measured with a pH-meter XS PH510 (Eutech Instruments, Singapore); EC was determined using the METERLAB, CDM 210 (Radiometer Analytical, France). The sodium absorption ratio (SAR) was calculated using the following equation (with concentrations in meq L^{-1}) (Richards 1954): $SAR = [(Na^{+})/ [(Ca^{2++} Mg^{2+})/ 2] 1/2$.

2.3. Soil chemical analysis

At the end of both irrigation seasons soil samples were collected at the depths of 0.00–0.20 and 0.21–0.40 m. Each sample was composed of 3 sub-samples (one for each of the three bins of the same treatment) collected exactly in the halfway point between the plant collar and the nearest irrigating dripper (Fig. 1). Soil samples were then stored at 4 °C, sieved through a 2 mm sieve, all roots and visible plant residue were removed by hand and a sub-sample was air-dried. These soil samples were used to evaluate soil pH, EC and total mineral content (e.g., heavy metals). Soil pH and EC were determined in a soil:water 1:1.2 (v/v) proportion suspension after 30 min of equilibration, following the recommendations of Tedesco (1995). Heavy metals were determined by wet mineralisation by treating 0.5 g of dry soil with 6 mL of HCl (37%), 2 mL of HNO_3 (65%) and 2 mL of H_2O_2 (30%) at 180° in an Ethos TC microwave labstation (Milestone, Bergamo, Italy). Solutions were filtered with filter papers (Whatman42Ò) and all the extracts were analysed by plasma spectrometer (Ametek Spectro, Arcos, Kleve, Germany).

Total Nitrogen was determined through Kjeldahl method, as follows. For the determination of soil nitrate (NO_3)-N and nitric (NO_2)-N concentrations, soil samples were shaken at 90 rpm for 1 h with a solution of 2 M KCl (100 mL) at a soil:solution ratio of 1:10, and after soil sedimentation, limpid solution was collected and stored at −20°C until analysis. Nitrate and nitrite determinations were made using an auto analyser (Auto Analyzer AA-3; Bran+Luebbe, Norderstadt, Germany).

2.4. Plant nutritional status

During mid-summer 20 mature leaves per plant were collected from randomly selected shoots. Leaves were treated as described in (Perulli et al., 2019) and then analysed for macro-micronutrients and heavy metals concentrations. Briefly, P, K, Ca, Mg, Na, S, Al, B, Ba, Cu, Fe, Mn, Sn, Zn were determined by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, Ametek Spectro Arcos EOP, Kleve, Germany), after digestion with nitric acid (HNO_3) by a microwave lab station (Ethos TC-Milestone, Bergamo, Italy), while N was determined by the Kjeldahl method. The same analyses were performed at harvest (85 DAT), on 6 representative fruit per treatment to determine mineral concentrations.

Leaf chlorophyll content was measured using the SPAD-502 meter (Konica Minolta Inc., Tokyo, Japan). The SPAD parameter was chosen since it is universally recognised that the leaf chlorophyll content and the plant's N supply are positively correlated (Peng et al., 2021). Two measurements per leaf were performed: one on the left leaf margin and one on the right one. One leaf per plant was tested. All plants in the bins were measured for chlorophyll content.

2.5. Water relations

Leaf and stem water potentials were monitored at 78 DAT. Measurements were performed at 12.00 hour using a Scholander pressure chamber (Soilmoisture Equipment Corp., Santa Barbara, CA, USA). Leaf water potential was measured on one well exposed leaf per plant (9 leaves per treatment) following the recommendations of Turner and Long (1980). Similarly, stem water potential was measured on one leaf per tree which was previously covered with aluminium foil and placed in plastic bags for at least 90 minutes, to allow equilibration with the stem, according to the methodology described by McCutchan and

Shackel (1992) and Naor et al. (1995).

2.6. Net photosynthesis

Leaf net photosynthesis (A) was determined at 12.00 hour on the same day when water potentials were recorded, using a portable gas analyser (Li-COR 6400, LI-COR, Lincoln, Nebraska, USA) equipped with a light emitting diode (LED) source and an external photosynthetic photon flux density (PPFD) sensor. Measurements were carried out on one leaf per plant (9 leaves per treatment). During each measurement, light intensity inside the cuvette was maintained constant during the measurement by setting the level of light at the incident light level as recorded by the PPFD sensor immediately before the measurements.

2.7. Plant yield and fruit quality

At 85 DAT, final yield (i.e., fruit plant^{-1}) was assessed for each treatment. The main fruit quality parameters (fruit weight, diameter, firmness, pH, titratable acidity, soluble solid content, dry matter content) were assessed on 60 fruit per treatment. Fruit firmness was assessed through to the 53220 FTA Fruit Texture Analyser (T.R. Turoni srl, Italy). Soluble solids content was determined by a digital refractometer (ATAGO CO., LTD, Japan). Fruit dry matter content was determined on fruit slices which were dried at 65°C for several days and weighted with a precision Mettler scale, Model PE3600 (METTLER TOLEDO LLC, USA).

2.8. Statistical analysis

Fruit quality, fruit yield, leaf and stem water potential and leaf photosynthesis were compared among treatments using a one-way ANOVA analysis followed by a Tukey HSD test. Analyses were carried out using R software (www.r-project.org).

Data of tissues mineral concentration were instead analysed as in a randomized block design and when analysis of variance showed a statistical effect, means were separated by the SNK Test using SAS 9.0 (SAS Institute Inc., Cary, NC, USA). Statistical significance was established for $P < 0.05$. For each data means and standard error (SE) were calculated.

3. Results and discussion

3.1. Physical-chemical properties of irrigation water

TW and FW physical-chemical parameters (in 2021 and 2022), are reported in Table 1. TW presents higher phosphorus (P) and potassium (K) concentrations than fresh water (FW) but rather low nitrates concentrations (NO_3 - N), almost comparable to FW. These concentrations can be explained by the fact that the WWTP discharges within a nitrate vulnerable zone, for which Italian regulations prescribe lower N limits (Legislative Decree n°152/2006 -'Environmental standards' 2006). Also, N, P and K levels were lower (Christou et al., 2017; García-Valverde et al., 2023; Licata et al., 2019; Tzortzakis et al., 2020a) or at times comparable (Hewa et al., 2020) to other studies that used tertiary treated wastewater as water source for tomato crop irrigation. Different elements concentrations were quite similar between the two growing seasons (2021 and 2022): only aluminium (Al), lithium (Li), boron (B) and silicon (Si) show a remarkable variation between the two years analyses. All the trace elements found in these waters remain, for both the years, well below the recommended maximum concentrations of trace elements for irrigation water, indicated by FAO (Ayers and Westcot, 1985). Considering the same FAO guidelines, TW presents electrical conductivity (EC) and sodium adsorption ratio (SAR) levels corresponding to the 'slight to moderate' degree of restriction use ($0.3 < EC < 1.2$ and $3 < SAR < 6$) (Ayers and Westcot, 1985), meaning that its use for irrigation can be carried on without significative restrictions. According to the guidelines reported by (Pedrero et al., 2010b), in the present study, wastewater has no restriction on use for boron (≤ 0.7 mg L^{-1}) and chloride (≤ 140 mg L^{-1}), while the sodium ion endowment is particularly high (≥ 9 mg L^{-1}).

Table 1

Physical-chemical parameters measured in wastewater (TW) and freshwater (FW). Data indicated for each parameter represent an average value (n=8) ± standard deviation. (dl) detection limit.

	TW		FW	
Water type	Tertiary treated wastewater		Fresh water	
Chemical Parameters	2021	2022	2021	2022
pH	7.80 ± 0.05	8.12 ± 0.11	7.42 ± 0.02	7.95 ± 0.07
EC (dS m^{-1})	1.11 ± 0.06	1.14 ± 0.03	0.63 ± 0.03	0.59 ± 0.01
SAR	5.10 ± 0.15	3.53 ± 0.20	1.90 ± 0.02	0.51 ± 0.01
COD (mg L^{-1})	4.0 ± 0.30	7.3 ± 0.95	-	-
BOD (mg L^{-1})	13.3 ± 0.85	9.5 ± 0.84	-	-
NH_4-N	0.15 ± 0.01	0.09 ± 0.01	0.11 ± 0.01	0.08 ± 0.01
NO_3-N	4.21 ± 0.67	4.20 ± 1.68	3.53 ± 0.02	4.20 ± 0.13
P (mg L^{-1})	0.08 ± 0.01	1.37 ± 0.02	0.04 ± 0.01	1.34 ± 0.01
K (mg L^{-1})	2.44 ± 0.30	2.94 ± 0.35	0.04 ± 0.01	0.42 ± 0.01
Ca (mg L^{-1})	9.92 ± 0.51	9.53 ± 0.12	10.5 ± 0.05	8.92 ± 0.09
Mg (mg L^{-1})	2.37 ± 0.13	2.45 ± 0.04	2.41 ± 0.02	2.20 ± 0.03
S (mg L^{-1})	2.38 ± 0.06	2.63 ± 0.07	2.09 ± 0.02	2.16 ± 0.03
Na (mg L^{-1})	12.7 ± 0.70	8.64 ± 0.49	4.84 ± 0.05	1.19 ± 0.02
Cl (mg L^{-1})	23.5 ± 1.05	-	7.76 ± 0.24	-
Al (µg L^{-1})	18.5 ± 1.04	45.4 ± 8.54	14.9 ± 1.10	14.8 ± 2.51
Li (µg L^{-1})	23.9 ± 0.04	6.28 ± 0.05	23.5 ± 0.02	5.80 ± 0.02
Fe (µg L^{-1})	-	34.4 ± 7.21	-	19.5 ± 2.63
B (µg L^{-1})	177 ± 6.71	5.50 ± 0.25	193 ± 2.00	< dl
Ba (µg L^{-1})	0.74 ± 0.35	< dl	-	< dl
Si (µg L^{-1})	21.1 ± 5.37	118 ± 2.31	-	97.3 ± 1.4
Sn (µg L^{-1})	87.9 ± 1.57	< dl	-	< dl
Sr (µg L^{-1})	79.9 ± 4.20	63.5 ± 0.68	-	67.6 ± 0.98
Zn (µg L^{-1})	-	10.5 ± 0.83	-	36.1 ± 8.21

Reclaimed water released by this WWTP is also compatible with the (EU) 741/2020 requirements (class B) (European Parliament, 2020), while only partially with the limits stated by the new Italian Presidential Decree, transposing the European Directive (DPR, 2023). According to this regulation, wastewater used for this study complies with the limit of 10 mg L^{-1} for TN, but not with the limit of 1 mg L^{-1} for TP, considering that this WWTP is designed to treat wastewater of 197.500 population equivalent (PE).

Table 2

Electrical conductivity (EC) and pH measured in FW+F, TW+F and TW soils during 2021 and 2022.

Treatment	Depth	Year	pH	EC (dS m^{-1})
FW+F	0–0.20 m	2021	8.13 ± 0.12	0.216 ± 0.01 b
TW+F			8.20 ± 0.17	0.356 ± 0.01 a
TW			8.02 ± 0.11	0.208 ± 0.01 b
Significance			ns	*
FW+F	0.21–0.40 m		8.12 ± 0.09	0.226 ± 0.05
TW+F			8.15 ± 0.05	0.278 ± 0.04
TW			8.24 ± 0.11	0.234 ± 0.01
Significance			ns	ns
FW+F	0–0.20 m	2022	7.96 ± 0.07 b	0.30 ± 0.01
TW+F			8.22 ± 0.07 ab	0.39 ± 0.05
TW			8.27 ± 0.05 a	0.38 ± 0.03
Significance			*	ns
FW+F	0.21–0.40 m		8.30 ± 0.11	0.14 ± 0.01 b
TW+F			8.40 ± 0.04	0.26 ± 0.02 a
TW			8.33 ± 0.11	0.24 ± 0.01 ab
Significance			ns	*

* Statistically significant at $P \leq 0.05$.

(ns) not significant.

Within the same parameters, means followed by the same letter are not statistically different.

3.2. Chemical soil properties

Electrical conductivity (EC) and pH measurements conducted in 2021 and 2022, at the end of each irrigation season, are reported in Table 2. Differences in pH values were not significant for the three fertigation systems except for the surface soil layer (0–0.20 m) in 2022 between FW+F and TW. This result is in accordance with Licata et al. (Licata et al., 2019). An increase in pH values for all the treatments is shown, more markedly for the 0.21–0.40 m soil layer, probably due to progressive leaching of soluble salts due to the irrigation water.

In 2021, only for the first 0.20 m of soil, the EC showed differences among the treatments with a significantly higher value for TW+F respect to TW and FW+F. Also, in the 0.21–0.40 m soil layer in 2022, the FW+F treatment showed a significantly lower EC level compared to the other treatments. According to FAO (FAO, 1988), tomato is classifiable as a moderately tolerant crop to soil salinity. Salinity can be a major treat to plant growth and cause poor and spotty stands of crops, uneven and stunted growth: salinity decreases water availability to plants due to increased soil osmotic pressure but can also lead to excessive concentration and absorption of individual ions toxic to plants (FAO, 1988). The analysed soil (Table 2) can be considered, for all treatments, in the non-saline class according to the FAO classification. In particular, in the TW+F and TW, the soil did not show an increase in EC levels despite the prolonged use of tertiary treated water. The EC values measured at soil level have not undergone a sharp increase as in previous studies (Christou et al., 2014; De Carlo et al., 2022; Disciglio et al., 2015). They remained in all cases below the value reported in another study (Libutti et al., 2018b) (0.7 dS m^{-1}) where tomato plants were irrigated with tertiary treated agro-industrial wastewater. However, the observed soil EC for all the treatments and for both the productive seasons, remained below the indicative threshold of 4.00 dS m^{-1}, which is the point at which a soil is considered saline (Qadir et al., 2001). The low levels of EC measured in TW and TW+F soils were probably attributable to the limited concentration of salts in the tertiary treated wastewater (Table 1), which were in fact well below the threshold indicated by (Cuartero and Fernández-Muñoz, 1998), which reports that, in most environmental conditions in which it is cultivated, tomato begins to lose yield with a water quality with EC values above 2–3 dS m^{-1}.

With regard to sodium concentration, it is proved that an excess of exchangeable sodium percentage (ESP) in sodic soils has a significant negative impact on physical soil properties (FAO, 1988). A pH range of 8–8.2, as in the case of all the treatments for 2021, is associated with a moderate sodicity hazard (ESP 5–15). In 2022, all soil samples fall again within the moderate sodicity hazard range (ESP 5–15), with the TW+F treatment at a depth of 20–40 cm reaching a peak pH of 8.4 (Table 2), (ESP 15–30) (FAO, 1988). Measurements of Na concentration, at both soil depths, have highlighted significative differences between FW+F (0.76 g kg^{-1} for 0–20 cm layer and 0.78 g kg^{-1} for 20–40 cm) and TW+F (1.29 g kg^{-1} for 0–20 cm layer and 1.24 g kg^{-1} for 20–40 cm) irrigated soils in 2022, while in 2021 there were no significative differences among the treatments. This could be due to the fact that TW-irrigated soils, deriving from the original soil rich in clay (Licata et al., 2019), retained greater amounts of adsorbed sodium than the control.

Soil main chemical parameters did not show significant differences among the treatments in 2021 (Table 3). Only B and S showed statistical differences among the treatments. The former was present to a greater concentration in FW than in SW in 2021, and this is reflected by the

Table 3
Soil chemical parameters.

Treatment	Year	N	P	K	Mg	Na	Ca	Fe	Mn	S	B	Ba	Zn
0–0.20 m	2021					g kg^{-1}						mg kg^{-1}	
FW+F		1.14 ± 0.01	0.74 ± 0.05	8.47 ± 0.06	7.61 ± 0.12	1.87 ± 0.01	45.7 ± 1.20	24.7 ± 0.22	0.70 ± 0.01	0.27 ± 0.01	20.1 ± 0.56	177 ± 1.98	85.8 ± 3.92
TW+F		1.16 ± 0.05	0.69 ± 0.01	8.46 ± 0.47	7.36 ± 0.01	1.83 ± 0.05	45.4 ± 0.11	24.1 ± 0.10	0.68 ± 0.01	0.27 ± 0.01	19.5 ± 1.21	173 ± 5.10	87.2 ± 2.52
TW		1.20 ± 0.03	0.70 ± 0.01	7.94 ± 0.52	7.45 ± 0.02	1.75 ± 0.06	45.3 ± 1.06	24.1 ± 0.28	0.70 ± 0.01	0.26 ± 0.01	19.7 ± 0.47	159 ± 12.8	80.7 ± 1.28
Significance		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
0.21–0.40 m						g kg^{-1}						mg kg^{-1}	
FW+F		1.09 ± 0.02	0.67 ± 0.02	8.60 ± 0.38	7.36 ± 0.02	1.83 ± 0.02	48.1 ± 0.80	24.2 ± 0.32	0.69 ± 0.02	0.29 ± 0.04	19.0 ± 1.81	181 ± 15.3	77.9 ± 5.72
TW+F		1.14 ± 0.07	0.68 ± 0.01	7.51 ± 0.92	7.36 ± 0.12	1.72 ± 0.05	45.7 ± 1.46	24.3 ± 0.20	0.71 ± 0.01	0.26 ± 0.03	17.1 ± 2.65	163 ± 24.2	82.1 ± 1.70
TW		1.19 ± 0.07	0.71 ± 0.05	8.98 ± 0.48	7.49 ± 0.21	1.89 ± 0.09	47.4 ± 1.32	24.6 ± 0.23	0.71 ± 0.01	0.26 ± 0.03	20.6 ± 1.32	185 ± 10.5	83.2 ± 2.23
Significance		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Treatment		N	P	K	Mg	Na	Ca	Fe	Mn	S	B	Ba	Zn
0–0.20 m	2022					g kg^{-1}						mg kg^{-1}	
FW+F		1.21 ± 0.01	0.73 ± 0.01	12.1 ± 1.13	8.23 ± 0.11	0.76 ± 0.06 b	49.6 ± 0.75	26.9 ± 0.85	0.82 ± 0.01	0.21 ± 0.01	22.1 ± 2.84	233 ± 24.2	87.5 ± 1.97
TW+F		1.23 ± 0.01	0.84 ± 0.08	14.7 ± 0.70	8.63 ± 0.01	1.29 ± 0.07 a	50.2 ± 0.29	27.1 ± 0.06	0.84 ± 0.01	0.21 ± 0.01	26.5 ± 0.34	284 ± 16.4	86.2 ± 0.18
TW		1.19 ± 0.01	0.72 ± 0.01	10.0 ± 2.89	7.94 ± 0.30	0.96 ± 0.18 b	50.9 ± 0.67	26.5 ± 0.41	0.83 ± 0.01	0.20 ± 0.01	13.8 ± 6.91	200 ± 46.0	83.2 ± 1.13
Significance		ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns
0.21–0.40 m						g kg^{-1}						mg kg^{-1}	
FW+F		1.18 ± 0.01	0.67 ± 0.03	13.2 ± 0.16	8.15 ± 0.15	0.78 ± 0.02 b	52.8 ± 2.23	26.4 ± 0.14	0.81 ± 0.01	0.16 ± 0.01 b	23.2 ± 0.74 b	248 ± 5.27	82.2 ± 2.19
TW+F		1.21 ± 0.01	0.74 ± 0.01	15.1 ± 0.54	8.53 ± 0.05	1.24 ± 0.06 a	50.6 ± 0.75	27.3 ± 0.06	0.85 ± 0.01	0.19 ± 0.01 a	26.6 ± 0.39 a	292 ± 10.9	85.7 ± 0.29
TW		1.08 ± 0.01	0.71 ± 0.01	13.6 ± 0.68	8.44 ± 0.06	1.11 ± 0.08 a	51.2 ± 0.44	27.3 ± 0.58	0.84 ± 0.01	0.18 ± 0.01 a	23.2 ± 0.91 b	260 ± 19.2	82.9 ± 0.71
Significance		ns	ns	ns	ns	**	ns	ns	ns	*	*	ns	ns

* *Statistically significant at $P \leq 0.05$.*
** *Statistically significant at $P \leq 0.01$.*
(ns) not significant.
Within the same parameters, means followed by the same letter are not statistically different.

FW+F soil, that had the highest concentrations. In 2022, on the other hand, B was below the detection threshold for FW and less diluted than in 2021 in tertiary treated water (Table 1). Since B can be reduced by leaching as salinity (Ayers and Westcot, 1985), it is likely that these ions percolated during the 2022 irrigation season from the topsoil to the deepest layer, leading to the significant difference between TW+F (26.6 mg kg^{-1}) and the other two treatments (23.2 mg kg^{-1}). To be noted that TW+F already had a very high B concentration (26.5 mg kg^{-1}) in the 0–20 cm range (Table 3). In terms of heavy metals, all soil samples had concentrations of copper (Cu), cadmium (Cd), chromium (Cr), mercury (Hg), lead (Pb) and nickel (Ni) below the detection level (Table 3). Zinc (Zn) concentration was below the threshold indicated by Italian legislation (300 mg kg^{-1}) (LD n°152, 2006) for all the treatments.

3.3. Mineral concentrations of plant tissues

At foliar level, analyses of the mineral concentration showed significant differences among the treatments for both years, especially for N and P in 2021 (Table 4). With regard to N, it can be seen that tomato plants in the FW+F (28.1 and 22.6 g kg^{-1}) and TW+F (29.1 and 20.9 g kg^{-1}) fertigation treatments had comparable leaf N concentrations, both in 2021 and 2022; TW treatment (22.1 and 14.9 g kg^{-1}) that did not receive the supplementary fertilizer dose and therefore did not reach the seasonal N requirement, had significantly less leaf N concentrations. In the case of P, on the other hand, the treatment with the highest concentrations was TW: this was probably due to the lower vegetative growth of these plants compared to TW+F and FW+F, which resulted in an increased P concentration in the leaf biomass. Comparable concentrations were also achieved for K among TW+F, FW+F and TW treatments in 2021 and 2022.This was probably due to a balance between the lower supply of K to the plants and the concentration effect. In light of these results, it is clear that the smart fertigation system was efficient in balancing nutritional inputs, leading to TW+F and FW+F plants actually reaching their nutritional requirements (Emilia-Romagna, 2021, 2022). The TW plants were not able to reach the leaf macronutrient requirement.

Sodium (Na) and copper (Cu) also showed significant differences between treatments in both years, with the former behaving like N and the latter like P. In particular, in 2021, TW+F showed a higher Na concentration (2.21 g kg^{-1}) respect to FW+F (1.76 g kg^{-1}) and TW (1.67 g kg^{-1}). The same pattern was repeated in 2022, with TW+F having a significantly higher leaf concentration (1.05 g kg^{-1}) than TW and FW+F (0.79 g kg^{-1} and 0.66 g kg^{-1}, respectively). In the case of Cu, in 2021, TW had a higher concentration (26.2 mg kg^{-1}) than TW+F (19.3 mg kg^{-1}) and FW+F (17.2 mg kg^{-1}).

A wide range of mineral concentrations in tomato fruits has been reported in recent literature, depending on variety, growing medium, climate, irrigation system and fertilisation method (Ahmed et al., 2023; Kovačič et al., 2023; Libutti et al., 2018a).

The 2021 macronutrients (N, P, K) fruit mineral concentrations fully reflected the proportions of the fertigation plan. In particular FW+F and TW+F showed comparable concentrations of N, P and K, while the TW treatment showed a significantly lower concentration only for N. P and K concentrations of TW, on the other hand, were in line with the other two treatments, probably due to the aforementioned concentration effect. This agrees with (Libutti et al., 2018b), which states that the most important fruit parameters (e.g., dry matter content, soluble solids content, titratable acidity, pH) were not influenced by treated wastewater irrigation. These analyses also confirm the macronutrient accumulation dynamics typical of tomatoes, where more P and K and less N are accumulated in the fruit than in the leaf tissues (Sainju et al., 2002). As far as micronutrients, there were significant differences in Ca concentrations between treatments in 2021, where TW was markedly elevated (1.00 g kg $^{-1}$ for TW; 0.74 g kg $^{-1}$ for TW+F; 0.85 g kg $^{-1}$ for FW+F). Probably, this was due to the fact that, during 2021, TW plants were less subjected to water stress periods and therefore Ca ions were easily transported to the fruit, leading to a higher calcium concentration in TW (compared to the other treatments). The unbalancing in the Ca concentration in fruits did not occur in 2022, where no significant differences were found among treatments. The concentrations of the micronutrients Mg, Na, Ca, S, Cu, Fe are slightly higher in fruits irrigated with tertiary treated wastewater, in agreement with (Kovačič et al., 2023). Compared to (Kovačič et al., 2023), the concentrations of Ba, Mn, Zn were similar in fruits irrigated with FW respect to the other two treatments. Fruit mineral concentrations in the present study were always below or comparable to (Kovačič et al., 2023) for all the above-mentioned elements except Na and B. Compared to (Libutti et al., 2018a), where fruits irrigated with tertiary treated wastewater of agro-industrial origin and with groundwater are compared, comparable values were shown for Ca, while much higher for Na (but in line with the present study if the 2022 results are considered). The proportion of Na concentrations between treatments in 2022 (but not in 2021) agrees with (Libutti et al., 2018a), where plants irrigated with tertiary treated wastewater accumulated more sodium in the fruit than those irrigated with ground water. For Mg and Ca, the proportions between TW and FW

Table 4

Leaf mineral concentrations of FW+F, TW+F and TW in 2021 and 2022 seasons.

Treatment	Year	N	P	K	Mg	Na	Ca	Cl	S	Cu	Fe	B	Ba	Mn	Zn
		g kg^{-1}								mg kg^{-1}					
FW+F		28.1 ± 0.03 a	1.89 ± 0.07 b	14.4 ± 0.45	5.59 ± 0.20	1.76 ± 0.14 ab	50.4 ± 1.95	48.7 ± 7.00	14.4 ± 0.66	17.2 ± 1.78 b	92.4 ± 2.04	97.2 ± 5.76	22.8 ± 0.71	41.9 ± 1.58	12.5 ± 0.98
TW+F	2021	29.1 ± 0.08 a	1.86 ± 0.11 b	14.1 ± 0.49	5.69 ± 0.51	2.21 ± 0.11 a	47.9 ± 3.68	53.4 ± 16.6	12.7 ± 1.09	19.3 ± 1.62 ab	85.7 ± 4.60	100 ± 0.88	24 ± 3.07	38.5 ± 1.69	16.9 ± 2.52
TW		22.1 ± 0.08 b	2.81 ± 0.17 a	14.6 ± 0.81	4.32 ± 0.23	1.67 ± 0.04 b	52.2 ± 2.10	25.7 ± 6.24	16.1 ± 0.82	26.4 ± 1.50 a	86.6 ± 6.64	106 ± 3.84	26.2 ± 1.59	42.4 ± 2.29	12.6 ± 1.47
Significance		***	**	ns	ns	*	ns	ns	ns	*	ns	ns	ns	ns	ns
		g kg^{-1}								mg kg^{-1}					
FW+F		22.6 ± 0.08 a	2.30 ± 0.08 b	9.26 ± 0.59	4.75 ± 0.28 a	0.66 ± 0.04 b	33.9 ± 3.64	8.97 ± 2.59	11.9 ± 1.16	11.5 ± 0.73 b	80.7 ± 3.57	59.6 ± 3.88 b	13 ± 1.59	28.5 ± 1.21 a	16.7 ± 1.64
TW+F	2022	20.9 ± 0.07 a	2.61 ± 0.15 b	9.61 ± 0.45	3.99 ± 0.30 ab	1.05 ± 0.06 a	31.5 ± 3.36	8.04 ± 8.01	11.7 ± 1.17	16.7 ± 1.28 a	73.9 ± 4.32	67.9 ± 4.06 ab	14.6 ± 2.17	29.1 ± 1.37 a	15.1 ± 1.22
TW		14.9 ± 0.04 b	3.41 ± 0.15 a	8.5 ± 0.17	3.43 ± 0.06 b	0.79 ± 0.03 b	31.6 ± 1.55	6.41 ± 0.32	11.1 ± 0.36	19.2 ± 0.92 a	66.5 ± 5.04	78.7 ± 4.37 a	15.7 ± 0.72	22.2 ± 1.06 b	17.3 ± 1.32
Significance		***	***	ns	**	***	ns	ns	ns	***	ns	*	ns	**	ns

** Statistically significant at $P \leq 0.05$.*

*** Statistically significant at $P \leq 0.01$.*

**** Statistically significant at $P \leq 0.001$.*

(ns) not significant.

Within the same parameters, means followed by the same letter are not statistically different.

are also in agreement with (Libutti et al., 2018a).

In the case of Na, the accumulation in the fruit fully reflected its presence in wastewater, which was higher concentrated in 2021 than in 2022. It is interesting to note that, in the case of the TW+F treatment, where sodium uptake was the highest, even when the difference with the other treatments were significant (year 2022), there was no reduction in potassium accumulation in the fruit tissue as shown by (Song and Fujiyama, 1996). This confirms that Na uptake was not such as to impair K uptake and accumulation in the fruit. In the year 2022, S also showed a significant difference among the treatments: TW+F and FW+F showed a comparable higher S fruit concentration (1.34 g kg^{-1} and 1.27 g kg^{-1} respectively), while TW had a significantly lower concentration (1.13 g kg^{-1}). This was probably due to a widening of the difference in S occurrence between TW and FW in 2022 compared to 2021, where the sulphur content of the two water sources was lower. In any case, from a food safety point of view, the fruits largely comply with the FAO/WHO (FAO and WHO, 2011) suggested heavy metal limits for Fe [425.5 mg kg^{-1}], Zn [60 mg kg^{-1}], Cu [40 mg kg^{-1}], Mn [500 mg kg^{-1}].

3.4. Nutrients saving

From Fig. 4, it can be seen that K was the most present element in the tertiary effluent and that it provided the highest percentage of savings in both years, up to 74.2% in 2021. In 2021, much larger volumes of water were brought in and therefore this may have compensated for the lower concentration of K than in 2022, which is why the savings are higher in 2021. For N, there was also a significant saving of up to 50% in 2022. Less advantageous was the saving for P, given the low phosphate content in tertiary effluent (Table 1), and therefore the need to integrate with artificial fertilizer. The results obtained for 2021 irrigation season are partly in agreement with those obtained by Licata et al. (Licata et al., 2019), where, however, higher macronutrient savings were achieved, especially with respect to the 2022 data. In fact, nutrient levels in WWTP effluents for 2022 were lower when compared to 2021 due to different influent compositions, changes in WWTP operation and other factors. Nevertheless, the obtained results show that the use of wastewater, even with low concentrations of certain parameters, results in considerable savings of fertilizers and that the savings are closely linked to the concentrations of nitrate, ammonium, P and K in the water used for irrigation. Based on the economic quotations of the corresponding fertilizers on the European market (European Commission, 2024), considering that the total expenditure for N, P, K fertilisers using fresh water would have been €177.91 ha^{-1}, the use of tertiary wastewater and the smart fertigation system resulted in savings in fertilizer purchase of €69.86 ha^{-1} (39.3%) in 2021 and €73.14 ha^{-1} (41.1%) in 2022. These findings highlight that sustainable fertigation management using wastewater allows to obtain a product comparable to those obtainable using fresh water, achieving significant savings in nutrient inputs and providing environmental benefits, in agreement with (Aiello et al., 2007; Al-Lahham et al., 2003; Cirelli et al., 2012; Hewa et al., 2020).

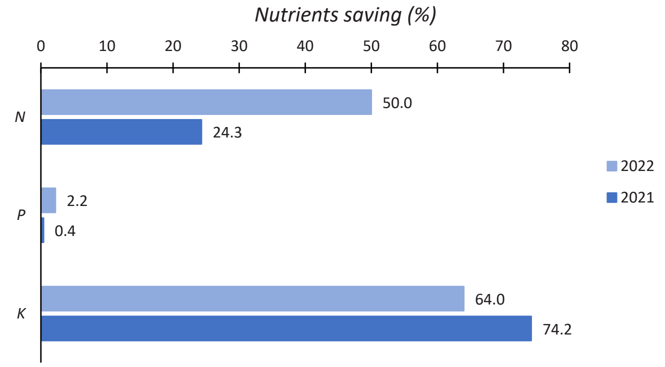

Fig. 4. Nutrients saving calculated on the comparison between TW+F and FW+F mineral fertilisers use in 2021 and 2022.

3.5. Physiological parameters

The measurements taken during the 2022 season (Fig. 5) showed values for the SPAD index that were completely similar in terms of trend and absolute values between the two treatments that received the same N nutrient requirements (TW+F and FW+F). These results agree with the data obtained on leaf mineral concentrations, where the two above-mentioned treatments had a comparable N concentration (Table 4).

The SPAD index trend for TW, on the other hand, was significantly reduced from TW+F and FW+F and characterised by lower values along the whole season (Fig. 5). These results indicate that TW plants irrigated only with wastewater, were not able to reach their nutritional N requirements and therefore showed significantly lower levels of chlorophyll in the leaves, as also confirmed by the leaf mineral N concentration data. In contrast, there were no significant differences in the level of chlorophyll of the plant when irrigated with tertiary or fresh water (TW+F and FW+F). The pathway of variation in chlorophyll concentration for the TW+F and FW+F treatments is consistent with (Sandoval-Villa et al., 2000), where a peak around 30 days after transplanting (DAT) is confirmed, followed by a decrease up to 50 DAT. The SPAD value then showed a new lower peak around 70 DAT, and then declined until harvest with the onset of chlorosis of the vegetative systems (Table 5).

Stem and leaf water potential measurements were carried out to evaluate differences in the water status of the plants at a time of the season when there is generally a high demand for water from the plant (Fig. 6). Indeed, plant stem water potential is an important parameter for linking

soil water content, soil salinity and plant physiological response (Zhang et al., 2023). It can be seen that TW+F and FW+F treatments showed more negative water potentials than TW. This could be likely explained by as a more developed and lush leaf apparatus, due to higher nutritional inputs (especially N). Based on these results, we can exclude plant water stresses related to wastewater saline effects.

Photosynthetic performance showed no significant differences among the three treatments with comparable levels of CO_2 assimilation (A), stomatal conductance (g_s) and transpiration rate (E) (Fig. 7). These results are in contrast to (Ahmed et al., 2023; Tzortzakis et al., 2020a) where it was found that the use of tertiary treated wastewater negatively affected the photosynthetic performance of plants. In particular for (Ahmed et al., 2023), this negative effect could be due to the scarce quality of wastewater used, which were completely untreated, in particular due to its high levels of salinity. Based on the literature (Agius et al., 2022; Cuartero and Fernández-Muñoz, 1998), an excess of salinity appears to have the highest burden in reducing photosynthesis. In absolute terms, the levels of stomatal conductance (g_s) and CO_2 assimilation (A) are perfectly in line with the atmospheric CO_2 treatment (400 ppm) of (Halpern et al., 2019).

3.6. Fruit quality

Quality analysis carried out at harvest produced contrasting results between the two years (Table 6). This is probably due to the fact that during the 2021, some management problems affected the treatments. In particular, there was a prolonged interruption of irrigation in the TW+F treatment bins, which caused plant water stress, thus anticipating the end of the crop cycle. The fruit quality data of TW+F treatment are therefore not very indicative as they refer to a limited number of harvested fruits.

The average fruit weight showed the lowest value (72.3 g) for TW+F, while TW (82.1 g) showed a value more similar to that of the control (FW+F, 85 g). This can probably be attributed to the fact that the plants in the TW produced fewer fruits due to the reduced availability of

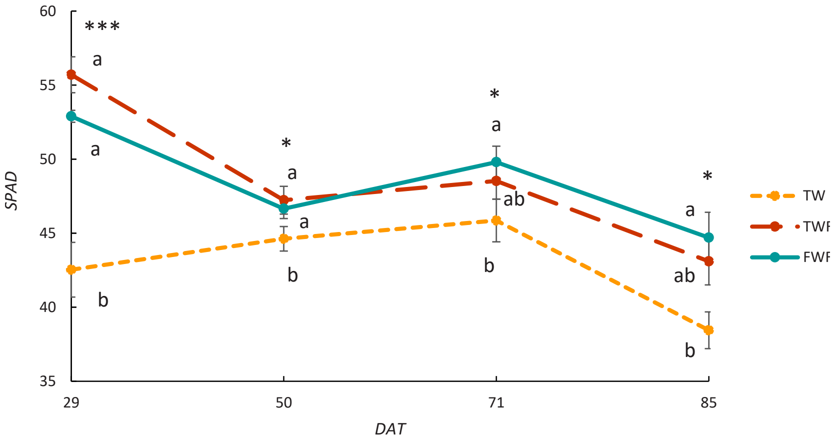

Fig. 5. Foliar chlorophyll contents. (*) Statistically significant at $P \leq 0.05$; (***) Statistically significant at $P \leq 0.001$; (ns) not significant. Data followed by same letters in the same date are not significantly different.

Table 5
Fruit mineral concentrations of FW+F, TW+F and TW in 2021 and 2022 seasons.

Treatment	Year	**N**	**P**	**K**	**Mg**	**Na**	**Ca**	**Cl**	**S**	**Cu**	**Fe**	**B**	**Ba**	**Mn**	**Zn**
		g kg^{-1}								mg kg^{-1}					
FW+F	2021	16.3 ± 0.01 a	2.8 ± 0.11	21.6 ± 0.22	0.98 ± 0.06	1.13 ± 0.01	0.85 ± 0.03 b	18.3 ± 6.94	1.17 ± 0.05	5.95 ± 0.12	23.1 ± 1.33	40.2 ± 1.11	0.22 ± 0.02	6.64 ± 1.42	13.4 ± 0.91
TW+F		15.7 ± 0.10 ab	2.79 ± 0.23	22.7 ± 0.75	0.94 ± 0.06	1.24 ± 0.03	0.74 ± 0.01 c	22.7 ± 6.07	1.15 ± 0.06	6.07 ± 0.48	20.7 ± 1.72	40.3 ± 2.17	0.23 ± 0.03	5.56 ± 0.95	13.1 ± 0.38
TW		12.8 ± 0.04 b	2.7 ± 0.14	21 ± 0.41	0.92 ± 0.02	1.13 ± 0.03	1.00 ± 0.02 a	15.7 ± 0.33	1.06 ± 0.01	5.78 ± 0.03	23.6 ± 0.44	39.7 ± 4.10	0.47 ± 0.49	5.3 ± 0.29	12.6 ± 0.27
Significance		*	ns	ns	ns	ns	***	ns	ns	ns	ns	ns	ns	ns	ns
		g kg^{-1}								mg kg^{-1}					
FW+F	2022	14.7 ± 0.05 a	3.23 ± 0.11 b	25.6 ± 3.09	0.89 ± 0.03	0.26 ± 0.01 b	0.64 ± 0.04	4.32 ± 0.44	1.27 ± 0.04 ab	6.93 ± 0.38	25.7 ± 2.45	7.85 ± 0.24	1.14 ± 0.13	5.84 ± 0.20	17.9 ± 0.96
TW+F		14.3 ± 0.09 ab	3.28 ± 0.06 ab	31 ± 0.74	0.92 ± 0.03	0.40 ± 0.02 a	0.71 ± 0.08	9.11 ± 2.03	1.34 ± 0.03 a	6.98 ± 0.22	32.3 ± 7.22	7.96 ± 0.76	1.31 ± 0.18	6.08 ± 0.51	16.7 ± 0.39
TW		11.8 ± 0.05 b	3.59 ± 0.08 a	30.4 ± 1.32	0.97 ± 0.02	0.35 ± 0.01 a	0.63 ± 0.03	5.97 ± 1.09	1.13 ± 0.03 b	6.09 ± 0.39	27.7 ± 2.84	9.77 ± 0.61	1.6 ± 0.11	5.85 ± 0.36	16.9 ± 0.51
Significance		*	*	ns	ns	***	ns	ns	**	ns	ns	ns	ns	ns	ns

** Statistically significant at $P \leq 0.05$.*
*** Statistically significant at $P \leq 0.01$.*
**** Statistically significant at $P \leq 0.001$.*
(ns) not significant.
Within the same parameters, means followed by the same letter are not statistically different.

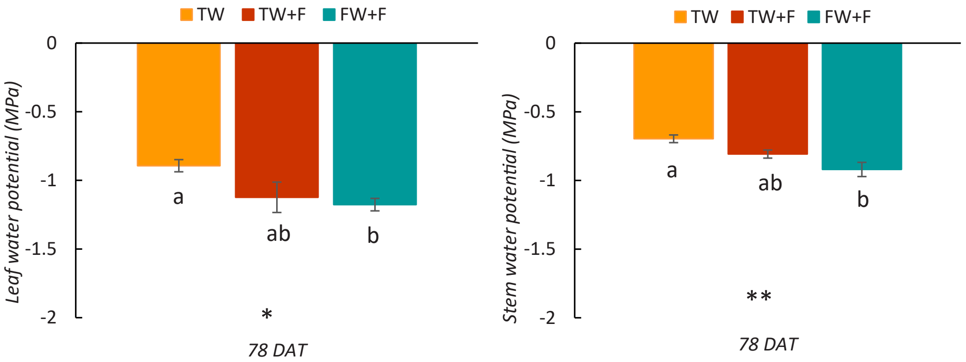

Fig. 6. Stem and leaf water potentials of TW+F, FW+F and TW plants measured at 78 DAT in 2022. (*) Statistically significant at $P \leq 0.05$; (**) Statistically significant at $P \leq 0.001$; (ns) not significant. Data followed by same letters in homogeneous groups are not significantly different.

nutrients, but with a larger size. In addition, the problem that occurred with the irrigation system may have stunted the growth of the TW+F fruits, distorting the result and emphasising the significance of the differences. As proof of this, it can be seen that in 2022, no significant differences between the treatments were evident, in agreement with (Aiello et al., 2007; Christou et al., 2014; Cirelli et al., 2012; Gatta et al., 2015) whereby the use of wastewater does not seem to influence the fruit weight. In (Al-Lahham et al., 2003), on the other hand, plants irrigated with wastewater produced significantly larger fruit. With regard to yield, the study (Tzortzakis et al., 2020a) reports similar results

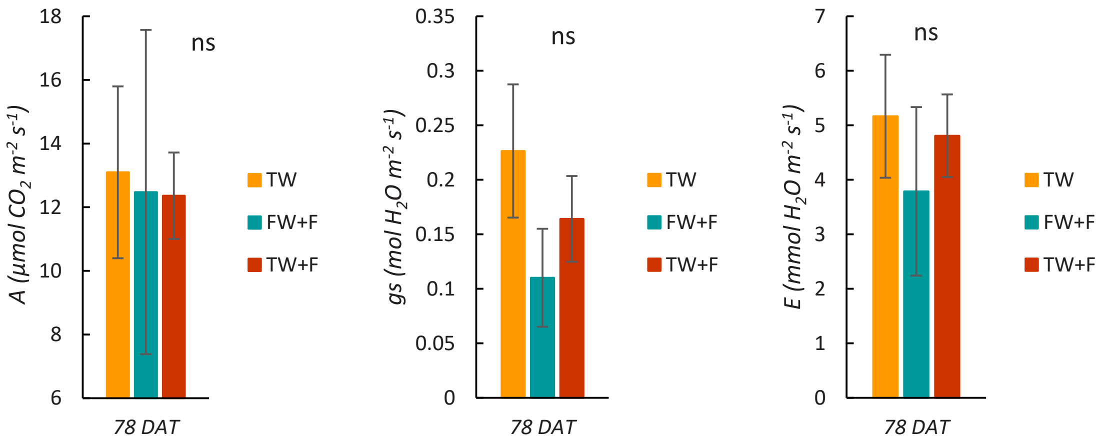

Fig. 7. CO_2 assimilation (A), Stomatal conductance (g_s) and transpiration rate (E). (*) Statistically significant at $P \leq 0.05$; (**) Statistically significant at $P \leq 0.01$; (***) Statistically significant at $P \leq 0.001$; (ns) not significant.

Table 6
Fruit quality parameters of TW+F, FW+F and TW plants in 2021 and 2022.

Treatment	Year	Average Fruit Weight	Hardness	pH	Titratable acidity	SSC	Dry Matter	Yield
		(g)	(kg cm^{-2})		(g l^{-1})	(°Brix)	(%)	(kg $plant^{-1}$)
FW+F		85.0 ± 5.78 a	0.80 ± 0.03 ab	4.51 ± 0.06	4.12 ± 0.79	6.13 ± 0.25 b	7.33 ± 0.09 b	-
TW+F	2021	72.3 ± 3.14 b	0.67 ± 0.04 b	4.47 ± 0.02	4.16 ± 0.31	7.18 ± 0.16 a	8.27 ± 0.17 a	-
TW		82.1 ± 5.13 ab	0.85 ± 0.04 a	4.47 ± 0.03	3.29 ± 0.10	5.53 ± 0.17 b	7.18 ± 0.10 b	-
Significance		*	*	ns	ns	***	***	-
FW+F		74.0 ± 3.80	1.02 ± 0.06	4.72 ± 0.07	4.10 ± 0.11 ab	5.86 ± 0.39	8.29 ± 0.51	1.02 ± 0.07 a
TW+F	2022	80.1 ± 5.02	1.16 ± 0.05	4.77 ± 0.09	3.44 ± 0.02 b	5.53 ± 0.36	8.24 ± 0.63	0.93 ± 0.08 a
TW		83.3 ± 6.58	1.05 ± 0.05	4.73 ± 0.09	4.99 ± 0.45 a	5.84 ± 0.12	7.23 ± 0.17	0.48 ± 0.03 b
Significance		ns	ns	ns	*	ns	ns	***

** Statistically significant at $P \leq 0.05$.*
*** Statistically significant at $P \leq 0.01$.*
**** Statistically significant at $P \leq 0.001$.*
(ns) not significant.
Data followed by same letters in homogeneous groups are not significantly different.

to the present study with values around 1 kg of product per plant.

The parameter of fruit hardness remained, for all the treatments and for both the years, between 0.67 and 1.16 kg cm^{-2}, values in agreement with (Demir and Sahin, 2017), where a decrease in firmness was recorded using wastewater compared to the control, a decrease that did not occur in our study: in 2022 there was no significant difference among treatments, while in 2021, TW+F recorded the lowest value, and TW had fruit with more consistent flesh. The present results seem to agree with (Warner et al., 2004), which stated that firmness of fruits was not affected by fertilizer N rate, and with (Demir and Sahin, 2017), where there was no significant reduction in hardness following wastewater irrigation. Fruit hardness is an important parameter for tomato quality (Demir and Sahin, 2017) and it prolongs storage for the commodity and maintains the quality of the fruit (Tzortzakis et al., 2020a).

pH values found in this study are consistent with (Disciglio et al., 2015; Heun Hong et al., 2000; Libutti et al., 2018a; Licata et al., 2019) and are typical of tomato fruits. The range 4.50–4.75 reflects the markedly acidic pH of tomatoes, which is an added value for tomato processing and storage. As can be seen from Table 6, it can be stated that both in 2021 and 2022, the pH was not influenced by irrigation with tertiary treated wastewater, showing no significant differences among treatments. This is in contrast to (Disciglio et al., 2015; Licata et al., 2019) where the fruits irrigated with wastewater showed a slightly lower pH level. The titratable acidity showed no significant difference among the treatments in 2021, in agreement with (Cirelli et al., 2012; Libutti et al., 2018a), while it showed a significant difference in 2022, with the highest value for the TW treatment. This is probably due to the fact that these plants probably reached the end of the production cycle by having less available nutrients. Fruits therefore ripened earlier while maintaining a higher organic acid content than in the other treatments. pH is a very important parameter for the evaluation of tomato fruit quality, since it influences the processing thermal condition required to grant an optimal conservation environment (Libutti et al., 2018a).

In 2021, there was a significantly higher accumulation of soluble solids in TW+F fruits (7.18 °Brix), respect to TW (5.53 °Brix) and FW+F (6.13 °Brix). This phenomenon contrasts with other studies (Cirelli et al., 2012; Disciglio et al., 2015; Licata et al., 2019) where plants irrigated with wastewater produced fruit with a lower concentration of soluble solids, although the differences were not statistically significant. It should be noted that the TW+F and FW+F values were markedly higher than those obtained from the above-mentioned studies. In 2022, however, the differences evened out and the values in absolute terms were fully comparable to those recorded by (Cirelli et al., 2012; Disciglio et al., 2015). The parameter of soluble solids in the fruit is very important for tomato processing (Agius et al., 2022) because high SSC improves the efficiency of tomato fruit processing due to the lower quantity of energy necessary to evaporate water from the fruit (Libutti et al., 2018a).

Also, high dry matter content (DM) is a desirable characteristic for the canning tomatoes industry since it improves the quality of the processed product (Libutti et al., 2018a). Again, we observed markedly significant differences between the treatments in 2021, while no differences emerge in 2022. Probably this discrepancy in 2021 is due to the early drying of the plants of the TW+F treatment. Data from 2022 in fact pointed in the same direction as several other studies (Cirelli et al., 2012; Disciglio et al., 2015; Libutti et al., 2018a; Licata et al., 2019) that confirmed that the use of wastewater does not influence the DM parameter.

With regard to yield, for which we only have data from 2022, the results obtained showed a comparable yield for the treatments that achieved the same nutritional requirements (FW+F and TW+F), demonstrating that the use of wastewater, when balanced form the main nutritional elements, as an irrigation source does not have a negative effect on crop productivity, in agreement with (Licata et al., 2019; Tzortzakis et al., 2020a). Even in the case of (Hewa et al., 2020), where plants irrigated with wastewater achieved a better yield, the authors point out that the quantity of water given is a much more impactful factor than the water quality itself in influencing yield. However, these quality data agree with those obtained by (Tzortzakis et al., 2020b), where plants irrigated with wastewater with and without soil fertilisation produced fruit with comparable average weight.

4. Conclusions

This research presents a two years field study of reuse of tertiary treated wastewater for processing tomato fertigation, showing suitability and benefits of this practice. This paper demonstrates the novel implementation of the smart fertigation system, which can be exploited to save nutrients and to cope with the natural fluctuations in the concentration of nutrients in the treated wastewater. Irrigation with tertiary treated wastewater (without mineral supply) was not able to meet whole nutritional requirements of the tomato, but it has allowed the significant savings in terms of macronutrient utilisation, related to the characteristics of the wastewater used: 24.3% for N, 0.4% for P, 74.2% for K in 2021; 50% for N, 2.2% for P, 64% for K in 2022. The absence of any negative effects of tertiary treated wastewater on soil properties and plant physiology was achieved. This respectively guarantees the suitability of the soil for the cultivation of this crop, and the absence of any salinity water stress for the plants. Analyses of leaf and fruit mineral concentrations showed no accumulation of critical elements beyond the safety thresholds, proving that the resulting product is perfectly marketable and consumable. It is shown that under the same conditions, the growth and productivity of plants irrigated with wastewater are similar compared to the control ones irrigated with mains water. Also, at the level of fruit quality at harvest, no significant differences were shown between plants irrigated with fresh or tertiary treated wastewater with the same nutritional intake. Further studies will be needed to verify the sustainability of direct reuse of tertiary treated wastewater for crop fertigation, with respect to potentially problematic factors that this study did not address: these include the presence of emerging contaminants (CECs), long-term salinization of soils, and the conveying of bacteria and/or genes for antibiotic resistance.

Funding

This research was funded by the region of Emilia-Romagna (the program POR-FESR 2014–2020) through the project "VALorizzazione di acque reflUE e fanghi in ottica di economia CircolarE e simbiosi INdustriale (VALUE CE-IN, CUP I31F18000080009, https://valuecein.eu/project/) and the project “Safe and Sustainable Solutions for the Integrated Use of Non-Conventional Water Resources in the Mediterranean Agricultural Sector (FIT4REUSE)” which has received funding from the Partnership on Research and Innovation in the Mediterranean Area (PRIMA) under grant agreement No 1823. PRIMA is supported by the European Union’s Horizon 2020 research and innovation program.

CRediT authorship contribution statement

Giulio Demetrio Perulli: Writing – review & editing, Validation, Methodology, Data curation, Conceptualization. **Giordano Odone:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Attilio Toscano:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Stevo Lavrnić:** Writing – review & editing, Validation. **Giuseppe Mancuso:** Writing – review & editing, Validation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors are grateful to HERA S.p.a. and Irritec S.p.a. for the logistical and scientific support during the experimental activity.

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