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Efficiency in water and nutrient use in treated wastewater for three horticultural crops

Eficiência no uso da água e nutrientes presentes na água residuária tratada em três culturas hortícolas

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ABSTRACT
Irrigated agriculture primarily aims to maximizing crop productivity. One way to achieve this goal is through the use of treated wastewater (TWW). The objectives of this study were to evaluate the productivity of lettuce, beet, and radish irrigated with wastewater treated by a septic tank system (SODIS + 125 mg.L-1 H_2O_2) (TWWS) and constructed wetlands (TWWCW); calculate the amounts of macronutrients nitrogen (N), phosphorus (P), and potassium (K) supplied through irrigation; and assess the effect of irrigation with TWWS and TWWCW on water use efficiency. The experiment was conducted under field conditions at the Faculty of Agronomic Sciences - UNESP, Botucatu, SP. Lettuce and beet productivity was higher when cultivated with TWWCW compared to TWWS, showing an increase of 8.5% (75% TWWCW) and 30.8% (100% TWWCW), respectively. For radish, productivity was higher with TWWS compared to TWWCW, providing an increase of 19.7% (50% TWWS). Regarding nutrient input from TWWS and TWWCW, they partially met the nutritional needs, supplying more than 70% of the nitrogen demand of the vegetables. For lettuce and radish, the highest Water Use Efficiency – Irrigation (WUEI) and Water Use Efficiency – Irrigation + Precipitation (WUEIP) values were obtained through irrigation with TWWS, providing a minimum increase of 15% in the final productivity of the vegetables. In beet, the highest WUEI and WUEIP values were obtained through irrigation with TWWCW, providing a minimum increase of 50% in the final productivity.

Palavras-Chave
produtividade
macronutrientes
agricultura sustentável

RESUMO
A agricultura irrigada visa sobretudo a maior produtividade das culturas. Umas das maneiras de atingir esse objetivo, é através da utilização de água residuária tratada – ART. Os objetivos desse trabalho foram avaliar a produtividade da alface, beterraba e rabanete, irrigadas com água residuária tratada pelo sistema tanque séptico (SODIS + 125 mg.L-1 H_2O_2) (ARTS) e alagados construídos (ARTAC); calcular a quantidade dos macronutrientes nitrogênio (N), fósforo (P) e potássio (K), fornecidos via irrigação; e avaliar o efeito da irrigação com ARTS e ARTAC na eficiência do uso da água. O experimento foi conduzido em condições de campo, na Faculdade de Ciências Agronômicas – UNESP, Botucatu, SP. A produtividade da alface e da beterraba foi superior no cultivo com ARTAC em comparação ao ARTS, apresentando uma elevação de 8,5% (75% ARTAC) e 30,8% (100% ARTAC), respectivamente. Para o rabanete, a produtividade foi superior no cultivo com ARTS em relação a ARTAC, proporcionando um incremento de 19,7% (50% ARTS). Em relação ao aporte nutricional a ARTS e ARTAC, atenderam parcialmente as necessidades nutricionais, suprindo mais de 70% da demanda por nitrogênio das hortaliças. Para a alface e o rabanete, os maiores valores de EUAI e EUAIP foram obtidos através da irrigação com ARTS, proporcionando um incremento mínimo de 15% na produtividade final das hortaliças. Na beterraba, os maiores valores de EUAI e EUAIP foram obtidos através da irrigação com ARTAC, proporcionando um incremento mínimo de 50% na produtividade final.

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Introduction

Irrigated agriculture primarily aims for increased crop productivity. One way to achieve this is through the use of treated wastewater (TWW), which provides water and nutrients to plants. Horticulture, widely practiced in Brazil, has also incorporated TWW reuse, resulting in higher yields compared to conventional cultivation for crops such as lettuce (LONIGRO et al., 2016; VERGINE et al., 2017), beet (HUSSAR et al., 2005; GOMES et al., 2015), and radish (ZAVADIL, 2009; LIMA et al., 2016).

Moreover, the water scarcity scenario, marked by both qualitative and quantitative scarcity, drives the need for innovations in irrigated agriculture that enhance water use efficiency (WUE) provided by irrigation water alone (WUEI) and/or combined with effective precipitation (WUEIP).

The use of alternative water sources for irrigation, such as treated municipal wastewater, is already practiced and recommended in several countries worldwide (FARHADKHANI et al., 2018). This practice helps prevent the improper disposal of this effluent with high nutritional potential, incorporating sustainable practices into irrigated agriculture, such as water reuse and conservation.

The successful use of TWW is extensively discussed in the scientific community and has led to increased WUEI and WUEIP in crops such as lettuce (BALKHAIR et al., 2013) beet (HASSANLI et al., 2010), and radish (BALKHAIR et al., 2014). Additionally, TWW reuse can meet the water and nutritional needs of agricultural crops.

Before being used for irrigation, wastewater needs some form of treatment to reduce the concentration of pathogenic microorganisms, avoiding contamination of crops and end consumers. Treatment processes reduce nutrient concentrations, but the effluent still has a high fertilization potential (FARHADKHANI et al., 2018).

Moreover, costs associated with chemical fertilization can make agricultural production financially challenging.

Therefore, the objectives of this study were to evaluate the agricultural productivity of lettuce, beet, and radish irrigated with wastewater treated by the septic tank system (SODIS + 125 mg.L^{-1} H_2O_2) (TWWS) and constructed wetlands (TWWCW); calculate the amounts of macronutrients N, P, and K supplied via irrigation with TWWS and TWWCW, comparing them with the fertilizer recommendations for vegetables, aiming to determine the percentage savings from chemical fertilizer application provided by TWW reuse; and assess the effect of irrigation with TWWS and TWWCW on water use efficiency, considering both irrigation water alone (WUEI) and combined with effective precipitation (WUEIP).

Materials and methods

The experiment was conducted in the field from July to October 2017 at the Faculty of Agronomic Sciences of São Paulo State University "Júlio de Mesquita Filho" (FCA/UNESP) in Botucatu, SP (22º 51' 12"S, 48º 25' 45"W, and 763 m average altitude). The climate is Cwa warm temperate (mesothermal), humid, according to the Köppen classification. The average annual temperature ranges from 17.1 to 23.2 °C, and the total average rainfall is approximately 1,500 mm. The soil in the experimental area belongs to the Red Latosol (EMBRAPA, 2006).

To evaluate the productivity of lettuce (Vera), beet (Early Wonder Tall Top), and radish (F1 Hybrid HS 2030), they were cultivated in beds (2.0 x 0.5 m), each with a drip line between the two rows of plants, with each plant considered a repetition. The spacing between plants was 0.25, 0.1 and 0.1 m for lettuce, beet, and radish, respectively.

The vegetables were irrigated using drip irrigation with two types of treated wastewater (TWWS and TWWCW) through two different systems. TWWS came from the first treatment system, composed of a septic tank + solar disinfection + 125 mg.L^{-1} H_2O_2 (QUELUZ and SÁNCHEZ-ROMÁN, 2014). TWWCW was obtained from the second treatment type, consisting of three constructed wetland beds (QUELUZ et al., 2017).

The irrigation depth was calculated using tensiometers and applied in five different compositions, formed with 0, 25, 50, 75, and 100% of TWWS and TWWCW, supplemented with water from the FCA University Campus supply, from a deep well (WS). Irrigation was not performed on days with precipitation or on subsequent days when tensiometer readings indicated no need for irrigation.

The experimental design used was randomized blocks, organized in a 2 x 5 factorial scheme, considering the two sources of treated wastewater (TWWS and TWWCW) and the five irrigation depth compositions (100%, 75%, 50%, 25%, and 0% TWW).

The macronutrient levels of nitrogen (N), phosphorus (P), and potassium (K) in TWWS and TWWCW were evaluated weekly in the laboratory of the Department of Soils and Environmental Resources at FCA/UNESP.

Soil samples (0 – 20 cm) were also collected for chemical analysis at the UNESP Soil Laboratory. Based on soil analysis and fertilizer recommendations for lettuce (TRANI and RAIJ, 1997), beet (TIVELLI et al., 2011), and radish (TRANI and RAIJ, 1997), the amount of fertilizers needed to complete the crops' production cycle was calculated (Table 1).

Table 1. Recommended Nutrient Quantities for Each Crop

Nutrient	Recommendation* (Kg.ha^{-1})		
	Lettuce	Beet	Radish
N	100	160	40
P	30	-	180
K	86	168	130

*These values are recommended for topdressing fertilization, and for potassium (K), it replenishes an additional 30% from the base fertilization.

Source: Authors (2024).

In the 0% TWW composition, chemical fertilization was carried out according to recommendations for lettuce and beet crops, considering the entire production cycle. In radish cultivation, no planting fertilization was done since this crop was planted after lettuce harvest.

Therefore, complete fertilization recommended for the entire cycle was considered in the calculations.

For compositions with TWW, the amount of macronutrients (Equation 1) N, P, and K supplied by TWWS and TWWCW was calculated based on their chemical characterization and the volume of water applied daily (determined via tensiometry). The percentage applied of N, P, and K via irrigation with TWWS and TWWCW was then calculated (Equation 2), and a comparison was made with the specific fertilizer recommendation for each crop.

$$N_A = C * VART * f \qquad \text{Eq. 1}$$

Where:
NA: Amount of applied nutrient ($kg.ha^{-1}$);
C: Concentration of the nutrient present in the nutrient solution ($mg.L^{-1}$);
VART: Volume of nutrient solution applied per crop cycle, 126.5; 409.2, and 212.5 $L.m^{-2}$ for lettuce, beetroot, and radish, respectively;
f : 0.01; constant for unit conversion.

$$PE = \frac{N_a * 100}{QNR} \qquad \text{Eq. 2}$$

Where:
PE: Percentage of nutrient savings, %;
NA: Amount of applied nutrient ($kg.ha^{-1}$);
QNR: Recommended nutrient quantity ($kg.ha^{-1}$).

After harvest, samples from each crop were weighed using an electronic analytical balance Gehaka BG 1000 (precision of 0.1 g), for the calculation of their respective productivities, according to Equation 3.

$$P = \frac{P_f}{A_c} \qquad \text{Eq. 3}$$

Where:
P: Productivity ($kg.ha^{-1}$);
Pf: Fresh mass (kg);
Ac: Cultivated area (ha).

Beet roots were classified according to caliber, as commercial (classes 50, 90, and 120 mm) and non-commercial (roots with cracks, holes, and pest occurrences). Radish roots were also classified as commercial (free of cracks, not spongy, with a diameter ≥ 20 mm) and non-commercial (roots with cracks, holes, and pest occurrences), according to the methodology proposed by Cardoso and Hiraki (2001).

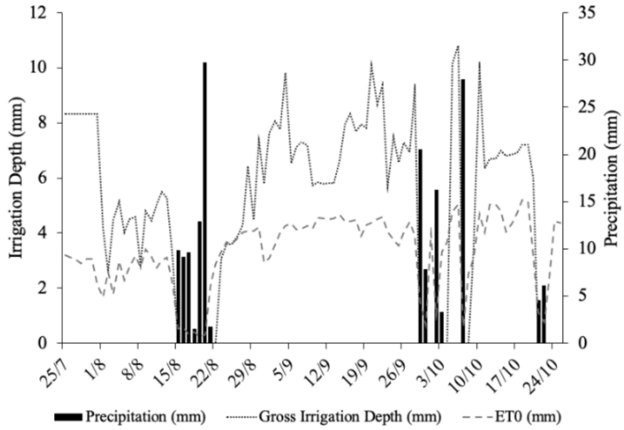
To determine water use efficiency (WUE, $kg.m^{-3}$), a ratio was made between crop productivity ($kg.ha^{-1}$) and the volume of water received (m^3) in a specific area (ha), considering two situations: the first determined water use efficiency considering only the water supplied by irrigation (WUEI, $kg.m^{-3}$), and the second determined water use efficiency considering the water supplied by irrigation combined with effective precipitation (WUEIP, $kg.m^{-3}$).

The data obtained were evaluated through analysis of variance using the Scott-Knott test with a 5% probability, using the Sisvar 5.6 software (FERREIRA, 2007).

Results and discussion

In Figure 1, the results of reference evapotranspiration, precipitation, and irrigation depth can be observed. Irrigation was not performed on days with precipitation or when the average measured tension was less than 7 KPa, indicating that the soil had reached field capacity at this tension.

Figure 1. Daily values of reference evapotranspiration (ET0), precipitation, and gross irrigation depth (GID) during the experiment



Productivity

The results of vegetable productivity irrigated with TWWS and TWWCW are presented in Table 2.

Table 2. Vegetable productivity

Irrigation water	Compositions of irrigation depth (%)	Productivity ($ton.ha^{-1}$)		
		Lettuce	Beet	Radish
AA	0	31.34 b	176.16 a	51.46 a
TWWCW	25	34.09 b	185.95 a	60.46 a
	50	32.04 b	233.85 b	55.08 a
	75	36.48 b	258.80 b	60.04 a
	100	35.05 b	288.45 b	54.92 a
TWWS	25	25.24 a	188.58 a	51.75 a
	50	30.46 b	202.18 a	65.92 a
	75	33.62 b	235.60 b	57.33 a
	100	27.81 a	220.50 a	55.75 a

Means followed by the same lowercase letter in the column do not differ from each other at a 5% probability level, according to the Scott-Knott test.

Source: Authors (2024)

According to the data in Table 2, the highest productivities were obtained with 75% irrigation depth, reaching 36.48 and 33.62 $ton.ha^{-1}$ for TWWCW and TWWS, respectively. These values were higher than conventional cultivation, although not statistically different.

Consistent with the findings of this study, Vergine et al. (2017) achieved a productivity of approximately 38 $ton.ha^{-1}$ in lettuce cultivation irrigated with treated wastewater and added P (50 $Kg.ha^{-1}$) and N (125 $Kg.ha^{-1}$). Similarly, Lonigro et al. (2016) reported a productivity of 31.37 $ton.ha^{-1}$ when evaluating lettuce development irrigated with tertiary-treated domestic sewage.

For beet, as shown in Table 2, productivity was numerically higher in TWWS and TWWCW irrigated crops compared to conventional planting.

The highest average productivities were observed in compositions of 100% TWWCW and 75% TWWS, reaching 288.45 and 235.6 $ton.ha^{-1}$, respectively.

Compositions of 50% TWWS and 100% TWWCW produced the highest percentage of non-commercial roots, which are those with deformities or cracks, at approximately 12.50% and 2.50%, respectively.

Gomes et al. (2015), evaluating the influence of irrigation with treated wastewater (aerobic and anaerobic processes) on beet, achieved a lower productivity (47.72 $ton.ha^{-1}$) with the application of 50% of the recommended N for the crop. This is lower than the highest productivity (288.45 $ton.ha^{-1}$) found in this study.

Hussar et al. (2005), assessing the efficiency of treated wastewater reuse in an anaerobic reactor for beet irrigation, reported a productivity of 163.87 $kg.ha^{-1}$ for the treatment with 100% wastewater without fertilization, which is also lower than the results of this study. This supports the nutritional quality of TWWS and TWWCW and the beneficial effect of these effluents on plants, leading to better crop yield.

Comparing the commercial root productivity of beet, the highest values were obtained with 100% TWWCW (281.24 $ton.ha^{-1}$) and 75% TWWS (217.93 $ton.ha^{-1}$), differing statistically ($p < 0.05$). In all compositions evaluated, the highest concentration of commercial roots occurred in the class ranging from 50 to 90 mm (100% in the control, 82.5% in TWWS, and 62.5% in TWWCW), followed by the class from 90 to 120 mm (7.5% in TWWS and 36.3% in TWWCW), and there was no production of roots larger than 120 mm.

Sediyama et al. (2011), evaluating the effect of soil cover and doses of sludge from a swine wastewater settling pond on beet productivity, also found that incorporating organic material into the cultivation system resulted in higher commercial productivity (38.66 $ton.ha^{-1}$). According to the same authors, there was a predominance of commercial roots in the class between 50 and 90 mm (85.4%), similar to the results obtained in this study.

For radish, as shown in Table 2, an overall assessment of total productivity, although not statistically different, irrigation with TWWS and TWWCW provided higher averages for this variable compared to conventional planting (WS). The highest values were 65.92 $ton.ha^{-1}$ in the 50% TWWS composition and 60.46 $ton.ha^{-1}$ in the 25% TWWCW composition.

Lower radish productivity values than those found in this study were reported by Lima et al. (2016), who obtained a productivity of 18.02 $ton.ha^{-1}$ with the application of 25 $ton.ha^{-1}$ of sewage sludge, and Zavadil (2009), who reported 29.3 and 22.3 $ton.ha^{-1}$ when evaluating the performance of the crop irrigated with treated domestic effluent by secondary and primary processes, respectively.

Regarding commercial productivity, it was observed that the 50% TWWS and 25% TWWCW compositions provided the highest productivity values, as well as roots of better commercial quality, with values of 61.20 and 58.30 $ton.ha^{-1}$, respectively. The 100% TWWS and 75% TWWCW compositions produced the highest percentage of non-commercial roots, which are those that are spongy or have cracks, at approximately 24.99% and 28.56%, respectively.

Nutritional Input

Table 3 describes the concentrations of macronutrients (N, P and K) in the water from different systems. Table 4 presents the values related to the nutritional input provided by TWW for lettuce and the respective percentage of savings when compared to conventional planting (Table 1).

Table 3. Concentration of macronutrients present in WS, ARTS, and ARTAC

Macronutrients	Concentration ($mg.L^{-1}$)		
	WS	TWWS	TWWCW
Total N	2.80	41.72	39.20
Total P	0.54	2.3	0.38
K	16.00	18.00	14.20

Source: Authors (2024)

Table 4. Nutritional input through irrigation with TWWS and TWWCW, and percentage of fertilizer savings based on topdressing fertilization for lettuce

Treatments		Macronutrients ($kg.ha^{-1}$)			Percentage of savings (%)		
		N	P	K	N	P	K
TWWS	25%	19.28	0.98	8.32	19.27	3.28	9.67
	50%	38.55	1.97	16.63	38.55	6.56	19.34
	75%	57.83	2.95	24.95	57.83	9.84	29.01
	100%	77.11	3.94	33.27	77.11	13.12	38.68
TWWCW	25%	18.11	0.18	6.56	18.11	0.58	7.62
	50%	36.22	0.35	13.12	36.22	1.17	15.26
	75%	54.34	0.53	19.68	54.34	1.76	22.89
	100%	72.45	0.70	26.24	72.45	2.34	30.52

Source: Authors (2024)

TWWS in all proportions provided a greater amount of NPK compared to TWWCW; however, these values were lower than the recommended values for lettuce. In compositions with TWW, even at 100% TWW providing a higher nutritional input than the others, 75% TWWS showed the highest lettuce productivity, followed by 100% TWWS and 75% TWWCW.

Thus, based on the productivity results (Table 2), it can be stated that despite the lower nutrient quantity applied by TWWS compared to conventional cultivation, all proportions are viable as they showed higher lettuce yield. Even though these productivity values do not show statistical differences ($p < 0.05$), the 100% TWWS composition provided a yield 11.8% higher than conventional cultivation, with savings of 77.11%, 13.12%, and 38.68% for N, P and K, respectively, in addition to providing a 100% savings in the use of higher quality water.

Table 5 presents the values related to the nutritional input provided by TWW for beet and the respective replacement percentages compared to conventional planting (Table 1).

TWWS in all proportions provided a greater amount of N, P, and K compared to TWWCW; however, these values were lower than the recommended values for beet, except in the 100% TWWS and TWWCW compositions, where the N input was 23.00% and 15.57% higher than recommended.

Table 5. Nutritional input through irrigation with TWWS and TWWCW, and percentage of fertilizer savings based on topdressing fertilization for beet

Treatments		Macronutrients ($kg.ha^{-1}$)			Percentage of savings (%)		
		N	P	K	N	P*	K**
TWWS	25%	49.20	2.51	21.23	30.75	-	12.64
	50%	98.40	5.02	42.45	61.50	-	25.27
	75%	147.60	7.54	63.68	92.25	-	37.91
	100%	196.80	10.05	84.91	123.00	-	50.54
TWWCW	25%	46.23	0.45	16.75	28.90	-	9.97
	50%	92.46	0.90	33.49	57.79	-	19.94
	75%	138.68	1.34	50.24	86.68	-	29.90
	100%	184.91	1.79	66.98	115.57	-	39.87

*For beet cultivation, the recommendation is not to add P in topdressing fertilization.

**For potassium (K), 30% of the planting fertilization and 100% of the topdressing fertilization were considered.

Source: Authors (2024)

Even though compositions with TWWS provided a higher nutritional input, the 100% TWWCW had the highest beet productivity, followed by 75% TWWCW and 75% TWWS.

Based on the productivity results (Table 5), it can be stated that despite the lower nutrient quantity applied in the compositions of 25%, 50%, and 75% TWWCW and TWWS compared to conventional cultivation, all proportions are viable for providing higher beet yields. The lowest productivity (25% TWWCW) obtained in this study is 5.6% higher than conventional cultivation, with savings of 28.89% and 9.97% for N and K, respectively, in addition to providing a 25% savings in well water used for irrigation.

Furthermore, the 100% TWWCW composition allowed the highest beet productivity (288.45 $ton.ha^{-1}$), 63.7% higher than that obtained with conventional cultivation, without the use of clean water and with savings of 115.57% and 39.872% for N and K, respectively.

Table 6 presents the values related to the nutritional input provided by TWWS and TWWCW and the respective replacement percentages for radish cultivation, compared to conventional planting (Table 1).

Table 6. Nutritional input through irrigation with TWWS and TWWCW, and percentage of fertilizer savings based on topdressing fertilization for radish

Treatments		Macronutrients ($kg.ha^{-1}$)			Percentage of savings (%)		
		N	P	K	N	P	K
TWWS	25%	22.17	1.13	9.56	55.41	0.63	7.36
	50%	44.33	2.26	19.13	110.83	1.26	14.71
	75%	66.50	3.40	28.69	166.24	1.89	22.07
	100%	88.66	4.53	38.25	221.66	2.51	29.43
TWWCW	25%	20.83	0.20	7.54	52.07	0.11	5.80
	50%	41.65	0.40	15.09	104.14	0.22	11.61
	75%	62.48	0.61	22.63	156.20	0.34	17.41
	100%	83.31	0.81	30.18	208.27	0.45	23.21

Source: Authors (2024)

The TWWS in all compositions provided a greater amount of N, P, and K compared to the TWWCW. Regarding N, the 25% composition for TWWS and TWWCW was the only one that supplied 55% and 52% of the nutritional recommendation for radishes, respectively. The others provided values higher than recommended.

Based on the productivity results (Table 2), the 50% TWWS composition yielded the highest radish productivity, 26.7% higher than conventional cultivation, with savings of 100%, 1.26%, and 14.71% for N, P, and K, respectively, in addition to providing a 50% savings in well water use.

Similarly, in this study, the same behavior was observed, where the highest average productivities were obtained through irrigation with TWWS, where the K concentration was also higher. K is the most extracted nutrient by plants storing reserves in underground organs, used for sugar translocation, activation of enzymatic systems involved in plant metabolism, and required for achieving high yields, directly influencing plant growth, justifying the increased productivity of radish roots.

In terms of nutritional content, comparing TWWS and TWWCW with the treated domestic effluent used by Dantas et al. (2014) in radish cultivation, it was found that the N – Total concentration in TWWS (41.72 $mg.L^{-1}$) and TWWCW (39.20 $mg.L^{-1}$) was higher than that found by Dantas et al. (2014), who obtained an average concentration of 31.96 $mg.L^{-1}$. Regarding P – Total, the opposite was observed, with lower values of 2.13, 0.38, and 14.02 $mg.L^{-1}$, respectively.

In general, both TWWCW and TWWS provided a higher supply of N to the crops. A similar trend was observed by Montemurro et al. (2017) when evaluating the effect of irrigating sweet fennel and lettuce with treated domestic sewage, noting a 54% nitrogen fertilizer saving.

The high availability of N in wastewater leads to increased vegetative growth and, consequently, higher crop yields. Additionally, continuous supply through wastewater irrigation reduces losses due to gasification and leaching (Montemurro et al., 2017), maximizing N availability for plant metabolism, as observed in this study.

Regarding P, the highest supply was observed for lettuce and radish under the 100% TWWS composition, providing savings of 7.04% and 2.51%, respectively. Cuba et al. (2015), studying lettuce development in hydroponic cultivation with treated domestic sewage effluent, observed an 11% saving with monoammonium phosphate.

Regarding K, the highest savings percentages were obtained in the 100% TWWS composition, with values of 20.74%, 40.81%, and 29.43% for lettuce, beet, and radish, respectively. Similar percentages were obtained in cultivation with treated wastewater by Cuba et al. (2015) in lettuce, reporting 49%.

As observed in this study, for N, both TWWS and TWWCW partially met the nutritional demand for lettuce and beet and completely for radishes, compared to the recommended values for these crops. However, even with a lower nutrient supply, the yield of all three crops exceeded that of conventional cultivation, except for lettuce in the 25%, 50%, and 100% TWWCW compositions.

This result can be attributed to various factors, such as specific characteristics of TWWS and TWWCW, the soil used, and nutritional management. The latter is due to the fact that in TWW irrigation, through drip irrigation, water and nutrient application occurs at high frequency and low volume. Thus, small doses of nutrients are provided to the crops daily. In the conventional cultivation system, nutrient dosages are provided, for example, four or five times, depending on the productive cycle of each crop.

This can lead to nutrient losses through volatilization and leaching, consequently affecting the expected plant yield.

According to Montemurro et al. (2017), wastewater fully or partially meets the nutritional demand of agricultural crops. However, there may be variation in nutrient concentrations depending on the physical and chemical characteristics of the effluent. It is essential to emphasize the importance of proper management of these elements to avoid damage caused by excess, both in the soil and in the plants.

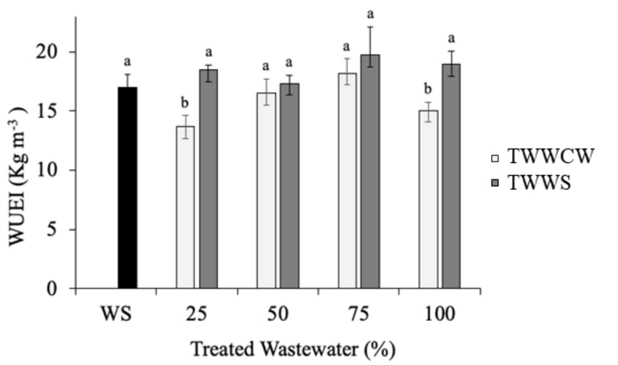
Proper nutrient management can contribute to better crop development due to the high concentration of nutrients and organic matter, favoring water retention in the soil and nutrient fixation.

These results are consistent with the literature, where increased productivity is directly related to the nutritional quality of treated wastewater, promoting crop development.

Water Use Efficiency

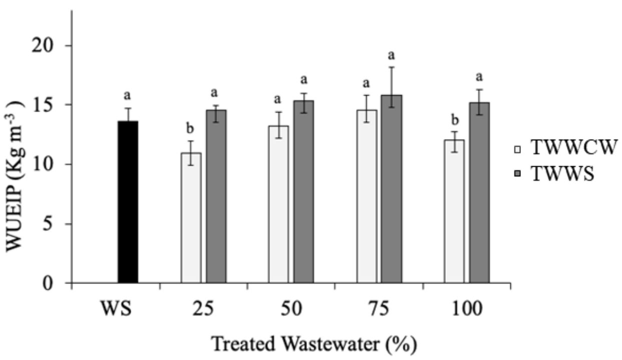
WUEI and WUEIP values for lettuce are presented in Figures 2 and 3, respectively.

Figure 2. WUEI for lettuce. Means followed by the same letter do not differ from each other at a 5% significance level according to the Scott-Knott test



Source: Authors (2024)

Figure 3. WUEIP for lettuce. Means followed by the same letter do not differ from each other at a 5% significance level according to the Scott-Knott test



Source: Authors (2024)

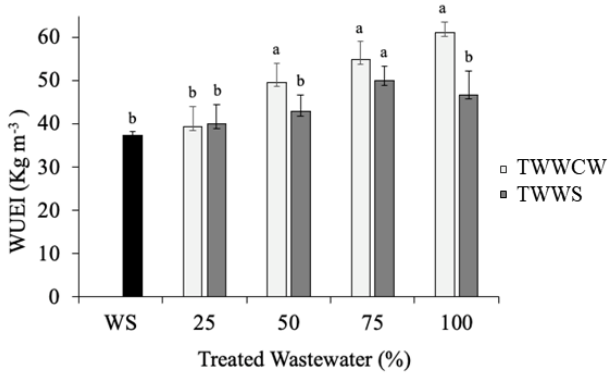
For lettuce, it was observed that both WUEI and WUEIP for TWWS were numerically higher compared to conventional cultivation, although not statistically different, in all irrigation depth compositions. The highest values were obtained at 19.74 and 19.08 kg.m^{-3} in the 75% TWWS composition, respectively. Regarding TWWCW, WUEI and WUEIP values for the 25% and 100% compositions were lower and statistically different compared to the control. In comparison to 0% TWW, the 50% composition was lower, and the 75% composition was higher for both WUEI and WUEIP; however, these values are statistically equal. The highest averages were 18.19 and 19.74 kg.m^{-3} for WUEI and 17.58 and 19.08 kg.m^{-3} for WUEIP, obtained in the 75% TWWCW and 75% TWWS compositions, respectively.

Balkhair et al. (2013), studying the effect of drip irrigation with six different dilutions of treated domestic wastewater on lettuce yield, obtained values higher than those reported in this research. The highest value obtained by the authors for irrigation water use efficiency was 25.0 kg.m^{-3} in the treatment with 60% domestic effluent.

The results of WUEI and WUEIP for lettuce, irrigated with TWWCW and TWWS, are superior compared to conventional planting, except for the 50% and 100% compositions for TWWCW. Similar results were reported by Magalhães et al. (2015).

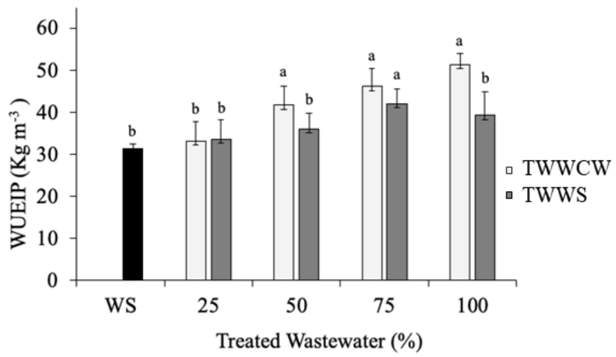
For beet, the results of WUEI and WUEIP are presented in Figures 4 and 5, respectively.

Figure 4. WUEI for beet. Means followed by the same letter do not differ from each other at a 5% significance level according to the Scott-Knott test



Source: Authors (2024)

Figure 5. WUEIP for beet. Means followed by the same letter do not differ from each other at a 5% significance level according to the Scott-Knott test



Source: Authors (2024)

For beet irrigated with TWWS, WUEI and WUEIP values were superior to conventional cultivation in all compositions, but this difference was significant only in the 75% composition. For TWWCW, values in all compositions were significantly higher than 0% TWW, except for 25%.

The highest averages were 61.15 and 49.95 kg.m^{-3} for WUEI and 57.49 and 46.96 kg.m^{-3} for WUEIP, obtained in the 100% TWWCW and 75% TWWS compositions, respectively.

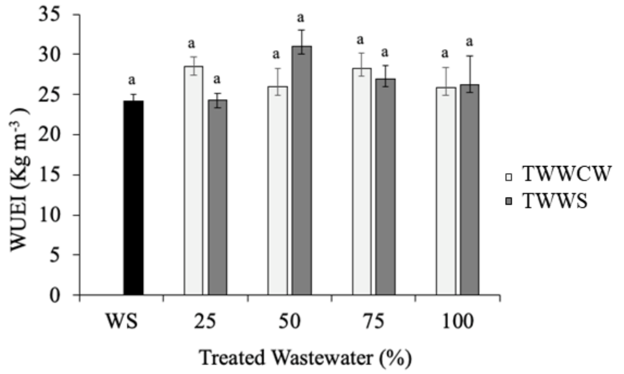
Contrary to the observations in this study, Hassanli et al. (2010), researching the effects of different irrigation systems and applying treated domestic effluent to sugar beet, found considerably lower WUEIP values of 9 kg.m^{-3}.

Kiymaz and Ertek (2015), studying the effect of different irrigation and nitrogen levels on sugar beet yield during 2012 and 2013 in Turkey, obtained results lower than those in this study. The highest WUEI and WUEIP values presented by these authors were 22.8 and 13.0 kg.m^{-3}.

The WUEI and WUEIP values obtained in this study are higher than those reported by Topak et al. (2011), who, evaluating the effects of deficit irrigation on sugar beet yield in the semi-arid region of Turkey, achieved average values of 8.32 and 11.5 kg.m^{-3}, respectively, indicating a lower biomass-to-water consumption ratio.

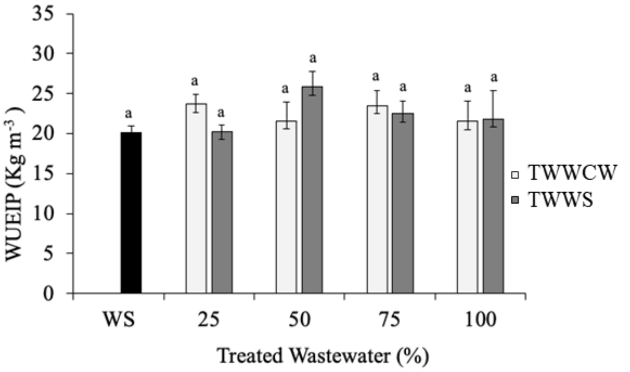
For radish, the results of WUEI and WUEIP are presented in Figures 6 and 7, respectively.

Figure 6. WUEI for radish. Means followed by the same letter do not differ from each other at a 5% significance level according to the Scott-Knott test



Source: Authors (2024)

Figure 7. WUEIP for radish. Means followed by the same letter do not differ from each other at a 5% significance level according to the Scott-Knott test



Source: Authors (2024)

It was observed that for radish, irrigated with both TWWS and TWWCW, WUEI and WUEIP values were higher compared to conventional cultivation in all irrigation depth compositions, although all were statistically equal.

The highest averages were 28.45 and 31. kg.m^{-3} for WUEI and 26.58 and 28.58 kg.m^{-3} for WUEIP, obtained in the 25% TWWCW and 50% TWWS compositions, respectively.

Balkhair et al. (2014) evaluated the effect of irrigation using treated domestic sewage (secondary treatment) on radish cultivation, testing different irrigation depth compositions with wastewater and groundwater. The highest WUEI values obtained by the authors were 13.25, 13.23, and 12.89 kg.m^{-3} in treatments with groundwater, 60%, and 100% treated wastewater, respectively. However, these results are lower than those obtained in this study.

In general, irrigation with TWWCW and TWWS favored the yield of the three evaluated crops and consequently WUEI and WUEIP. This positive result may be related to the nutritional content of the wastewater used. According to Balkhair et al. (2013), the incorporation of nutrients into the soil through TWW irrigation improves its physical and nutritional content, favoring chlorophyll and total carotenoid levels in plants, resulting in increased biomass and crop yield. Moreover, Zavadil (2009) also found better yields for lettuce, radish, carrot, potato, and sugar beet irrigated with treated municipal wastewater.

In line with the results of this study, Tunc and Sahin (2016) also observed an increase in WUEI and WUEIP in cabbage cultivation due to irrigation with wastewater, compared to cultivation with clean water. The authors achieved an increase of 122.3% in WUEIP and 82.3% in WUEI in treatments with effluent in 2010.

Another factor that may have favored WUEI and WUEIP was the soil irrigation management used in this study. This method results in a lower volume of applied water compared to climate-based management. Thus, the applied depth is smaller, and consequently, the water use efficiency indices are higher. A higher amount of water applied to radishes reduces water use efficiency, as was also observed by Topak et al. (2011) for sugar beet and by Magalhães et al. (2015).

Conclusions

Lettuce productivity was higher in cultivation with TWWCW compared to TWWS and conventional irrigation. The highest yields for both systems were obtained in the 75% composition, providing values of 36.48 and 33.62 ton.ha^{-1} for TWWCW and TWWS, respectively.

For beet, productivity was higher in cultivation irrigated with TWWCW compared to TWWS and conventional irrigation. The highest averages were achieved in the 100% TWWCW and 75% TWWS compositions, with values of 288.45 and 235.60 ton.ha^{-1}, respectively.

Radish productivity was higher in cultivation with TWWS compared to the others. The 50% TWWS and 25% TWWCW compositions provided the highest yield values of 65.92 and 60.46 ton.ha^{-1}, respectively.

For lettuce, TWWS and TWWCW partially met the nutritional needs, but the crop yield was higher than conventional cultivation, except for the 25%, 50%, and 100% TWWCW compositions.

For beet, TWWS and TWWCW partially met the nutritional needs, except for the 100% TWWS and TWWCW compositions, which provided a nutrient supply of 23.0% and 15.57% of N, higher than recommended. However, the crop yield was higher than conventional cultivation in all irrigation depth compositions.

For radish, TWWS and TWWCW fully met the N needs in the 50%, 75%, and 100% compositions, and partially met the needs of P and K. However, the crop yield was higher than conventional cultivation in all irrigation depth compositions.

For lettuce, the highest values of Water Use Efficiency Index (WUEI) and Water Use Efficiency Index for Productivity (WUEIP) were obtained through irrigation with TWWS in the 75% composition. In beet, the highest values of WUEI and WUEIP were obtained through irrigation with TWWCW in the 100% composition. In radish cultivation, the highest values of WUEI and WUEIP were obtained through irrigation with TWWS in the 50% composition.

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