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The environmental assessment of soil chemical properties irrigated with treated wastewater under arid ecosystem of Al-Ahsa, Saudi Arabia

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Abstract

Purpose – The present study focused on examining the effect of treated wastewater (TWW) on soil chemical properties. Also, efforts were made to compare the soil chemical properties under TWW irrigation with that under groundwater (GW).

Design/methodology/approach – During the years 2021 and 2022, surface and subsurface soil samples were randomly collected in triplicate by using an auger fortnightly at two depths (20 and 40 cm) from the selected spot areas to represent the different types of irrigation water sources: TWW and GW. Samples of the GW and the TWW were collected for analysis.

Findings – This study examines the impact of TWW on soil characteristics and the surrounding environment. TWW use enhances soil organic matter, nutrient availability and salt redistribution, while reducing calcium carbonate accumulation in the topsoil. However, it negatively affects soil pH, electrical conductivity and sodium adsorption ratio, although remaining within acceptable limits. Generally, irrigating with TWW improves most soil chemical properties compared to GW.

Originality/value – In general, almost all of the soil's chemical properties were improved by irrigating with TWW rather than GW. Following that, wastewater is used to irrigate the soil. Additionally, the application of gypsum to control the K/Na and Ca/Na ratios should be considered under long-term TWW and GW usage in this study area in order to control the salt accumulation as well as prevent soil conversion to saline-sodic soil in the future. However, more research is needed to thoroughly investigate the long-term effects of using TWW on soil properties as well as heavy metal accumulation in soil.

Keywords Water quality, TWW, GW, Soil chemical properties, SAR

Paper type Technical paper

Introduction

Droughts caused by global warming have created a water deficit in several parts of the world, particularly in arid and semiarid regions that are severely water-stressed (Mahmoud, Hassanin, Borham, & EmanEmara, 2018; Hamed, Galal, Soliman, & Emara, 2019). The Arabian Peninsula is dominated by the Kingdom of Saudi Arabia, which is one of the world's most arid countries, with no permanent rivers or lakes. (Al-Harbi *et al.*, 2009; DeNicola, Aburizaiza, Siddique, Khwaja, & Carpenter, 2015). Groundwater (GW) is the primary water

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source in arid regions used for agricultural and urban purposes (Sener & Davra, 2013; Uyan & Cay, 2013). During the 1970s, GW resources were primarily used in agriculture in the Kingdom. However, due to rapid urbanization, industrialization and population growth, GW resources are already in short supply, posing a concern in terms of both quantity and quality. (Khan, ElKashouty, & Bob, 2020).

In this direction, the uses of treated wastewater (TWW) are increasing globally (Singh, 2021), and wastewater reuse is recognized as one of the most essential strategies for dealing with water scarcity (Ghernaout, 2017; Ghernaout, Elboughdiri, & Al Arni, 2019; Rizzo *et al.*, 2020). Because agriculture consumes a large amount of water, using TWW for crop production is critical (Singh, 2021). Many studies around the world have highlighted the importance of evaluating the TWW (Elfanssi, Ouazzani, & Mandi, 2018; Anshassi, Laux, & Townsend, 2019; Farhadkhani, Nikaeen, Hadi, Gholipour, & Yadegarfar, 2020). In the Middle East, the use of TWW for irrigation was found to affect the quality of the soil and crop productivity compared to the use of freshwater (Jeong, Jang, Seong, & Park, 2014; Farhadkhani *et al.*, 2018); in Saudi Arabia, Eamrat, Lapkratok, Mingyai, and Shakya (2022) found that the production of alfalfa and wheat increased by 10% due to the usage of TWW. Reusing wastewater for agricultural irrigation, on the other hand, lowers the quantity of water collected from water resources. Thus, using the TWW for food production becomes one of the challenges facing Saudi Arabia in the coming decades.

The bulk of the soil in Al-Ahsa, on the other hand, is sandy and sandy loam, with very little clay and organic matter (Al-Barrak & Al-Badawi, 1988); the soil also contains sand- and silt-sized particles (Al-Hawas, 1989) and it contains a lot of calcium carbonate ($CaCO_3$) (Bashour, Al-Mashhady, Devi Prasad, Miller, & Mazroa, 1983; Chapman, 1974). The physical and chemical characteristics of the soil are influenced by changes in nutrient status resulting from the utilization of wastewater for irrigation. This practice enriches the soil with nutrients and organic matter, conserves water and nutrients and reduces water pollution (Khalid *et al.*, 2018; Sara, 2019). Long-term irrigation with sewage water, on the other hand, can deteriorate and damage the soil (García-Carrillo, Luna-Ortega, Gallegos-Robles, Preciado-Rangel, & Cervantes-Vázquez, 2020). Furthermore, multiple investigations have scrutinized the consequences of utilizing TWW for irrigation, yielding diverse outcomes ranging from favorable to moderate and adverse. The salient affirmative ramifications associated with TWW irrigation encompass augmented yield and boosted levels of macronutrients and micronutrients in plant tissue (Chávez, Rodas, Prado, Thompson, & Jiménez, 2012). Furthermore, favorable ecological impacts incorporate enhanced soil fertility (Hamilton *et al.*, 2007; Khan, Daniel, Konjit, Thomas, & Eyasu, 2011; Ganjegunte, Ulery, Niu, & Wu, 2018), decreased release of residual water (Toze, 2006; Chen, Lu, Zhang, Yi, & Jiao, 2014) and reduced uptake of GW (Muyen, Moore, & Wrigley, 2011). Conversely, opposing effects entail potential entry of impurities into the surroundings, thereby contaminating the soil, GW and plant tissues, coupled with the risk of harboring pathogens, heavy metals (Muyen *et al.*, 2011; Pereira, Stoffella, & Melfi, 2011; Shakir, Zahraw, & Al-Obaidy, 2017), toxins (e.g. pharmacological agents) (WHO, 2006; Bahri, Drechsel, Raschid-Sally, & Redwood, 2009; Gibson, Durán-Álvarez, Estrada, Chávez, & JiménezCisneros, 2010) and pesticides within the water supply (Chefetz, Ilani, Schulz, & Chorover, 2006; Muller *et al.*, 2012; Hajjami *et al.*, 2012).

The primary goal of this study is to unravel the intricate environmental consequences of employing TWW as an irrigation source on a multitude of soil chemical attributes in the enchanting Al-Ahsa Oasis. By comparing these impacts to conventional GW irrigation, this research aims to shed light on the sustainable utilization of TWW, unveiling its potential to transform soil quality and foster environmental stewardship in this mesmerizing oasis.

Materials and methods

Description of the area

The research areas are located in the eastern region of Saudi Arabia, between 25°23’ N and 49°39’ E, at a height of 155 m above sea level. (Figure 1). The lands are regarded as the biggest Oasis cultivated with date palm (*Phoenix dactylifera* L.) (Biro Turk & Aljughaiman, 2020), with GW and TWW from the Al-Hassa sewage treatment facility being utilized for irrigation since the 1990s. Summer temperatures in the region can reach 45°C. However, in the winter, the air temperature can reach 5°C, with an average yearly precipitation of roughly 50 mm (Al-Zarah, 2011).

The primary soil type in the chosen area is sandy and sandy loam soils, which comprise a variety of soil classes including Gypsiorthids, Haplaquepts, Calciorthids, Torripsamments, Salorthids and Torriorthents (Allbed, Kumar, & Sinha, 2018). As a consequence, it is assumed that the research location is in an arid environment. Some physical characteristics, however, were tested, and the average findings are shown in Table 1.

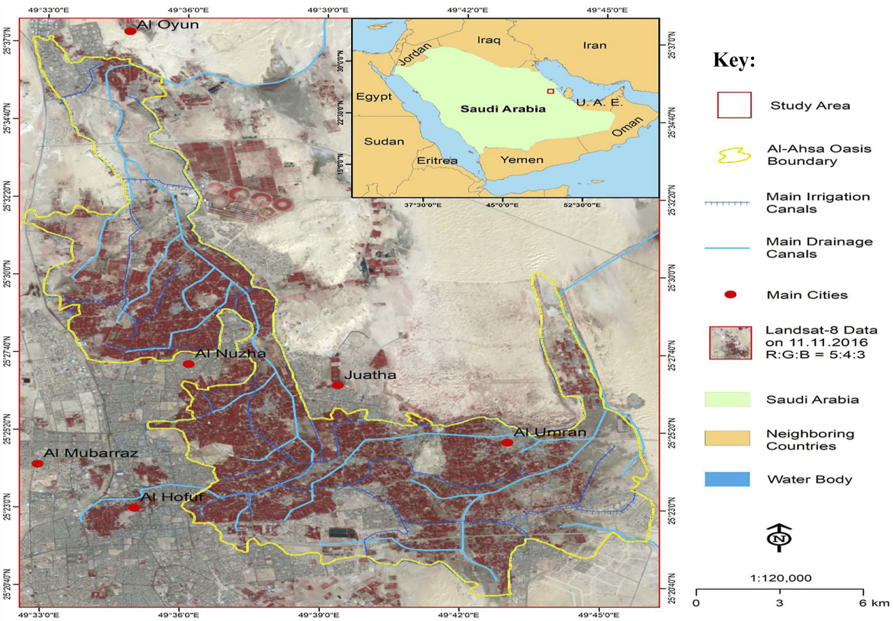

Figure 1.
Location of the study area

Source(s): Figures by authors

Table 1.
Average results of the soil physical properties in the study area

Location	Particle size distribution, % Sand	Silt	Clay	Texture	Bulk density (g/cm^3)	Porosity %	CECMeq/100g
TWW_{Soil}	72.32	10	17.68	Sandy loam	1.43	42.64	19.43
GW_{Soil}	88.21	7.99	3.8	Sandy	1.52	46.04	15.56

Source(s): Tables by authors

Soil and water sampling and analysis

During the years 2021 and 2022, surface and subsurface soil samples were randomly collected in triplicate by using an auger fortnightly at two depths (20 and 40 cm) from the selected spot areas to represent the different types of irrigation water sources: TWW and GW. Samples of the GW and the TWW were collected for analysis. From each depth, the collected soil samples were well mixed, air dried, mashed and passed through 2 mm sieve, then were subjected to chemical analysis. Water samples were collected semiannually from the two water sources and immediately sent to the laboratory for chemical and biological analyses.

The hydrometer method was used to determine particle size distribution (Gee & Bauder, 1994). Chemical analysis such as soil pH was determined in suspension (paste) using a pH meter, soil electric conductivity (EC) was measured in extracted soil solution (1:5 based soil) using the EC meter, and sodium adsorption ratio (SAR) was calculated according to Page, Miller, and Keeney (1982), using the following equation:

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}}$$

where

Na: Sodium, **Ca:** Calcium and **Mg:** Magnesium, all concentrations in meq/L.

Furthermore, titration method according to Bloom, Meter, and Crum (1985) was used to determine the carbonates (CO_3^{-}) and bicarbonates (HCO_3^{-}), the calcimeter method (Loeppert & Suarez, 1996) was used to measure $CaCO_3$ and the wet digestion method was used to determine the soil organic carbon (SOC) (Page *et al.*, 1982; Nelson & Sommer, 1996). The concentrations of Na^{+}, K^{+}, Ca^{+2}, Mg^{+2} and Cl^{-} were identified and quantified using an ion chromatography IC instrument (Helmke & Sparks, 1996).

Statistical analysis

All the obtained data were subject to SAS software which is used for variance analyses (SAS, 2000).

Results and discussion

Groundwater (GW) and treated wastewater (TWW) quality

The average values of GW and TWW that were used for irrigation of the date palm during the evaluation period are presented in Table 2. Evidently, the composition of TWW in terms of pH, EC_w and TSS is lower than GW, reflecting the superiority of the TWW. However, pH and EC_w values in both water sources were in the permissible range to be used for irrigation under date palm as confirmed by Al Omron, El-Maghraby, Nadeem, El-Eter, and Al-Mohani (2012), Sanchez *et al.* (2012) and Adil *et al.* (2015), even though the TWW pH (6.49) value is shown to be acidic and the EC_w of both water sources (2.97 and 1.85 dS/m, for GW and TWW, respectively) apparently to be nonsaline water.

In terms of sodium (Na^{+}), potassium (K^{+}), calcium (Ca^{+2}), magnesium (Mg^{+2}) and anions such as carbonate (CO_2^{-}), bicarbonate (HCO^{-}), chloride (Cl^{-}) and nitrate (NO_3^{-}) content, the GW outperforms TWW.

The influence of water quality on soil chemical properties

The average chemical characteristics of both soils under two different water sources (GW and TWW) are presented in Table 3, and Figures 2, 3, 4 and 5.

Table 2.
Average values of chemical composition of the groundwater (GW) and treated wastewater (TWW) used for irrigation

Parameter	Unit	GW	TWW
		Average results	
pH	pH Unit	8.02	6.49
EC_w	dS/m	2.97	1.85
TSS	mg/L	71.65	3.95
TDS	mg/L	1900.80	1184.00
Floating materials	–	Absent	
Na^+	meq/L	15.94	8.26
K^+	meq/L	0.55	0.51
Ca^{2+}	meq/L	10.76	6.95
Mg^{2+}	meq/L	6.95	3.41
CO_3^-	meq/L	1.11	0.36
HCO_3^-	meq/L	4.09	3.02
Cl^-	meq/L	17.94	10.32
SO_4^-	meq/L	10.75	5.06
$NO_3{-}N$	mg/L	11.18	3.65
$NH_3{-}N$	mg/L	1.04	0.79
B	mg/L	0.47	0.24
BOD	mg/L	8.00	26.00
COD	mg/L	22.00	187.00
Turbidity	NTU	2.74	2.01
T. hardness	mg $CaCO_3$ L	881.87	516.29

Source(s): Tables by authors

Table 3.
Effect of irrigation using GW and TWW on soil chemical properties

Parameter	Unit	GW irrigated soil			Irrigated soil with TWW		
		V_{Min}	V_{Max}	G-mean	V_{Min}	V_{Max}	G-mean
pH	Unit	7.18	7.60	7.37	7.10	7.70	7.36
ECe	dS/m	1.40	1.63	1.50	0.97	1.51	1.19
T.D.S.	mg/L	896.00	1043.20	957.17	620.80	966.40	760.94
Na^+	meq/L	7.41	18.49	11.87	7.07	25.05	12.65
K^+	meq/L	0.26	3.61	1.60	0.26	5.60	2.40
Ca^{2+}	meq/L	7.30	12.83	9.54	11.30	18.83	14.35
Mg^{2+}	meq/L	4.33	6.16	5.07	7.60	10.60	8.82
Cl^-	meq/L	9.25	17.50	12.58	10.50	24.00	15.94
SO_4^-	meq/L	7.50	17.14	11.39	15.88	30.92	21.95
HCO_3^-	meq/L	3.00	6.67	4.45	0.70	4.45	2.21
O.M.	%	0.98	1.14	1.03	1.31	1.85	1.53
SAR		3.07	6.00	4.81	2.30	6.53	3.93
$CaCO_3$	%	4.66	12.31	11.81	1.25	5.82	1.55

Source(s): Tables by authors

Electric conductivity (EC) dS/m

(1) The EC (dS/m) is used to evaluate the quality of soil as well as indicate the salinization status (Oubane, Khadra, Ezzariai, Kouisni, & Hafidi, 2021). In this study, the soil ECe reading fluctuated among the measured samples, which ranged from 1.40 to 1.63 dS/m and 0.97 to 1.51 dS/m, with average values of 1.50 and 1.19 dS/m under both water sources (GW and TWW, respectively), reflecting the increased EC of soil irrigated with GW by 20% as compared to TWW. In sandy soil, severe soil salinization occurs

as a result of high evaporation and low precipitation, resulting in higher soil pH values (Zhao, Liu, Liu, Huang, & Li, 2018). However, under both irrigation water (GW and TWW), the ECe (dS/m) increased gradually, this increase is due to the added volume of water, along with the attached salts, during the irrigation of date palm, this finding was supported by many researchers (Qian & Mecham, 2005; Gross, Azulai, Oron, Nejidat, & Ronen, 2005; Bedbadis, Rouina, Boukhris, & Ferrara, 2014; Liu, Cui, Li, Du, Gao, & Fan, 2018; Du *et al.*, 2022), as they discovered that when TWW was

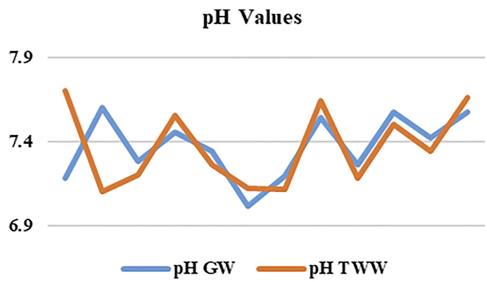

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Figure 2.
Fluctuation of soil pH as affected by groundwater (GW) and treated wastewater (TWW)

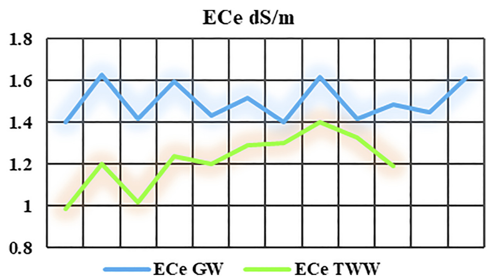

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Figure 3.
Soil ECe as affected by groundwater (GW) and treated wastewater (TWW)

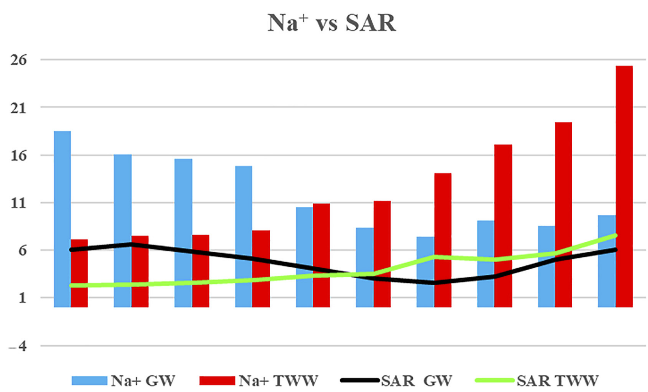

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Figure 4.
Na^+ meq/L and SAR as affected by groundwater (GW) and treated wastewater (TWW)

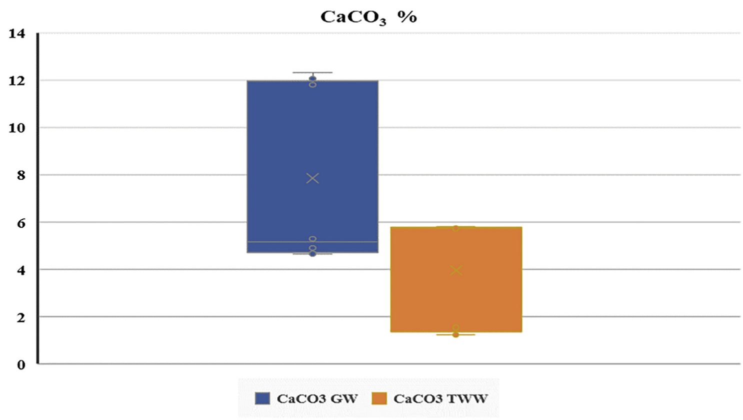

Figure 5. Calcium carbonate ($CaCO_3$%) as affected by groundwater (GW) and treated wastewater (TWW)

Source(s): Figures by authors

utilized for irrigation, the (ECe) increased, even though, the ECe under TWW was lower than that observed under GW. Meanwhile, as noted by Xua, Wub, Changb, and Zhanga (2010), irrigation with wastewater led to increase in the soil EC after a few years. Salinity has a variety of negative effects on soil parameters, including increased soil pH, Exchangeable sodium percentage (ESP) and SAR, as well as decreased cation exchange capacity (CEC) and the soil microbial community (Qadir, Ghafoor, & Murtaza, 2000; Zhang, Wang, Xue, & Wang, 2019).

(2) pH and Organic Matter O.M.%

Climate, soil buffering systems, plants and other variables all impact soil pH, which is an essential soil chemical property that controls many soil qualities (Hong & Chen, 2019). In this study, the soil pH values ranged from 7.18 to 7.60 and 7.10 to 7.70, with an average of 7.37 and 7.36 in GW and TWW, respectively. There was a slight increase in soil pH with two water sources, in which the pH mean values were almost similar under both water sources. Furthermore, the use of TWW increased the organic matter in the soil by around 30% as compared to the soil irrigated with GW, in which the average organic matter contents in the soil were 1.03% and 1.53% under GW and TWW, respectively. Under the right conditions, wastewater application could improve soil quality (e.g. organic matter) (Hidri, Fourti, Jedidi, & Hassen, 2013) and aeration (Qiang, Sun, & Ning, 2022). These obtained results might have been explained under this condition, as the factor that could affect the SOC content is the pH, and the use of TWW with a low pH value would positively encourage the accumulation of SOC. These findings were in agreement with Al Omran *et al.* (2012), whom they found that long-term irrigation with wastewater increased organic matter in soil, and also with Zhou, Han, Liuand Li (2019), whom they demonstrated that organic matter accumulation benefits from a low pH, and carbon and nitrogen dynamics in agricultural soils are regulated by pH (Kemmitt, Wright, Keith, & Jones, 2006). On the other hand, the soil texture may have played another role in organic matter accumulation, where it was obviously observed that the O.M. content in the soil with texture of sandy loam was higher than with sandy soil, this finding was in harmony with Baldock and Skjemstad (2000) whom they reported that clay and fine silt particles aid in the preservation of soil organic matter, and in contrast, due to the rapid degradation of O.M. in sandy soil (Lado *et al.*, 2012).

The fluctuation of soil pH, due to the low buffering capacity of the noncalcareous soil, as a result of irrigation (wetting and drying), caused by the hydrolysis of $CaCO_3$, played a vital role in the rearrangement and availability of nutrients in the soil and the precipitation and distribution of $CaCO_3$, as well as salt accumulation, as shown in Figures 2 and 3. This observation was in line with Rattan, Datta, Chhonkar, Suribabu, and Singh (2005), whom they noted that using the TWW causes rearranging of salts within the soil profile and some elements tended to accumulate on the soil surface.

(3) Macronutrient, Sodium (meq/L) and Sodium Adsorption Ratio (SAR)

From the obtained results, it's clear that the mean concentration of macronutrient (meq/L) of irrigated soil with wastewater is significantly higher than that of GW. The value of calcium, magnesium and sulfur increased significantly in wastewater-irrigated soil (Singh, Deshbhratar, & Ramteke, 2012; Sushil, Kochar, Vikas, & Khokhar, 2019; Ali *et al.*, 2022).

The quality of irrigation water in terms of concentration of Na is an important variable to be considered when using wastewater for irrigation (Ofori, Puškáčová, Růžičková, & Wanner, 2021). Whereas many critical problems in soil properties could be observed in the case of using irrigation water with excess sodium percentage such as breakdown of structure, and dispersion of soil which results in decreased water and air infiltration, crusting, etc. The mean values of sodium (Na^+) and SAR are shown in Table 3 and illustrated in Figure 4. However, according to the Na^+ values, the concentration fluctuated accordingly depending on the time, applied water as well as the fluctuation of soil pH. It's worth mentioning that the concentration of Na^+ was affecting the SAR in the soil, whereas the values of SAR also fluctuated accordingly. Additionally, the values of SAR ranged from 3.07 to 6.0 and 2.30 to 6.53 with an average of 4.81 and 3.93 under the soil irrigated with GW and TWW, respectively, similar result was noted by Tsigoida and Argyrokastritis (2020), Galavi, Jalali, Ramroodi, Mousavi, and Galavi (2010) and de Albuquerque *et al.* (2006), whom they observed an increase in SAR ($p \leq 0.05$) due to irrigation with wastewater. Even though the Na^+ composition of GW is roughly twice as high as that of TWW, which resulted an average increase in SAR under the GW by only 18.12%, but the mean values of SAR are still in the permissible range based on FAO standards (Pescod, 1992). This could be explained by the ability of sandy soil to drain and leach the sodium beyond the root zone to deeper soil layer as it was supported by Lado *et al.* (2012), whom they described that the irrigation water (fresh or/and TWW) reached the deep layer in sandy soil due to the high permeability, low content of clay as well as the low CEC in which preferred to move the Na^+ downward. Some Na^+ might bond with Cl^- and form a salt which increases the soil salinity. Furthermore, excessive Na^+ concentrations in the soil solution or in CEC can result in saline-sodic soil, which leads to a loss of natural soil quality (Yu *et al.*, 2010; Abhayawickrama *et al.*, 2020).

In this regard, gypsum has been shown to maintain K^+/Na^+ and Ca^{2+}/Na^+ ratios, lower soil pH and give S to crops growing in salty soils (Abdelhamid, Eldardiry, & El-Hady, 2013; Abdel-Fattah, 2015; Capaldi, Gratão, Reis, Lima, & Azevedo, 2015; Ahmed *et al.*, 2016).

(4) Calcium carbonate $CaCO_3$%

As well know that $CaCO_3$ is generally accumulated in dry regions. In this area of study, the presence of $CaCO_3$ is due to either the parent material or a secondary source from the accumulation as a result of the irrigation water used (Al-Barrak, 2000; Alnajem, 2021; Al-Saeedi, 2022). The mean values of $CaCO_3$ as a percentage are illustrated in Table 3 and Figure 5. Considering GW as a reference in this case study, the $CaCO_3$% decreased in the soil irrigated with TWW compared to the one irrigated with GW. The values of $CaCO_3$ ranged from 4.66 to 12.31% and 1.25 to 5.82%, with mean values of 11.81 and 1.55% in the tested soils under GW and TWW, respectively. However, Qian and Mecham (2005) discovered a minor reduction in $CaCO_3$ when soil was irrigated with TWW. Even with higher content of Mg^{+2} and Ca^{+2} in the soil irrigated with TWW compared to the GW, the accumulation of $CaCO_3$ in the soil was decreased. This phenomenon could be attributed to 1) the higher content of these cations in the used GW for irrigation which led to the accumulation of more $CaCO_3$ in upper soil layer, 2) the effect of soil pH fluctuation during wet and dry conditions in which the hydrolysis process led to the release of more cations (Ca^{+2} and Mg^{+2}) in the soil solution, which could then be either absorbed by the plant or leached beyond the root zone. In this regard, some researchers applied the soil columns experiments using tap water with high concentration of Ca^{+2} and Mg^{+2} compared to the wastewater, and they concluded that these elements were leached through the soil (Chahal, Gurpal, Peter, & Bielinski, 2011; Abegunrin, Awe, Idowu, & Adejumobi, 2016; Tsigoida & Argyrokastritis, 2020). In contrary, some other researchers found that the accumulation of $CaCO_3$ increased by using TWW for irrigation (Bedbabis *et al.*, 2015; Raeisi-Vanani *et al.*, 2017; Sara, 2019). Evidently, in this situation, the addition of $CaCO_3$ will enhance the soil's porosity, which will somewhat improve the hydraulic capabilities as reported by Khlosi (2015), Hafshejani and Jafari (2017) and Chen *et al.* (2020).

Conclusion

This study examines the impact of TWW on soil characteristics and the surrounding environment. TWW use enhances soil organic matter, nutrient availability and salt redistribution, while reducing $CaCO_3$ accumulation in the topsoil. However, it negatively affects soil pH, electrical conductivity and SAR, although remaining within acceptable limits. Generally, irrigating with TWW improves most soil chemical properties compared to GW.

Adequate treatment of TWW is crucial to prevent soil contamination by toxic heavy metals, pathogens and pollutants, safeguarding human and environmental health. The research findings emphasize the importance of using TWW for irrigation to mitigate concerns related to salt buildup and the accumulation of macro- and microelements in the root zone, as well as their migration into GW.

Furthermore, the application of gypsum to regulate K/Na and Ca/Na ratios should be considered for long-term TWW and GW usage in the study area. This approach helps control salt accumulation and prevents soil conversion to saline-sodic soil in the future.

Further research is needed to address the following aspects related to the use of treated wastewater (TWW) for irrigation:

(1) Comprehensive assessment of environmental impacts: Although the study indicates positive effects of TWW on soil characteristics, further research should evaluate the broader environmental impacts. This includes investigating the potential presence of toxic heavy metals, pathogens and pollutants in inadequately treated TWW, which could lead to soil contamination and pose risks to human and environmental health.

(2) Long-term effects on soil properties: The current study provides insights into the short-term effects of TWW on soil properties. However, long-term investigations are necessary to understand the sustained impact of TWW irrigation on soil fertility, including organic matter content, nutrient availability and pH levels. Longitudinal studies can provide a more comprehensive understanding of the effects over time.

(3) Heavy metal accumulation in soil: Given the possibility of heavy metal presence in TWW, further research is required to assess the accumulation of heavy metals in the soil over time. Investigating the potential pathways of heavy metal uptake by plants and evaluating their long-term impact on soil health and ecosystem integrity are crucial.

(4) Gypsum application and salt management: The study suggests considering gypsum application to regulate salt accumulation and prevent soil conversion to saline-sodic

soil under long-term TWW and GW usage. Further research should explore optimal gypsum application rates and strategies for effective salt management in TWW-irrigated soils.

(5) Safe and efficient TWW utilization: It is important to investigate the optimal types and qualities of TWW for irrigation, along with suitable application rates and methods. Additionally, field management practices should be studied to ensure the safe and effective use of TWW while minimizing any potential negative impacts on soil chemical properties.

By addressing these research gaps, a more comprehensive understanding of the long-term effects, potential risks and best practices for TWW utilization in irrigation can be achieved, promoting sustainable soil management and environmental conservation.

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