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Treated wastewater reuse and its impact on soil properties and potato and corn growth

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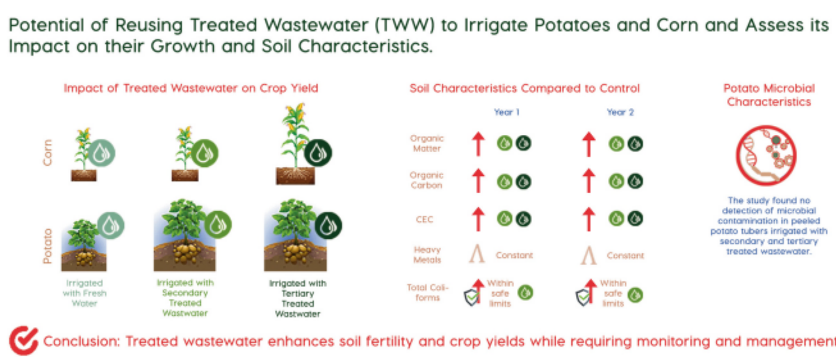
HIGHLIGHTS

- Irrigation with treated wastewater increased organic matter, enhanced soil fertility, and increased potato and corn yield.
- Heavy metals concentrations in TWW-irrigated soils remained within safe limits.
- Potato field with secondary-treated wastewater showed some contamination with total coliform.
- Sodium level in soils irrigated with tertiary-treated wastewater require monitoring and management.
- With monitoring, tertiary-treated wastewater could be better option than secondary-treated wastewater for irrigation.

GRAPHICAL ABSTRACT



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ABSTRACT

Water scarcity is a growing challenge in semi-arid regions. Many farmers have resorted to treated wastewater (TWW) as an available and low-cost water source. This study investigated the impact of irrigating potato (*Solanum Tuberosum*) and corn (*Zea mays*) with tertiary-treated (TW) and secondary-treated (SW) wastewater compared to freshwater, over two years. We studied the impact of TWW reuse on soil properties, soil microbes, crop yield, and potato tuber health. Irrigation of both corn and potato with TW significantly increased organic matter (OM) content; on average across both years and crops OM increased by about 35 % under SW and 42 % under TW. TWW irrigation also increased cation exchange capacity (CEC) by the second year under SW and TW in potato (average 67 %), and by the second year under TW in corn (average 13 %). TWW also enhanced soil fertility with no heavy metals contamination. However, potato field irrigated with SW showed high levels of total and thermotolerant coliforms in soil, exceeding predefined thresholds, in the second season. No microbial contamination was recorded in TW-irrigated fields, however, it raised salinity concerns compared to control with 935 mg Na /kg in TW soil compared to 465 mg/kg in control soil during the first season in potato soil. Significant increases in potato tillers, number of tubers (average 6 tubers/plant in TW vs 3 tubers/plant in the control), and

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tuber weight were recorded in season two under TW irrigation. Both SW and TW increased corn biomass during both seasons. In conclusion, TW is a sustainable alternative water source that enhances crop yields and improves soil quality. This study highlighted the critical role of TWW management and monitoring to address challenges such as salinity and microbial contamination. Further research is required to optimize TWW long-term reuse sustainable agriculture, balancing crop benefits while safeguarding human health.

1. Introduction

With water scarcity being a concerning global issue, caused by a population exponential increase and climate change, treated wastewater (TWW) reuse serves as a promising alternative resource for irrigation (Contreras et al., 2017). The agricultural sector consumes a total of 70 % of water worldwide (Hoekstra and Mekonnen, 2012; Waughray, 2011; Clemmens et al., 2008; Tanji and Kielen, 2002). Treated wastewater is a source of both water and nutrients such as phosphorus, nitrogen, potassium, and many micronutrients, making it highly desirable for agricultural use (Contreras et al., 2017). Moreover, a substantial portion of the nitrogen and phosphorous available in the TWW can be directly utilized by plants because it is in a more readily available form or mineralized form (Sengupta et al., 2015; Poustie et al., 2020). Being rich in nutrients, it decreases the reliance on fertilizers, subsequently decreasing crop production costs, and help enhancing crop productivity and soil fertility (Chen et al., 2015). Thus, TWW has been shown to enhance yields (Sato et al., 2013), encouraging increased adoption globally (Aziz and Farissi, 2014).

Despite its benefits, TWW can cause health risks when used for crop irrigation (Ungureanu et al., 2020) due to the presence of heavy metals and pathogenic organisms (Mahfooz et al., 2020), which can be absorbed by the plant roots and interfere with the food cycle (Mahmood and Malik, 2014). TWW reuse has expanded in the absence of strict and long-term monitoring of both soil and crop quality. Potato is an important crop globally and has strategic importance for some Mediterranean countries including Lebanon, both in terms of food security being a staple crop and in terms of economics being a cash crop. Lebanon produces around 300,000 tons of potato per year (Choueiri et al., 2017) with the Bekaa valley accounting for >70 % of the total potato cultivation area (Dal et al., 2021). Corn is another crop that is grown in the Bekaa valley for silage and along with potato production are big water consumers leading Lebanese farmers to use TWW as an alternative to the scare freshwater resources in the country. Irrigation with TWW is important to be monitored with all crops and especially potato because the edible portion is the underground tuber. Serious public health and environmental risks could ensue, which are addressed in this study. Previous studies have primarily examined the use of SW for drip irrigation of potatoes, observing some microbial contamination on potato tubers, notably with total Coliforms (Alkhaza'leh et al., 2023). This Study evaluates the use of TWW which are available to some farmers in the Bekaa region at two levels of treatment in terms of the effects on soil and crop quality and potential heavy metal contamination hazards. Additionally, assessment of the impact on microbial contamination of potato tubers was conducted. A previous study in Jordan reported a remarkable increase in biomass and grain yield of vetch and barley irrigated with secondary-treated municipal wastewater (Mcheik et al., 2017). And in Cyprus, Economou et al. (2023) suggests the use of TWW for nutrient recovery for potato production as well as reduction of the impact of wastewater discharge into surface water. Therefore, our study aimed to assess and compare the reuse of TWW on two different crop types, potato which is a tuber crop eaten cooked and field corn whose edible parts are above the ground and not in direct contact with the irrigation water. We also aim to investigate the potential negative impacts which can affect soil with TWW reuse such as salinity and trace metal contamination to provide additional knowledge and data for soil managers and policy makers.

The overall aim of the study is to investigate the impact of TWW on soil properties and on the yield and quality of potato and corn under semi-arid conditions. Specifically, the objectives are to:

1. Assess the impact of irrigation with treated wastewater over a two year period on the physical, chemical and microbial properties of soils
2. Evaluate the effects of irrigation with TWW on potato yield and quality and on the yield of field corn.

2. Methodology

2.1. Study area, experimental design

An experiment was carried out during two growing seasons, 2022 and 2023 at the Advancing Research Enabling Communities Center, AREC – American University of Beirut AUB, Lebanon (33.9253 N lat., 36.07549E long.) in the Bekaa Valley. The average air temperature was 13.1 °C, higher than that in the second season with 11.5 °C. In contrast, the total precipitation was higher in the second season with 475 mm, as compared to 422 mm in the first season. The field experiment site, previously cultivated with barley, followed a complete randomized design in a drip-irrigation system with three replicates ($n = 3$) for each of the three treatments, a control (freshwater sourced from a well), a secondary treated wastewater (SW) and a tertiary treated wastewater (TW). SW and TW were transported from a tertiary treatment plant, situated in the nearby city of Zahle, which collects and treats domestic, industrial and rainwater. Soil samples were collected before the initiation of the experiment on the 4th of November 2021 as a baseline.

Both *Solanum tuberosum* (potato) and *Zea mays* (corn) crops were sown in rows within 4.5 m × 6 m plots in a silty clay loam, with 6 plots per treatment, including control, SW and TW, adding up to 18 plots. The planting dates were April 21st, 2022, for both potato and corn in season one, and April 3rd and June 5th, 2023, for corn and potato, respectively, in season two. Harvesting took place on September 1st, 2022, for both potato and corn in the first season, and on August 25th and September 20th, 2023, for corn and potato, respectively, in the second season. The seeding rate was 200 kg per dunum for potato, and 4 kg per dunum for corn adhering to the standard farming practices in the Bekaa Valley. It is worth mentioning that potato yields are influenced by climatic conditions, impacting the crop cycle, crop yield and affecting pest and disease spread and water requirements. Subtropical regions, located between 23 and 30° latitude, include the dry 'Mediterranean' and 'warm temperate' climates. These regions offer longer growing seasons, increasing productivity, but high temperatures also stress crops and raise water needs (Economou et al., 2023). As for the corn, it is a warm-season crop that thrives in soil temperatures of 29–32 °C for optimal germination and emergence. In light soils, nighttime temperatures below 10 °C can further hinder emergence (Ennen and Jeschke, 2019).

Based on the reference evapotranspiration (ET0) for the Bekaa area between April and August, the water requirements of potato and corn were calculated to be 560 mm and 420 mm, respectively. The potato crop had the greater water requirement at peak demand in summer; 6.5 m^3 are needed per treatment during both stage III (tuber initiation) and stage IV (tuber bulking). Each of these stages span a duration of two weeks, which is equivalent to 54 mm of precipitation. Therefore, to meet this demand, two HDPE tanks with a 4 m^3 capacity each were installed for each treatment (TW and SW) and replenished twice a week with the respective type of wastewater. The tanks were fitted onto a drip tape irrigation system fitted with a screen and a disk filter (1.5″ filters) and a centrifugal pump of 1.5 HP. Freshwater was sourced directly from AREC's well water network. All treatments were irrigated 4 times a week, with each treatment receiving 1 h per day in both corn and potato fields throughout June. In July, August and September, irrigation hours were extended gradually based on ET0 and field conditions. A starter 50 kg of NPK (20–20–20) fertilizer was evenly distributed across all plots at the beginning of each season. An additional 100 kg of urea was applied to the potato field, along with 1 l of tebuconazole and 250 ml of 2,4 D + MCPA herbicide during mid-season.

2.2. Soil sampling

Soil samples were taken, to a depth of 15 cm depth using a shovel, in a randomized manner in each replicate plot, to ensure representativeness and eliminate bias, and pooled to create one soil sample per replicate plot. Soil sampling was conducted before the initiation of the experiment for baseline analysis, and after harvesting the potato and corn at the end of both seasons which allowed for the comparison of pre- and post-cultivation soil conditions. Soil samples were dried at 40 °C, to reduce moisture content and prevent microbial activity that could alter the sample composition, then sieved to pass through a 2 mm sieve. Particle size analysis, using the Bouyoucos hydrometer method (Bashour and Sayegh, 2007), indicated that the soil texture of the study area was silty clay loam in the first and second seasons noting that the same fields were used in both seasons.

2.3. Chemical characterization of TWW, control soils and amended soils

Soil samples were characterized for their physico-chemical properties as described in Bashour and Sayegh (2007) which details soil analysis for semi-arid soils. pH and electrical conductivity (EC) were determined in 1:2.5 soil:water suspension using HQ40d multi-meter with PHC 101 probe (HACH, Colorado, US) and Thermo-Fisher Scientific EU TECH handheld meter (Eutech Instruments Pte Ltd., Ayer Rajah Crescent, Singapore), respectively. Organic matter (OM) was measured by the Walkley – Black combustion method (Nelson and Sommers, 1982) and OC calculated by multiplying the organic matter by a factor of 1.72. The cation exchange capacity (CEC), which relies on the exchange of sodium (Na^+) using ammonium acetate, was measured using a flame photometer (BWB Technologies). Available heavy metals concentrations (cadmium (Cd), chromium (Cr), nickel (Ni), lead (Pb), copper (Cu) and zinc (Zn)) in soil were quantified using an Atomic Absorption Spectrophotometer (AA – 6300 Shimadzu) after soil extraction with DTPA.

Available phosphorus (PO_4^{3-}-P) was measured using a spectrophotometer (Optima SP-300 model, Tokyo, Japan) at a wavelength of 882 nm according to the "Olsen method" (Olsen, 1954). Extractable potassium (K^+), sodium (Na^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) were measured according to Bashour and Sayegh (2007), after extracting the soil with 1 N ammonium acetate. The concentrations of K^+ and Na^+ were measured by a flame photometer (BWB Technologies), while Ca^{2+} and Mg^{2+} were measured on an atomic absorption spectrophotometer (AA – 6300 Shimadzu). Soil chemical values were reported as mean values, with corresponding ± standard deviation based on $n = 3$.

Treated wastewater samples were monitored at the outlet of the Zahle treatment plant each month, simultaneously with the experimental period. These samples underwent physio-chemical and microbial (total and thermotolerant (fecal) coliforms) analyses by the service lab of the Lebanese Agricultural Research Institute (LARI) according to the standard methods that are used for official monitoring of water by the relevant Lebanese ministries.

2.4. Microbial analysis of soil and potato tubers

Microbial contamination of the soil that was irrigated with the control irrigation (well water) and treated water (SW and TW) was assessed through various parameters, including total viable count, total coliforms, thermotolerant coliforms, *E. coli*, *Salmonella* sp., *Pseudomonas aeruginosa*, *Enterococci* spp., *Listeria monocytogenes*, *Bacillus* spp., sulfite-reducing bacteria, yeast, and molds. The microbiological limits for soil samples which are presented in Tables 4 and 5 are based on FAO guidelines (FAO, 2010b) as follows: Total viable count ranges from 10ˆ8 to 10ˆ10 CFU/g. Total coliforms should not exceed 5000 CFU/g, and thermotolerant coliforms should be less than 1000 CFU/g. *E. coli* presence is limited to a maximum of 1000 CFU/g. *Salmonella* sp. counts should be between 1000 and 1,000,000 CFU/g, while *Pseudomonas aeruginosa* and *Enterococci* spp. are allowed in the range of 1000 to 1,000,000 CFU/g. *Listeria monocytogenes* should be absent in a 25 g sample, while *Bacillus* spp. counts should fall between 10ˆ3 and 10ˆ5 CFU/g. Sulfite-reducing bacteria should be in the range of 10 to 100 CFU/g, and Yeast and molds are limited to between 10ˆ3 and 10ˆ5 CFU/g. Given that potatoes are tubers that grow in direct contact with irrigation water, microbial analysis was conducted to assess the impact of the TWW on their safety for consumption. Post-peeling, the tubers were analyzed for various microorganisms, including total coliforms, *E. coli, Staphylococcus aureus,* Sulfate reducing bacteria*, Clostridium perfringens, Listeria monocytogenes, Pseudomonas aeruginosa, Salmonella* sp. All microbial analyses were carried out at LARI, using standard methods for the examination of soils and vegetables (Compost Quality Standards, Organic Ag Advisors and BBC Laboratories, Inc.). Soil and potatoes microbial values were reported as mean values, ± corresponding standard deviation.

2.5. Plant sampling and analysis

Plants were harvested by collecting 5 plants per replicate plot at the time of plant maturity when each of the crops were ready for harvesting; this amounted to 45 samples of potato plants and 45 samples of corn, making up the three replicates from each of the three treatments. The harvesting process involved carefully extracting the plants from the soil while minimizing root damage. At the time of harvest, various growth parameters were assessed to evaluate plant development and productivity. For each plant, the following were measured and presented in the figures as averages from the five sampled plants:

- Plant length (cm): The height of the plant was measured from the base to the highest point of the plant to assess overall growth.
- Plant weight (g): The entire plant (including roots and stems minus the cob or tuber) was weighed using an analytical balance to determine total biomass.
- Corn and potato weight (g): The corn cobs and tubers of potato were carefully separated from the plants and weighed individually to determine the yield per plant. This was done using a high-precision analytical balance to ensure accurate measurements.
- Number of tubers (for potato): The number of tubers produced per plant was counted. This provided insights into the productivity of the potato plants.
- Number of potato tillers: The number of tillers was counted to assess the vegetative growth and branching, which is an indicator of the plant's ability to produce multiple tubers.
- Number of leaves: The number of leaves per plant was recorded for both corn and potato to understand leaf development and the plant's capacity for photosynthesis.

The analysis results were reported as replicate mean values ± standard deviation of the mean, to provide an overall representation of the plant growth and yield while accounting for variability within the samples.

2.6. Statistical analysis of data

Soil and plant analyses were carried out on independent triplicate samples (field replicates) from each treatment. The collected data, including all soil and plant parameters, were subjected to one-way analysis of variance (ANOVA) using Minitab 17 software. ANOVA was used to determine if there were any statistically significant differences among the mean values of the treatments. A significance level of $P < 0.05$ was used to assess whether the differences observed were statistically significant, providing a threshold for rejecting the null hypothesis of no difference between groups.

To further investigate specific differences between treatment means, Fisher's Least Significant Difference (LSD) test was employed as a post-hoc analysis. This test is particularly useful for comparing pairwise differences between the treatments after finding a significant overall effect in the ANOVA. A P-value <0.05 was considered to indicate statistically significant differences between individual treatments. Values are means of three replicates ± the standard deviation of the mean. Within each table, mean values followed by different letters denote statistically significant differences according to the Fisher's Least Significant Difference (LSD) test ($P < 0.05$) with soil treatment values being compared to the control, i.e., differentiating means between treatments within a season.

3. Results and discussion

3.1. Baseline characterization of TWW

Wastewater SW and TW samples were screened during the first season only to assess their safety for reuse as per the FAO guidelines for physicochemical properties and heavy metals drafted for Lebanon (Table 1). Microbial parameters were also examined but only for TW being the only type of wastewater that undergoes treatment for microbial contaminants. The results showed that pH and EC for both SW and TW, were around 7 and 800 μS/cm, respectively. Given that irrigating with TWW is considered a significant nutrient source, macronutrients analyses are presented in Table 1. The two types of TWW are comparable with some exceptions, mainly in COD and nitrate which were on average greater in the TW than the SW. Orthophosphates (PO_4^{3-}-P) showed similar values in SW and TW (0.1 mg/l). Ammonium (NH_4-N) was higher in SW, 1.5 mg/l, compared to TW with 1.1 mg/l, which could be linked to the additional treatment at the tertiary level (Kesari et al., 2021). Both K^+ and Ca^{2+} concentrations were slightly higher in TW than in SW in both seasons, while Na^+ showed higher values in SW. All the assessed physical and chemical properties of TWW were within FAO limits, affirming its potential as a viable substitute for fresh water in irrigation due to favorable physicochemical and element characteristics. Nonetheless, the pathogen analysis revealed that SW and TW had pathogenic bacteria, particularly fecal coliforms (thermotolerant coliforms), exceeding FAO's thresholds (Table 1).

Table 1
Baseline physicochemical and microbial characteristics of the treated wastewater (SW and TW) compared to FAO 2010 (b) limits. Values are averages of three months ± the standard deviation of the mean ($n = 3$). Allowable limits are given according to the FAO (2010b).

Chemical and microbial parameters	FAO limits	SW	TW
pH	6.5–8.4	7.1 ± 0.2	7.0 ± 0.2
EC (μS/cm)	3000	798.4 ± 66.4	806 ± 65
TDS (ppm)	2000	445.1 ± 37.1	448.5 ± 44
NH_4-N (mg/L)	5	1.5 ± 0.6	1.1 ± 0.8
NO_3-N (mg/L)	30	0.7 ± 0.7	2.5 ± 2.1
PO_4^{3-}-P (mg/L)	2	0.1 ± 0.1	0.1 ± 0.1
Na^+ (mg/L)	920	52.8 ± 17.9	49.5 ± 16.5
K^+ (mg/L)	12	12.6 ± 6.9	13.1 ± 5.2
Ca^{2+} (mg/L)	400	68.7 ± 6.9	75.8 ± 5.3
COD (mg/L)	250	203 ± 4.2	249 ± 14.1
Total coliforms (CFU/100 ml 37 °C)	1000	<1000	<1000
Fecal (thermotolerant) coliforms (CFU/100 ml 44 °C)	100	<1000	<1000

3.2. Soil physicochemical properties: post-harvest

3.2.1. pH and EC fluctuations

The soil analysis at the end of the experiment indicated a slight but insignificant increase in pH in TW and SW compared to the control in both seasons in potato field (Tables 2 and 3).

In both fields there was an inconsistent increase in EC between the treated soils and the control during both seasons, with a significant increase in EC under TW irrigated in both fields in first seasons (Tables 2 and 3). Moreover, a significant EC increase was observed in SW potato field during the 2nd season as compared to the control. Several studies affirm that irrigation with SW or TW leads to a significant increase in EC (Shakir et al., 2017; Kallel et al., 2012), linked to an increase in dissolved salts or ions in treated waters (Mishra et al., 2023). This increase in soil salinity has a negative impact on crops (Ibekwe et al., 2018; Levy and Tai, 2013; Ngara et al., 2012), affecting their physiology and anatomy, and reducing their productivity. Osmotic stress brought on by high salinity can reduce the water potential of plants by causing it in their root zone (Mishra et al., 2023; Djanaguiraman and Prasad, 2013). However, our study did not show salinity issues, except visual symptoms of burnt leaf tips and yellowish leaves on corn plants, over the two seasons and the EC levels and significance was not problematic as per Bashour and Sayegh (2007) and the FAO limits (Table 1).

3.2.2. Organic matter, organic carbon, and moisture content

Treated wastewater contains organic matter derived from various sources, including plant residues, domestic wastewater, and industrial effluents. This was reflected in our results, where both potato and corn fields, showed a significant increase in % OM and % OC in SW and TW irrigated soils as compared to the control in both seasons (Tables 2 and 3). There was an increase in the first season which was sustained in the second year; for example, OM increased from 1.6 % to 2.2 % and 2.6 % in the SW and TW, respectively, compared to the control in the second year. These findings align with several studies including Becerra-Castro et al. (2015) and Farhadkhani et al. (2018), who showed that soil irrigated with wastewater had a higher OM content than soil irrigated with fresh water. Irrigating with TWW contributes to an increase in soil OM content (Sdiri et al., 2023; Ibekwe et al., 2018; Minz et al., 2011), which stimulates microbial activity in the soil. This enhanced microbial activity can lead to the decomposition of organic matter and the formation of humic substances, contributing to the more stable pool of organic carbon in the soil, and enhancing carbon cycling thus, higher soil fertility (Gans et al., 2005). Moreover, microbial activity help in the formation of soil aggregates which improve soil structure and protect soil OM from rapid decomposition. Nutrient cycling and rhizosphere interactions are two other factors that may have contributed to OM formation in our study. However, it takes several years to build soil OM and two seasons of using TWW might not be enough to judge whether the increase in OM will be permanent or temporary. Continued inputs of plant residue or other organic inputs, including presence of active crop roots, is necessary for maintaining and enhancing soil OM content. Further monitoring on the long-term is recommended to study the impact of TWW on soil OM.

It is expected that with an improvement in OM content the soil would be able to retain more water. This was observed in the second year in both crops irrigated with TW where the soil moisture content was found to be on average about 6 % (in SW and TW treated soils) compared to 4.8 % in the control at the time of soil sampling at the end of the season.

Table 2
Physicochemical and heavy metal analysis from the potato irrigated with SW and TW during the first and second season. Values are means of three replicates ± the standard deviation of the mean. Mean values followed by different letters denote statistically significant differences according to the Fisher's Least Significant Difference (LSD) test ($P < 0.05$) with soil treatment values being compared to the control, i.e., differentiating means between treatments within a season.

Potato soil	Control soil		Soil irrigated with SW		Soil irrigated with TW	
Parameter	First season	Second season	First season	Second season	First year	Second season
Physico-chemical						
pH	8.2 ± 0.1 a	7.5 ± 0.01 a	8.3 ± 0.1 a	7.5 ± 0.01 a	8.3 ± 0.02 a	7.5 ± 0.04 a
EC (μS/cm)	214.5 ± 7.6 a	141.6 ± 4.8 a	206 ± 23.1 a	166 ± 4.4 b	306.3 ± 27.2 b	183.9 ± 8.02 c
PO_4^{3-}-P (mg/kg)	2141 ± 38.2 a	562 ± 69.2 a	2357 ± 132.6 a	824.8 ± 16.3 b	2952 ± 357.4 b	832.1 ± 72.9 b
K^+ (mg/kg)	502 ± 14.7 a	422 ± 73.3 a	535 ± 17.8 a	728 ± 151.2 a	498 ± 21.6 a	816 ± 93.5 b
Na^+ (mg/kg)	374 ± 67 a	542 ± 79 a	633 ± 34 b	1030 ± 200 b	689 ± 74 b	1026 ± 102 b
Ca^{2+} (mg/kg)	5391 ± 82.4 a	2505 ± 407.6 a	5393 ± 74.1 a	2596 ± 629.1 a	5478 ± 97.9 a	2809 ± 457.2 a
Mg^{2+} (mg/kg)	262 ± 12 a	554 ± 68.8 a	323 ± 8.2 b	732 ± 255.3 ab	272 ± 22.9 a	964 ± 129.9 b
Soil moisture (%)	6.4 ± 1.6 a	4.6 ± 0.2 a	6.5 ± 1.5 a	4.7 ± 0.03 a	7.4 ± 1.0 a	5.9 ± 0.05 b
OC (%)	1 ± 0.2 a	1 ± 0.2 a	1.3 ± 0.1 b	1.3 ± 0.1 b	1.2 ± 0.3 ab	1.3 ± 0.1 b
OM (%)	1.7 ± 0.3 a	1.6 ± 0.3 a	2.2 ± 0.1 b	2.2 ± 0.2 b	2.1 ± 0.5 ab	2.6 ± 0.1 b
CEC (meq/100 g)	41 ± 2.9 a	43 ± 6.4 a	42 ± 6.9 a	72 ± 10 b	46 ± 6.2 a	72 ± 6 b
Heavy metals (mg/kg)						
Cr	0.08 ± 0.05 a	0.03 ± 0.02 a	0.02 ± 0.01 a	0.03 ± 0.01 a	0.6 ± 0.02 a	0.07 ± 0.05 a
Cd	0.06 ± 0.08 a	0.07 ± 0.01 a	0.17 ± 0.01 b	0.07 ± 0.01 a	0.17 ± 0.01 b	0.06 ± 0.0 a
Pb	0.4 ± 0.4 a	1 ± 0.2 a	0.7 ± 0.05 a	0.9 ± 0.05 a	0.7 ± 0.1 a	0.9 ± 0.1 a
Ni	1.9 ± 0.4 a	1.6 ± 0.2 b	1.5 ± 0.1 a	1.4 ± 0.3 ab	1.9 ± 0.3 a	1 ± 0.1 a
Zn	1.8 ± 0.1 a	2 ± 0.02 b	1.7 ± 0.1 a	1.8 ± 0.06 a	1.7 ± 0.03 a	1.9 ± 0.1 ab
Cu	2.9 ± 0.1 a	2.5 ± 0.1 b	2.7 ± 0.2 a	2 ± 0.04 a	1.9 ± 1.7 a	2.3 ± 0.2 b

Table 3
Physicochemical and heavy metal analysis from the corn field irrigated with SW and TW during the first and second season. Values are means of three replicates ± the standard deviation of the mean. Mean values followed by different letters denote statistically significant differences according to the Fisher's Least Significant Difference (LSD) test ($P < 0.05$) with soil treatment values being compared to the control, i.e., differentiating means between treatments within a season.

Corn soil	Control soil		Soil irrigated with SW		Soil irrigated with TW	
Parameter	First season	Second season	First season	Second season	First season	Second season
Physico-chemical						
pH	8.1 ± 0.1 a	7.5 ± 0.1 a	8.2 ± 0.05 a	7.5 ± 0.04 a	8.2 ± 0.04 a	7.6 ± 0.06 a
EC[a] (μS/cm)	184 ± 13.8 a	177 ± 0.4	195.3 ± 13.6 a	177.4 ± 0.4	285.3 ± 59 b	177.9 ± 0.2
PO_4^{3-}-P (mg/kg)	2128 ± 100.2 a	409.4 ± 52 a	3330 ± 185.1 b	782.4 ± 38.1 b	2382 ± 191.3 a	849 ± 32.7 b
K^+ (mg/kg)	565 ± 8.9 a	591 ± 81.6 a	612 ± 13.3 a	661 ± 92.6 a	690 ± 16.8 a	894 ± 127.7 b
Na^+ (mg/kg)	465 ± 27 a	614 ± 66 a	661 ± 81 b	812 ± 30 b	935 ± 21 c	803 ± 115 b
Ca^{2+} (mg/kg)	5327 ± 30.6 a	2578 ± 128.4 a	5364 ± 33.6 a	2662 ± 128.4 ab	5333 ± 22.6 a	2866 ± 130 b
Mg^{2+} (mg/kg)	249 ± 14.6 a	263 ± 35 a	270 ± 11.1 a	297 ± 42.3 a	281 ± 34.6 a	511 ± 85.1 b
Soil moisture (%)	6.2 ± 1.3 a	4.8 ± 0.5 a	6.8 ± 1.3 a	4.8 ± 0.2 a	6.7 ± 1.1 a	6.0 ± 1.4 b
OC (%)	1 ± 0.2 a	1 ± 0.1 a	1.4 ± 0.1 b	1.2 ± 0.1 b	1.4 ± 0.2 b	1.2 ± 0.05 b
OM (%)	1.6 ± 0.4 a	1.7 ± 0.3 a	2.4 ± 0.1 b	2.1 ± 0.2 b	2.4 ± 0.3 b	2.3 ± 0.1 b
CEC (meq/100 g)	42 ± 2.2 a	38 ± 1.4 a	45 ± 7.1 a	39 ± 2.3 a	48 ± 3.8 a	51 ± 8.6 b
Heavy metals (mg/kg)						
Cr	0.04 ± 0.03 a	0.04 ± 0.01 a	0.10 ± 0.03 b	0.07 ± 0.02 b	0.06 ± 0.02 ab	0.07 ± 0.01 ab
Cd	0.16 ± 0.0 a	0.24 ± 0.07 a	0.16 ± 0.03 a	0.16 ± 0.13 a	0.17 ± 0.01 a	0.16 ± 0.066 a
Pb	0.8 ± 0.1 b	0.8 ± 0.2 ab	0.7 ± 0.03 b	0.7 ± 0.1 a	0.5 ± 0.2 a	0.9 ± 0.02 b
Ni	1.8 ± 0.2 a	1.1 ± 0.4 a	1.6 ± 0.1 a	0.9 ± 0.2 a	1.5 ± 0.02 a	1 ± 0.1 a
Zn	1.6 ± 0.03 b	1.7 ± 0.1 a	1.4 ± 0.03 a	1.6 ± 0.05 a	1.4 ± 0.2 a	1.6 ± 0.02 a
Cu	2.9 ± 0.1 b	2.9 ± 0.3 b	2.8 ± 0.02 b	2.6 ± 0.3 ab	2.5 ± 0.1 a	2.1 ± 0.1 a

[a] Corn EC data during the second season was not normally distributed and no statistics were done.

Soil moisture was only statistically greater than the control in control fields under TW in the second season. It should be noted that the soil water content is normally low at the end of the season even under irrigation due to the high temperature and evaporation under the dry conditions in this semi-arid region during August and September. Soil moisture retention will take longer to develop, mainly because it is correlated with soil OM that requires time, multiple application and favorable weather conditions to accumulate in the soil. Thus, TW, being higher in OM (Tables 2 and 3), likely enhanced the soil's water holding capacity in both fields after two seasons of consecutive TWW application as explained by Han et al. (2023). The increase in soil moisture improves the soil humus content and mitigates the long-term risk of erosion, noting that this is a crucial geo-environmental concern in Lebanon (Bou Kheir et al., 2006).

3.2.3. *Chemical properties of the TWW irrigated soils*

Similar to moisture trends, statistically significant increase in CEC was recorded only in the second season in both SW and TW irrigated potato plots (both measuring 72 meq/100 g), and in TW irrigated corn plot (51 meq/100 g), in comparison with the control which was at 43 meq/100 g and 39 meq/100 g in potato and corn fields, respectively. In summary, irrigating with TWW, particularly with TW, significantly influenced the soil's CEC over two years on the same plots. These findings align with Albalasmeh et al. (2022) who demonstrated that soil irrigated with TWW had significantly higher EC, OM, and CEC compared to a control. Moreover, the increase in CEC is associated with increased OM, a crucial indicator of soil fertility (Xue et al., 2022; Hashem and Qi, 2021; Antolín et al., 2005). Additionally, higher CEC increases the soil's capacity to form complexes with minerals and binds heavy metals thus reducing their availability for crop uptake, aiding in nutrient retention and mitigating the impact of toxic elements (Abou Jaoude et al., 2020; Antolín et al., 2005).

Furthermore, irrigation with TWW led to significant increase in nutrients (Tables 2 and 3). For instance, orthophosphates (PO_4^{3-}-P) levels in the soil were higher in both potato and corn plots with SW and TW irrigation compared to the control in the second season (Tables 2 and 3). Although similar increase in P was observed in the first season, it was only significant in TW (2952 mg/kg) in potato and SW (3330 mg/kg) in corn. This has to do with the initial high levels of P in SW and TW and the variation in water quality between seasons. This finding was aligned with a study conducted by Bedbabis et al. (2014) who reported an increase in P content due to the fertilization effect of the TWW. Struvite ($MgNH_4PO_4{\cdot}6H_2O$) recovery from wastewater during treatment is a well-known technology that provides a means to recover and upcycle phosphorous for reuse as a fertilizer or otherwise. Re-using TWW for irrigation from which struvite was not removed, forms another way of recycling this valuable but non-renewable supply nutrient, demonstrating the role of water reuse in circular economy (Krisht et al., 2024).

Sodium (Na^+) was affected by the application of TWW where SW and TW caused an increase in Na^+ compared to control in both fields and both seasons (Tables 2 and 3). These results are compatible with Mavi et al. (2012) and Ofori et al. (2021) who showed that irrigating with TWW elevates the Na^+ content of the soil. This increase is attributed to the residual Na^+ in TWW, which, even after purification, retains significant amounts from various sources, such as domestic sewage, industrial effluents, and agricultural drainage (Kesari et al., 2021). Consequently, it is essential to test and monitor the content of Na^+ in the TWW, especially on the long term, before it starts impacting crops and soil quality. Elevated Na^+ levels can lead to soil salinity or sodicity, affecting soil structure and reducing water infiltration rates, which then leads to the reduction of plant growth and productivity (Shrivastava and Kumar, 2015), at which point it would be costly to recover the soil. Moreover, as noted by Khalid et al. (2018, 2017), ensuring that there are no negative impacts of salinity which come from a high load of sodium ions is important to ensure that the benefits of TWW are gained instead of negative soil impacts that reflect on crop yield. A wide range of adaptations and mitigation strategies are required to cope with such impacts including efficient resource management and crop tolerance, which can help to overcome salinity stress.

The changes observed in Mg^{2+} and K^+ were similar to other parameters like CEC where a significant increase was found in TW irrigated soils, both in potato and corn fields, in the second season. Most of the changes in these two elements in the first season were not significant, except for few occasions such as Mg^{2+} in TW-irrigated plot in potato (Table 2) that was significantly different from the control. As for Ca^{2+}, no significant differences were observed within both fields during both seasons except for TW within the corn field in season two. The current findings are consistent with prior research by Poustie et al. (2020) and Sengupta et al. (2015). These studies indicate that TWW, containing diverse nutrients including essential macronutrients like Mg, P, and K, is a supplemental source of essential nutrients and contributes to enhanced crop growth. Additionally, micronutrients, as highlighted by Ofori et al. (2021), and Jones and Olson-Rutz (2016), serve as enzyme activators and catalysts, playing crucial roles in chlorophyll synthesis, nitrogen fixation, and metabolic regulation, thus improving nutrient absorption by making them readily available.

3.3. Heavy metals soil analysis: post-harvest

High amount of metals in water and soil poses serious environmental concerns (Walter et al., 2006). In this study, all the tested metals in both irrigated soils (soils irrigated with SW and TW) were below FAO's (2010a) permissible agricultural soil limits as shown in Table 1. The results indicate that most of the metal concentrations analyzed in soils irrigated with SW and TW were not significantly different from the control, but there were some instances where the concentrations changed. The Zn and Cu levels, for example, were significantly lower in corn irrigated with TW and SW as compared to the control in the first year. A similar trend for Zn and Ni was detected in the potato plots in season two (Tables 2 and 3), noting that the significance in a season and not the other may be influenced by the initial contamination level in the TWW. These observations align with Basta and McGowen (2004), where the addition of organic amendments to the soil (e.g. TWW, sludge, compost and biochar) reduced the bioavailability of contaminants through immobilization based on adsorption and/or precipitation reactions (Abou Jaoude et al., 2022; Castaldi et al., 2009, 2005; Garau et al., 2014; Mele et al., 2015). However, although the availability of OM in soils irrigated with TWW reduces the mobility of heavy metals as shown with some metals from this study, some researchers reported an increase in heavy metals solubility (Beesley and Dickinson, 2009) and extractability (Pardo et al., 2011) which was not observed in our study within the tested elements.

3.4. Soil and potato tubers microbial analysis

Results from the soil in the potato field irrigated with TWW did not show any total coliforms in season one (Table 4). However, season two had some total coliforms in the control soils as well as those irrigated with TWW; there was a higher level of total coliforms in soils irrigated with SW compared to TW and freshwater irrigation. As for the thermotolerant coliforms, it was not detected in the control and TW soils during both seasons but thermotolerant coliforms was measured in SW soils in both seasons within the potato field and was exceeding the admissible levels allowed in soils (Table 4).

As for the corn field, total coliform (TC) levels did not show fluctuation in soils irrigated with freshwater, TW and SW water in the first season. Despite soils irrigated with SW showing TC levels at 50 CFU/g, in contrast to 0 CFU/g for both the control and TW, this contamination remains below the threshold limits set by FAO (FAO, 2010b). However, there was 5.5 and 6.5 times more TC detected at the end of season two in SW and TW soils, respectively compared to the control in the corn field (Table 5). As for the thermotolerant coliforms, no contamination was detected, neither in SW and TW, nor in the control in the corn field.

Similarly, *Bacillus* spp. did not show statistically significant differences between treatments and control in potato and corn fields in the two seasons. However, there were numerically (not statistically significant) more *Bacillus* CFU's in the SW (in potato soil) and SW and TW (in corn soil) compared to the control during both years. Based on Wang et al. (2021) the *Bacillus* spp. present within treatments is a beneficial bacterium, producing antimicrobial compounds, while inhibiting the growth of harmful bacteria, including *E. coli*. *Enterococci* spp. is a fecal indicator bacterium (fecal indicator bacteria include total coliforms, *Escherichia coli*, and *Enterococcus* spp.) capable of growing, multiplying, and becoming established in environments outside the gastrointestinal tract. *Enterococcus* species, in particular, are more resilient in the environment compared to *E. coli* and are known for their ability to survive various environmental stressors, however, these bacteria are typically harmless and live in the human gut (Zaheer et al., 2020). Results showed that it increased significantly within both fields during the first season in SW, measuring 7000 CFU/g in potato field compared to 333 CFU/g in control soil, and measuring 6667 CFU/g compared to 0 CFU/g in control soil in corn field (Tables 4 and 5). Other species did not show significant variation in both seasons (Tables 4 and 5).

Regarding the peeled potato tubers, total coliforms, *E. coli, Staphylococcus aureus,* Sulfate reducing bacteria*, Clostridium perfringens, Listeria monocytogenes, Pseudomonas aeruginosa,* and *Salmonella* sp. Were either within the FAO limits or not detected (Table 6). These results align with Urbano et al. (2017) who showed that lettuce irrigated with TWW was not contaminated with pathogens, specifically that lettuce is eaten raw,

Table 4
Soil microbial results from the potato field, irrigated with freshwater, SW and TW, across the first and second seasons. Values are means of three replicates ± the standard deviation of the mean. Mean values followed by different letters denote statistically significant differences according to the Fisher's Least Significant Difference (LSD) test ($P < 0.05$) with soil treatment values being compared to the control, i.e., differentiating means between treatments within a season.

Potato soil	Control soil		Soil irrigated with SW		Soil irrigated with TW	
Soil microbial analysis (CFU/g)	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
Total viable count	33,333 ± 5774 a	41,000 ± 44,531 a	36,666 ± 25,166 a	233,333 ± 152,753 a	50,000 ± 30,000 a	120,000 ± 72,111 a
Total coliforms	0	2533* ± 1747 a	0	10333* ± 9504 a	0	2000* a
Thermotolerant coliforms	0	0	3333 ± 5774 b	35,000 ± 21,213 b	0	0
E. coli	0	0	0	0	0	0
Salmonella sp.	0	0	0	0	Abs	0
Pseudomonas aeruginosa	0	0	0	0	0	0
Enterococci spp.	333.3 ± 577 a	0	7000* ± 5196 b	0	1000 ± 1000 a	0
Listeria monocytogenes	0	0	0	0	0	0
Bacillus spp.	11,500 ± 12,021 a	5667 ± 4509 a	6667 ± 3512 a	36,667 ± 30,551 a	14,667 ± 9238 a	19,000 ± 26,963 a
Sulfite-reducing bacteria	0	0	0	0	0	0
Yeast and molds	20,000 ± 10,000 a	7333 ± 4619 a	18,000 ± 10,583 a	30,667 ± 35,233 a	10,333 ± 9074 a	9000 ± 9539 a

Value exceeding the thresholds (FAO, 2010b; Table 1) were marked with an asterisk (*).

Table 5
Soil microbial results from the corn field irrigated with freshwater, SW and TW during the first and second seasons. Values are means of three replicates ± the standard deviation of the mean. Mean values followed by different letters denote statistically significant differences according to the Fisher's Least Significant Difference (LSD) test ($P < 0.05$) with soil treatment values being compared to the control, i.e., differentiating means between treatments within a season.

Corn soil	Control soil		Soil irrigated with SW		Soil irrigated with TW	
Soil microbial analysis (CFU/g)	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
Total viable count	33,333 ± 32,146 a	96,667 ± 90,738 a	672,667 ± 1,149,505 a	73,333 ± 46,188 a	269,000 ± 247,958 a	306,667 ± 427,356 a
Total coliforms	0	1000 a	50 a	5500* ± 6364 a	0	6500* ± 4950 a
Thermotolerant coliforms	0	0	0	0	0	0
E. coli	0	0	0	0	0	00
Salmonella sp.	0	0	0	0	0	0
Pseudomonas aeruginosa	0	0	0	0	0	0
Enterococci spp.	0	0	6667* ± 4163 b	0	1667 ± 1528 ab	0
Listeria monocytogenes	0	0	0	0	0	0
Bacillus spp.	16,333 ± 13,051 a	2667 ± 1155 a	30,000 ± 10,000 a	4000 ± 1732 a	29,333 ± 28,746 a	11,333 ± 8083 a
Sulfite-reducing bacteria	0	0	0	0	0	0
Yeast and molds	50,000 ± 10,000 b	2000 ± 1000 a	10,333 ± 7234 a	7000 ± 5196 a	16,333 ± 20,793 a	7333 ± 3055 a

Value exceeding the thresholds (FAO, 2010b; Table 1) were marked with an asterisk (*).

Table 6
Results of the potato microbial characteristics (after peeling) of the control soil and soils irrigated with SW and TW during the first and second seasons.

		Control soil		Soil irrigated with SW		Soil irrigated with TW	
Potato tuber microbial analysis CFU/g	FAO limits	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
Total coliforms	<10	<10	<10	<10	<10	<10	<10
E. coli	<10	<10	<10	<10	<10	<10	<10
Staphylococcus aureus	<10	<10	<10	<10	<10	<10	<10
Sulfate reducing bacteria	0	0	0	0	0	0	0
Clostridium perfringens	0	0	0	0	0	0	0
Listeria monocytogenes	0 (not isolated)	0	0	0	0	0	0
Pseudomonas aeruginosa	<10	<10	<10	<10	<10	<10	<10
Salmonella	0 (not isolated)	0	0	0	0	0	0

and not peeled. In our study, the lack of total coliforms in the potato tubers could be attributed to the proper irrigation techniques, specifically drip irrigation.

Our results indicated some bacterial species occurring more so in the SW than in the TW irrigated soils suggesting that using tertiary TWW is more suitable from a microbial perspective as the tertiary treatment adds a treatment step for the removal of pathogens and coliforms (Kolekar et al., 2023). Kesari et al. (2021) explains that this is due to the application of UV light which acts as a disinfectant and kills the pathogens. Furthermore, these findings align with the observations of Urbano et al. (2017) that irrigation with TWW did not increase total coliforms levels in soil on lettuce cultivation who further indicated the absence of thermotolerant coliforms, particularly *E. coli*, in the soil throughout the experiment. This is a significant outcome, because *E. coli* is often used as a fecal contamination indicator. Another study by Garcia-Valverde et al. (2023), determined that consuming fruits from plants irrigated long-term with reclaimed water poses no health risk, supporting the potential for a circular water economy.

In summary, tertiary TWW emerged as an effective option from a microbiological standpoint. This can be attributed to the disinfectant properties of UV treatment, which is implemented as the final step in the treatment process. The thorough UV treatment likely eradicated any remaining pathogens in the water, thus highlighting its efficacy when utilized for soil irrigation.

Despite its merits, it is generally important to implement strict hygiene measures when using TWW due to the pathogens it might be carrying. The results have shown potential for some total and thermotolerant coliforms contamination, which can fluctuate over time from year/season to year/season, and which can be harmful for all users along the value chain of these crops starting with farmers and TWW operators and ending on the consumer's table. Aside from being a threat to the soil's ecosystem, pathogens contained in TWW are the greatest health concern when using this water for irrigation (Mechri et al., 2008). Some pathogens are not effectively destroyed or eliminated in the water treatment process, depending on the available technologies, such as total coliforms and thermotolerant coliforms contamination observed in SW irrigated soils. Undestroyed pathogens that remain in the TWW may accumulate in the soil and translocate to edible plant parts, and consequently reach the food chain (Domenech et al., 2018; Adegoke et al., 2018). Therefore, to reduce exposure and public health risks, certain guidelines need to be considered. It is important to track the population of pathogenic microorganisms in humans and soil through frequent examinations (Farhadkhani et al., 2018). Studying the correlations between multiple soil factors (soil water content, pH, temperature, humidity) and pathogenic organisms is required (Becerra-Castro et al., 2015; Bichai et al., 2012) and is something that was not conducted in our experiments. Moreover, the impact of different management practices (irrigation system, post-harvest practices) on the fate of pathogenic microorganisms is also important to understand (Hashem and Qi, 2021). Several studies reported no significant microbial effect on crops, consumers or the environment (Urbano et al., 2017; Orlofsky et al., 2016; Christou et al., 2016). Nonetheless soils irrigated with secondary TWW were found to be highly contaminated by thermotolerant coliforms and *E. coli* (Petousi et al., 2019). Some effective in-field and post-harvest control measures demonstrated by Farhadkhani et al. (2018) included using surface drip irrigation or subsurface drip irrigation, disinfection, washing, cooking at proper temperature and peeling of crops eaten raw. Besides adhering to water quality guidelines, such as WHO guidelines and to Sanitation Safety Plans (SSPs), a combination of active measures at the source of water, good agricultural practices at the farm level and additional preventive measures is needed to reduce possible risks and protect public health (Hashem and Qi, 2021).

3.5. Potato and corn: biomass and growth parameters

Several studies demonstrated the positive impact of utilizing TWW on biomass production compared to crop cultivation with well or fresh surface water. For example, this was noted in studies by Zidan et al. (2024) who studied the impact of TWW on maize, and Marofi et al. (2012) who studied the impact of raw and TWW on potatoes. In this study, the biomass production in year one and two, was assessed by counting the number of tillers, leaves and tubers, plant and tuber weight and plant height for the potato, and plant and corn weight, number of leaves and plant height were assessed for the corn. All parameters, except for plant height, did not show any significant differences between the control and the soils irrigated with TWW in potato (Fig. 1) in season one. In the second season under TW, the number of tillers was increased (12 tillers per plant compared to 8 in the control), there were more tubers and greater weight of tubers (Fig. 1).

As for corn, in the first season there was a greater plant weight (total biomass including roots minus the cob) in fields irrigated with TW, measuring 0.6 kg compared to those irrigated with fresh water or SW, both weighing 0.5 g/m^2 (Fig. 2). Corn plant height and weight were negatively impacted by TWW where fields irrigated with freshwater had greater values than TW and SW in the first season. Similar to potato in the second season which showed improvements under TWW, corn plant weight and height as well as corn cob weight was greater under SW and TW compared to the control (Fig. 2). This could be attributed to the cumulative effect of TW on the soil over two years, enriching it with nutrients and consequently boosting the yield. Moreover, seasonal variations may have significantly influenced the tillering. A study conducted by Scott Tilley et al. (2019), confirms that variations in temperature and timing of tillers initiation affect tiller development. Similar to potato, no significant change in the number of leaves was observed in corn during both seasons (Fig. 2). These results are consistent with Rezapour et al. (2021), that reported a notable increase in corn yield over a 15-year period of TWW irrigation.

The effect on plant height was observed for corn, but not for potatoes. These results are compatible with different studies mentioning a positive impact of TWW irrigation on corn. For instance, Zidan et al. (2024) observed that *corn* adapted well to TWW, benefiting from its nutrient content, and significantly enhancing plant growth compared to the relatively limited growth associated with freshwater water. And similar findings of TWW irrigation were observed by Rezapour et al. (2021) with an increase from 12.5 % to 28.1 % in corn yields.

Based on our results that show potential benefits on potato and corn

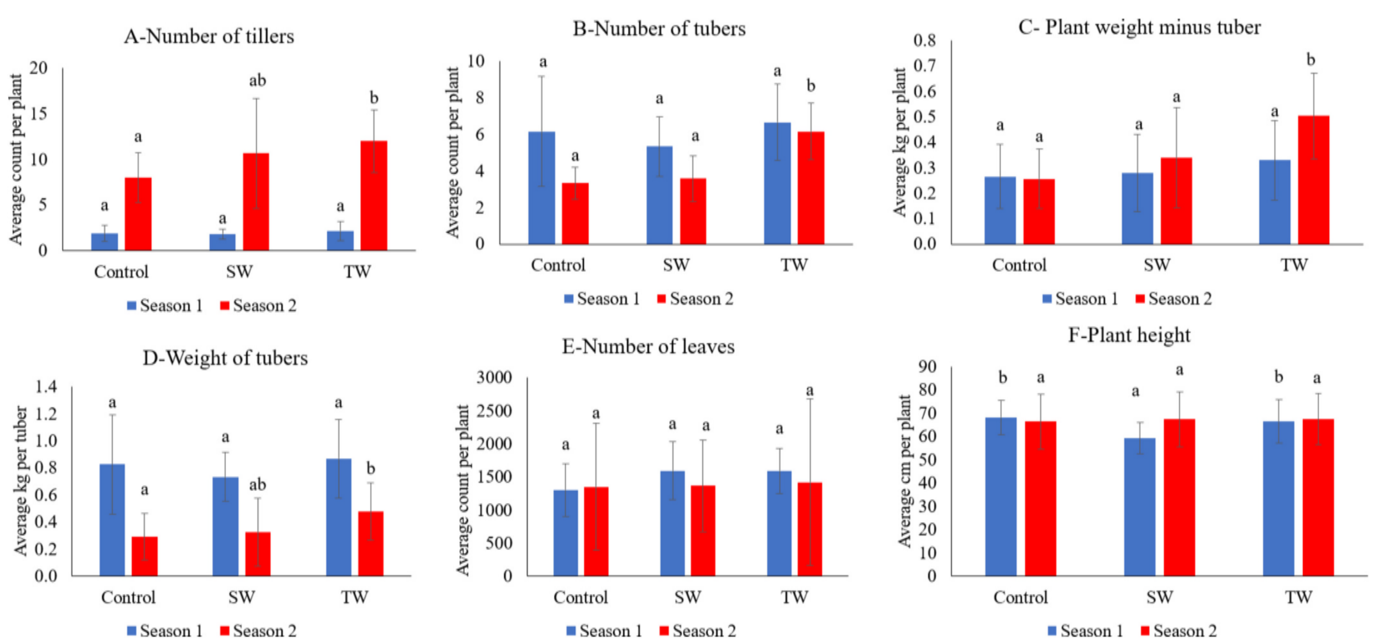

Fig. 1. Bar graphs for the potato plants (averaged from 5 sampled plants) during the first and second seasons, representing the averages ($n = 3$ replicates) of number of tillers, number of tubers, plant weight (kg), weight of tubers (kg), number of leaves and plant height (cm). Letter connotations indicate statistical significance between treatments within a season.

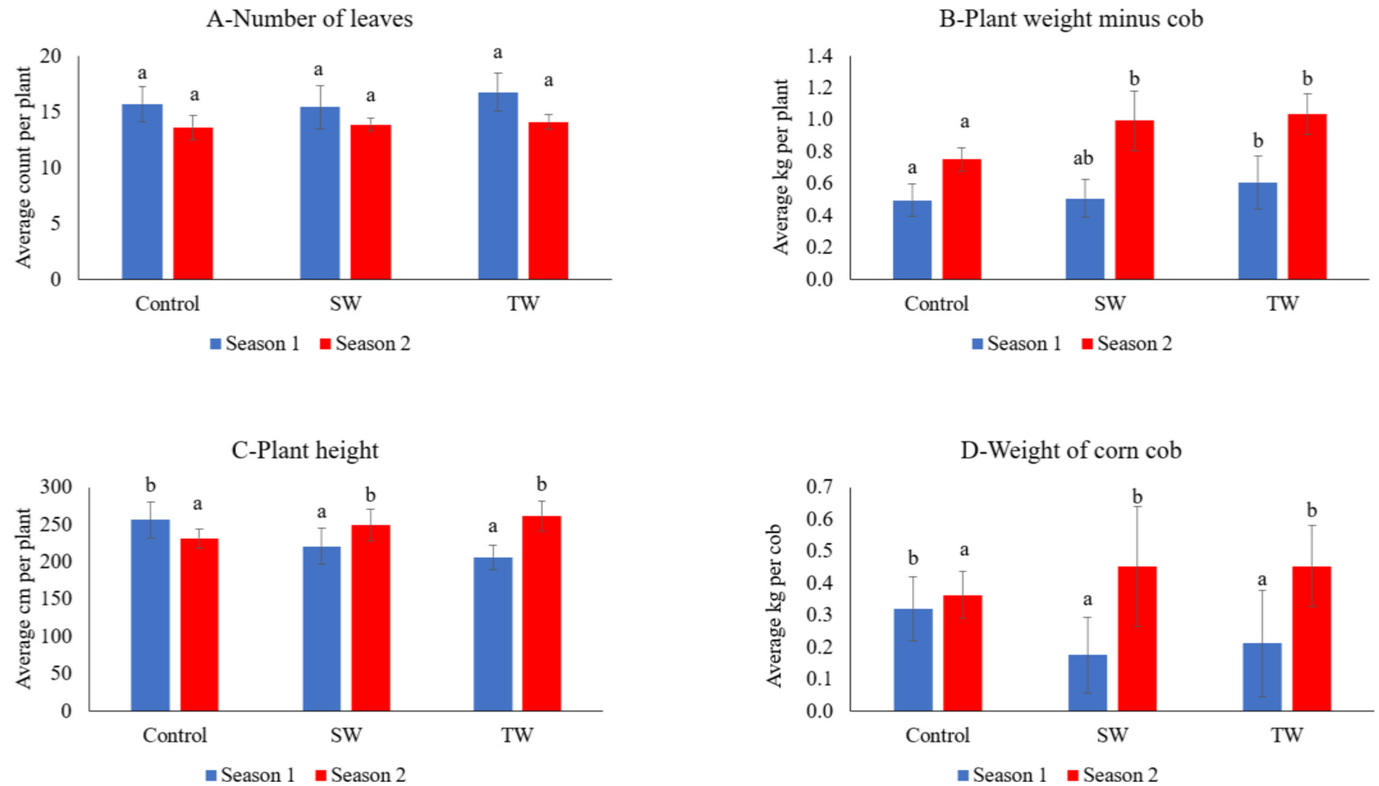

Fig. 2. Bar graphs for corn plants (averaged from 5 sampled plants) during first and second seasons, representing the average (n = 3 replicates), of the number of leaves, plant weight (kg), plant height (cm) and weight of corn cobs (kg). Letter connotations indicate statistical significance between treatments within a season.

production, irrigation with TWW in this semi-arid region can provide resiliency during drought and water scarcity. Additionally, there are benefits to transitioning from a linear (Korhonen et al., 2018) to circular economy in water use that can have impacts beyond soil and crop benefits to the reduction of production and transportation costs of agricultural inputs, water pumping costs, environmental avoidance costs, carbon footprint and other impacts (Mannina et al., 2022; Economou et al., 2023). Reuse of TWW for irrigation as an example of circular economy is a closed-loop system where crop nutrients are recycled and reused efficiently especially for elements with finite natural supplies such as phosphorous. The long-term implementation of TWW reuse in agricultural practices holds significant potential to reshape water management strategies and promote sustainable food production worldwide. A life cycle assessment (LCA) by Economou et al. (2023) reported on potato production in a Mediterranean climate and found that seasonal variability and yield output has environmental effects and carbon footprints. Therefore, including TWW reuse in potato and other crop production system, which adds to the variability, will have an effect on the life cycle of similar projects and warrants further research.

4. Study recommendations

- Based on the findings, it is recommended to prioritize TW irrigation over SW irrigation for water reuse in agriculture due to the potential microbial contamination present in SW treated water unless continued monitoring of SW shows consistent good quality water combined with strict hygiene practices and reduced exposure guidelines.
- Continuous monitoring of sodium levels, microbial activity, and crop health is crucial to avoid negative impacts on soil (salinity, sodicity, poor structure) and plants (toxicity, physiological stress) on the long-term.
- Enhance public awareness and education regarding the importance of responsible wastewater management and its impact on agricultural practices and public health.
- Evaluate synergies and tradeoffs between the effects of TWW on soil and yield improvement, and the environmental and health risks, along with its water-saving potential.

5. Conclusions

Irrigating potato and corn with TW showed promising results for crop yield and soil quality. The use of TW significantly increased soil OM and nutrients leading to higher potato and corn yields after the second year. Importantly, heavy metal levels remained within safe limits. However, raised sodium concentrations in the soils under TWW especially under TW could lead to concerns on salinity which need to be carefully monitored.

As for SW soils, it exhibited some microbial contamination exceeding safe thresholds recommended by FAO. Therefore, TW appears preferable, yet continuous monitoring of salinity and microbial activity is recommended, particularly with the potential variability in the TWW quality.

Despite promising results from TW reuse, ongoing research is important to fully assess the long-term effects on soil microbiology, soil quality, and crop quality. This understanding is vital for sustainable agriculture and informed decision-making on safe and sustainable irrigation practices. By prioritizing TW reuse, securing proper wastewater treatment at the wastewater treatment plant level, and conducting further research on crop irrigation, we find that there is good potential of TWW reuse for sustainable food production while safeguarding soil and human health.

In addition to field testing and research, it is essential to conduct economic and environmental studies to evaluate the long-term sustainability of utilizing TW or other TWW for irrigation. These studies would consider factors such as initial setup costs, maintenance expenses, and potential savings while using TW for irrigation. Moreover, TWW reuse for irrigation can be a viable circular economy practice which can as well support sustainable agricultural production systems. Future research on TWW reuse to assess the long-term social, economical, and agro- and eco-system implications will be critical to ensure that TWW is a viable solution for addressing global water scarcity and climate change.

CRediT authorship contribution statement

Lena Abou Jaoude: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **Farah Kamaleddine:** Writing – review & editing, Visualization, Methodology, Formal analysis. **Rania Bou Said:** Writing – review & editing, Project administration, Formal analysis, Data curation. **Rabi H. Mohtar:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Data curation, Conceptualization. **Razan Dbaibo:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Sandra F. Yanni:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Data curation, 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.

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Data availability

Data will be made available on request.

References

Abou Jaoude, L., Castaldi, P., Nassif, N., Pinna, M.V., Garau, G., 2020. Biochar and compost as gentle remediation options for the recovery of trace elements-contaminated soils. Sci. Total Environ. 711, 134511. https://doi.org/10.1016/j.scitotenv.2019.134511.

Abou Jaoude, L., Nassif, N., Garau, G., Darwish, T., Castaldi, P., 2022. Biochar addition decreases the mobility, bioavailability, and phytotoxicity of potentially toxic elements in an agricultural contaminated soil. Commun. Soil Sci. Plant Anal. https://doi.org/10.1080/00103624.2022.2063313.

Adegoke, A.A., Amoah, I.D., Stenström, T.A., Verbyla, M.E., Mihelcic, J.R., 2018. Epidemiological evidence and health risks associated with agricultural reuse of partially treated and untreated wastewater: a review. Front. Public Health 6, 376581. https://doi.org/10.3389/fpubh.2018.00337.

Albalasmeh, A.A., Alghzawi, M.Z., Gharaibeh, M.A., Mohawesh, O., 2022. Assessment of the effect of irrigation with treated wastewater on soil properties and on the performance of infiltration models. Water 14 (9), 1520. https://doi.org/10.3390/w14091520.

Alkhaza'leh, H., Abu-Awwad, A., Alqinna, M., 2023. Effect of irrigation with treated wastewater on potatoes' yields, soil chemical, physical and microbial properties. Jordan J. Earth Environ. Sci. 14 (2).

Antolín, M.C., Pascual, I., García, C., Polo, A., Sánchez-Díaz, M., 2005. Growth, yield and solute content of barley in soils treated with sewage sludge under semiarid Mediterranean conditions. Field Crop Res 94 (2–3), 224–237.

Aziz, F., Farissi, M., 2014. Reuse of treated wastewater in agriculture: solving water deficit problems in arid areas. Annals of West University of Timişoara Series of Biology 17, 95–110.

Bashour, I.I., Sayegh, A.H., 2007. Methods of Analysis for Soils of Arid and Semi-arid Regions. Food and Agriculture Organization of the United Nations, Rome, Italy, p. 119 (ISBN 978-92-5-105661-5.).

Basta, N.T., McGowen, S.L., 2004. Evaluation of chemical immobilization treatments for reducing heavy metal transport in a smelter-contaminated soil. Environ. Pollut. 127 (1), 73–82. https://doi.org/10.1016/s0269-7491(03)00250-1.

Becerra-Castro, C., Lopes, A.R., Vaz-Moreira, I., Silva, E.F., Manaia, C.M., Nunes, O.C., 2015. Wastewater reuse in irrigation: a microbiological perspective on implications in soil fertility and human and environmental health. Environ. Int. 75, 117–135. https://doi.org/10.1016/j.envint.2014.11.001.

Bedbabis, S., BenRouina, B., Boukhris, M., Ferrara, G., 2014. Effect of irrigation with treated wastewater on soil chemical properties and infiltration rate. J. Environ. Manage. 133, 45–50. https://doi.org/10.1016/j.jenvman.2013.11.007.

Beesley, L., Dickinson, N., 2009. Carbon and trace element mobility in an urban soil amended with green waste compost. J. Soil. Sediment. 10, 215–222.

Bichai, F., Polo-López, M.I., Ibañez, P.F., 2012. Solar disinfection of wastewater to reduce contamination of lettuce crops by Escherichia coli in reclaimed water irrigation. Water Res. 46 (18), 6040–6050.

Bou Kheir, R., Cerdan, O., Abdallah, C., 2006. Regional soil erosion risk mapping in Lebanon. Geomorphology 82 (3–4), 347–359.

Castaldi, P., Santona, L., Melis, P., 2005. Heavy metal immobilization by chemical amendments in a polluted soil and influence on white lupin growth. Chemosphere 60 (3), 365–371. https://doi.org/10.1016/j.chemosphere.2004.11.098.

Castaldi, P., Melis, P., Silvetti, M., Deiana, P., Garau, G., 2009. Influence of pea and wheat growth on Pb, cd, and Zn mobility and soil biological status in a polluted amended soil. Geoderma 151 (3–4), 241–248. https://doi.org/10.1016/j.geoderma.2009.04.009.

Chen, W., Pan, N., Wang, Y., Wu, L., 2015. Impact of reclaimed water irrigation on soil health in urban green areas. Chemosphere 119, 654–661.

Choueiri, E., Jreijiri, F., Wakim, S., El Khoury, Issa, Michel., Valentini, F., Dubla, N., Galli, D., Habchy, R., Akl, K., Stefani, E., 2017. Surveys of potato-growing areas and surface water in Lebanon for potato brown and ring rot pathogens. Phytopathol. Mediterr. 56 (1), 87–97. http://www.jstor.org/stable/44809280.

Christou, A., Maratheftis, G., Elia, M., Hapeshi, E., Michael, C., Fatta-Kassinos, D., 2016. Effects of wastewater applied with discrete irrigation techniques on strawberry plants' productivity and the safety, quality characteristics and antioxidant capacity of fruits. Agric Water Manag 173, 48–54.

Clemmens, A.J., Allen, R.G., Burt, C.M., 2008. Technical concepts related to conservation of irrigation and rainwater in agricultural systems. Water Resour. Res. 44, 1–16.

Contreras, J.D., Meza, R., Siebe, C., Rodríguez-Dozal, S., López-Vidal, Y.A., Castillo-Rojas, G., et al., 2017. Health risks from exposure to untreated wastewater used for irrigation in the Mezquital Valley, Mexico: A 25-year update. Water Res. 123, 834–850.

Dal, E., Díaz-González, A.M., Morales-Opazo, C., Vigani, M., 2021. Agricultural sector review in Lebanon. In: FAO Agricultural Development Economics Technical Study, 12. FAO, Rome.

Djanaguiraman, M., Prasad, P.V.V., 2013. Effects of salinity on ion transport, water relations and oxidative damage. In: Ecophysiology and Responses of Plants Under Salt Stress. Springer, pp. 89–114.

Domenech, E., Amorós, I., Moreno, Y., Alonso, J.L., 2018. Cryptosporidium and Giardia safety margin increase in leafy green vegetables irrigated with treated wastewater. Int. J. Hyg. Environ. Health 221 (1), 112–119.

Economou, F., Papamichael, I., Voukkali, I., Loizia, P., Klontza, E., Lekkas, D.F., Vincenzo, N., Demetriou, G., Navarro-Pedreño, J., Zorpas, A.A., 2023. Life cycle assessment of potato production in insular communities under subtropical climatic conditions. Case Studies in Chemical and Environmental Engineering 8, 100419. https://doi.org/10.1016/j.cscee.2023.100419.

Ennen, R., Jeschke, M., 2019. Cold Stress Effects on Corn Emergence. Pioneer Growing Point, Crop Focus. https://www.pioneer.com/CMRoot/Pioneer/US/Non_Searchable/agronomy/cropfocus_pdf/Cold-Stress-Corn-Emergence.pdf.

FAO, 2010a. Guidelines for the Reuse of Sewage Sludge in Agriculture. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2010b. Wastewater Reuse and Sludge Valorisation and Reuse. Proposition for Lebanese Wastewater Reuse Guidelines, Food and Agriculture Organization of the United Nations, Rome, Italy.

Farhadkhani, M., Nikaeen, M., Yadegarfar, G., Hatamzadeh, M., Pourmohammadbagher, H., Sahbaei, Z., Rahmani, H.R., 2018. Effects of irrigation with secondary treated wastewater on physicochemical and microbial properties of soil and produce safety in a semi-arid area. Water Res. 144, 356–364.

Gans, J., Wolinsky, M., Dumbar, J., 2005. Computational improvements reveal great bacterial diversity and high metal toxicity in soil. Science 309, 1387–1390.

Garau, G., Silvetti, M., Castaldi, P., Mele, E., Deiana, P., Deiana, S., 2014. Stabilizing metal(loid)s in soil with iron and aluminum-based products: microbial, biochemical, and plant growth impact. J. Environ. Manage. 139, 146–153.

Garcia-Valverde, M., Aragonés, A.M., Salinas Andújar, J.A., Gil García, M.D., Martínez-Bueno, M.J., Fernández-Alba, A.R., 2023. Long-term effects on the agroecosystem of using reclaimed water on commercial crops. Sci. Total Environ. 859 (Part 2), 160462.

Han, F., An, S., Liu, L., Ma, L., Wang, Y., Yang, L., 2023. Simultaneous enhancement of soil properties along with water-holding and restriction of Pb–Cd mobility in a soil-plant system by the addition of a phosphorus-modified biochar to the soil. J. Environ. Manage. 345, 118827.

Hashem, M.S., Qi, X., 2021. Treated wastewater irrigation—A review. Water 13, 1527.

Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proc. Natl. Acad. Sci. 109, 3232–3237.

Ibekwe, A.M., Gonzalez-Rubio, A., Suarez, D.L., 2018. Impact of treated wastewater for irrigation on soil microbial communities. Sci. Total Environ. 622, 1603–1610.

Jones, C., Olson-Rutz, K., 2016. Plant nutrition and soil fertility. Nutr. Manag. Module 2, 4449–4452.

Kallel, M., Belaid, N., Ayoub, T., Ayadi, A., Ksibi, M., 2012. Effects of treated wastewater irrigation on soil salinity and sodicity at El Hajeb region (Sfax-Tunisia). Journal of Arid Land Studies 22 (1), 65–68.
Kesari, K.K., Soni, R., Jamal, Q.M.S., Tripathi, P., Lal, J., Jha, N.K., Siddiqui, M.H., Kumar, P., Tripathi, V., Ruokolainen, J., 2021. Wastewater treatment and reuse: A review of its applications and health implications. Water Air Soil Pollut. 232 (208).
Khalid, S., Shahid, M., Dumat, C., Niazi, N.K., Bibi, I., Gul Bakhat, H.F.S., Abbas, G., Murtaza, B., Javeed, H.M.R., 2017. Influence of groundwater and wastewater irrigation on lead accumulation in soil and vegetables: implications for health risk assessment and phytoremediation. Int. J. Phytoremediation 19, 1037–1046.
Khalid, S., Shahid, M., Natasha, Bibi, I., Sarwar, T., Shah, A.H., Niazi, N.K., 2018. A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries. Int. J. Environ. Res. Public Health 15 (5), 895.
Kolekar, S., Sankapal, P., Khare, K., Chinnasamy, P., 2023. Assessment of recycled treated wastewater for sustainable tomato crop production: A comprehensive review. Environmental Challenges 13, 100791.
Korhonen, J., Honkasalo, A., Seppälä, J., 2018. Circular economy: the concept and its limitations. Ecol. Econ. 143, 37–46.
Krisht, G., Bou Said, R., Aboujaoude, L., Hajjar, T., Kamaleddine, F., Soufi, A.R., Bashour, I., Yanni, S.F., Mohtar, R., Dare, A., 2024. Irrigating with treated wastewater. In: Abraham, Martin A. (Ed.), Encyclopedia of Sustainable Technologies, Second edition. Elsevier, pp. 635–651 (ISBN 9780443222870). https://doi.org/10.1016/B978-0-323-90386-8.00091-7.
Levy, D., Tai, G.C.C., 2013. Differential response of potatoes (Solanum tuberosum L.) to salinity in an arid environment and field performance of the seed tubers grown with fresh water in the following season. Agric Water Manag 116, 122–127.
Mahfooz, Y., Yasar, A., Guijian, L., Islam, Q.U., Akhtar, A.B.T., Rasheed, R., Irshad, S., Naeem, U., 2020. Critical risk analysis of metals toxicity in wastewater irrigated soil and crops: A study of a semi-arid developing region. Sci. Rep. 10, 12845.
Mahmood, A., Malik, R.N., 2014. Human health risk assessment of heavy metals via consumption of contaminated vegetables collected from different irrigation sources in Lahore. Pakistan. Arabian Journal of Chemistry 7 (1), 91–99.
Mannina, G., Gulhan, H., Ni, B.J., 2022. Water reuse from wastewater treatment: the transition towards circular economy in the water sector. Bioresour. Technol. 363, 127951.
Marofi, S., Parsafar, N., Rahim, G., Dashti, F., Maroofi, H., 2012. The effects of wastewater reuse on potato growth properties under greenhouse lysimeteric condition. Int. J. Environ. Sci. Technol. 10. https://doi.org/10.1007/s13762-012-0108-9.
Mavi, S., Sanderman, J., Chittleborough, D.J., Cox, J.W., Marschner, P., 2012. Sorption of dissolved -affected soils: effect of salinity, sodicity and texture. Sci. Total Environ. 435–436, 337–344. https://doi.org/10.1016/j.scitotenv.2012.07.009.
Mcheik, M., Toufaily, J., Haj Hassan, B., Hamieh, T., Abi Saab, M.T., Rouphael, Y., Ferracin, E., da Shio, B., Bashabshah, I., Al Hadidi, L., 2017. Reuse of treated municipal wastewater in irrigation: a case study from Lebanon and Jordan. Water Environ. J. 31 (4), 552–558.
Mechri, B., Mariem, F.B., Baham, M., Elhadj, S.B., Hammami, M., 2008. Change in soil properties and the soil microbial community following land spreading of olive mill wastewater affects olive trees key physiological parameters and the abundance of arbuscular mycorrhizal fungi. Soil Biol. Biochem. 40 (1), 152–161.
Mele, E., Donner, E., Juhasz, A.L., Brunetti, G., Smith, E., Betts, A.R., Castaldi, P., Deiana, S., Scheckel, K.G., Lombi, E., 2015. In situ fixation of metal(loid)s in contaminated soils: A comparison of conventional, opportunistic, and engineered soil amendments. Environ. Sci. Technol. 49, 13501–13509.
Minz, D., Karyo, R., Gerstl, Z., 2011. Effects of treated municipal wastewater irrigation on soil microbiology. In: Levy, et al. (Eds.), Treated Wastewater in Agriculture: Use and Impacts on the Environment. Wiley, Hoboken, pp. 354–381 (ISBN: 978144328578).
Mishra, S., Kumar, R., Kumar, M., 2023. Use of treated sewage or wastewater as an irrigation water for agricultural purposes: environmental, health, and economic impacts. Total Environment Research Themes 6, 100051. https://doi.org/10.1016/j.totert.2023.100051.
Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter. Methods of soil analysis: part 2 chemical and microbiological properties, 9, 539–579.
Ngara, R., Ndimba, R., Borch-Jensen, J., Jensen, O.N., Ndimba, B., 2012. Identification and profiling of salinity stress-responsive proteins in Sorghum bicolor seedlings. J. Proteomics 75, 4139–4150.
Ofori, S., Puškáčová, A., Růžičková, I., Wanner, J., 2021. Treated wastewater reuse for irrigation: pros and cons. Sci. Total Environ. 760, 144026. https://doi.org/10.1016/j.scitotenv.2020.144026.
Olsen, S.R., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate (No. 939). US Department of Agriculture.
Orlofsky, E., Bernstein, N., Sacks, M., Vonshak, A., Benami, M., Kundu, A., Gillor, O., 2016. Comparable levels of microbial contamination in soil and on tomato crops after drip irrigation with treated wastewater or potable water. Agr Ecosyst Environ 215, 140–150.
Pardo, T., Clemente, R., Bernal, M.P., 2011. Effects of compost, pig slurry and lime on trace element solubility and toxicity in two soils differently affected by mining activities. Chemosphere 84, 642–650.
Petousi, I., Daskalakis, G., Fountoulakis, M.S., Lydakis, D., Fletcher, L., Stentiford, E.I., Manios, T., 2019. Effects of treated wastewater irrigation on the establishment of young grapevines. Sci. Total Environ. 658, 485–492.
Poustie, A., Yang, Y., Verburg, P., Pagilla, K., Hanigan, D., 2020. Reclaimed wastewater as a viable water source for agricultural irrigation: a review of food crop growth inhibition and promotion in the context of environmental change. Sci. Total Environ. 739, 139756.
Rezapour, S., Nouri, A., Jalil, H.M., Hawkins, S.A., Lukas, S.B., 2021. Influence of treated wastewater irrigation on soil nutritional-chemical attributes using soil quality index. Sustainability 13, 1952. https://doi.org/10.3390/su13041952.
Sato, T., Qadir, M., Yamamoto, S., Endo, T., Zahoor, A., 2013. Global, regional, and country level need for data on wastewater generation, treatment, and use. Agric Water Manag 130, 1–13.
Scott Tilley, M., Heiniger, R.W., Crozier, C.R., 2019. Measuring tiller development and mortality in winter wheat under field conditions. Agrosyst. Geosci. Environ. 2 (1), 1–11.
Sdiri, W., AlSalem, H.S., Al-Goul, S.T., Binkadem, M.S., Ben Mansour, H., 2023. Assessing the effects of treated wastewater irrigation on soil physico-chemical properties. Sustainability 15, 5793.
Sengupta, S., Nawaz, T., Beaudry, J., 2015. Nitrogen and phosphorus recovery from wastewater. Curr. Pollut. Rep. 1, 155–166.
Shakir, E., Zahraw, Z., Al-Obaidy, A.H.M.J., 2017. Environmental and health risks associated with reuse of wastewater for irrigation. Egypt. J. Pet. 26 (1), 95–102. https://doi.org/10.1016/j.ejpe.2016.01.003.
Shrivastava, P., Kumar, R., 2015. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi Journal of Biological Sciences 22 (2), 123–131. https://doi.org/10.1016/j.sjbs.2014.12.001.
Tanji, K.K., Kielen, N.C., 2002. Agricultural drainage water management in arid and semi-arid areas. In: FAO Irrigation and Drainage Paper. Food and Agriculture Organization, p. 61.
Ungureanu, N., Vlăduț, V., Voicu, G., 2020. Water scarcity and wastewater reuse in crop irrigation. Sustainability 12 (21), 9055.
Urbano, V.R., Mendonça, T.G., Bastos, R.G., Souza, C.F., 2017. Effects of treated wastewater irrigation on soil properties and lettuce yield. Agric Water Manag 181, 108–115. https://doi.org/10.1016/j.agwat.2016.12.001.
Walter, I., Martinez, F., Cala, V., 2006. Heavy metal speciation and phytotoxic effects of three representative sewage sludges for agricultural uses. Environ. Pollut. 139 (3), 507–514.
Wang, J., Li, L., Wang, Q., Dong, J., Liu, W., Zhang, H., 2021. Tertiary treated sewage sludge improves soil quality and enhances crop growth by regulating soil microbial community structure. Sci. Total Environ. 790, 148179.
An integrated sustainability index for effective water policy. In: Waughray, D. (Ed.), 2011. Water Security: The Water-Food-Energy-Climate nexus (World Economic Forum, Water Initiative). Island Press.
Xue, Q., Xie, S., Zhang, T., 2022. Biochar production and modification for environmental improvement. In: Tsang, D.C.W., Ok, Y.S. (Eds.), Biochar in Agriculture for Achieving Sustainable Development Goals. Academic Press, pp. 181–191.
Zaheer, R., Cook, S.R., Barbieri, R., et al., 2020. Surveillance of *Enterococcus spp*. reveals distinct species and antimicrobial resistance diversity across a One-Health continuum. Sci. Rep. 10, 3937. https://doi.org/10.1038/s41598-020-61002-5.
Zidan, K., Mandi, L., Hejjaj, A., Ouazzani, N., Assabbane, A., 2024. Soil fertility and agro-physiological responses of maize (Zea mays) irrigated by treated domestic wastewater by hybrid multi-soil-layering technology. J. Environ. Manage. 351, 119802. https://doi.org/10.1016/j.jenvman.2023.119802.