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℃. However, in the winter, the air temperature can reach 5℃, 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.

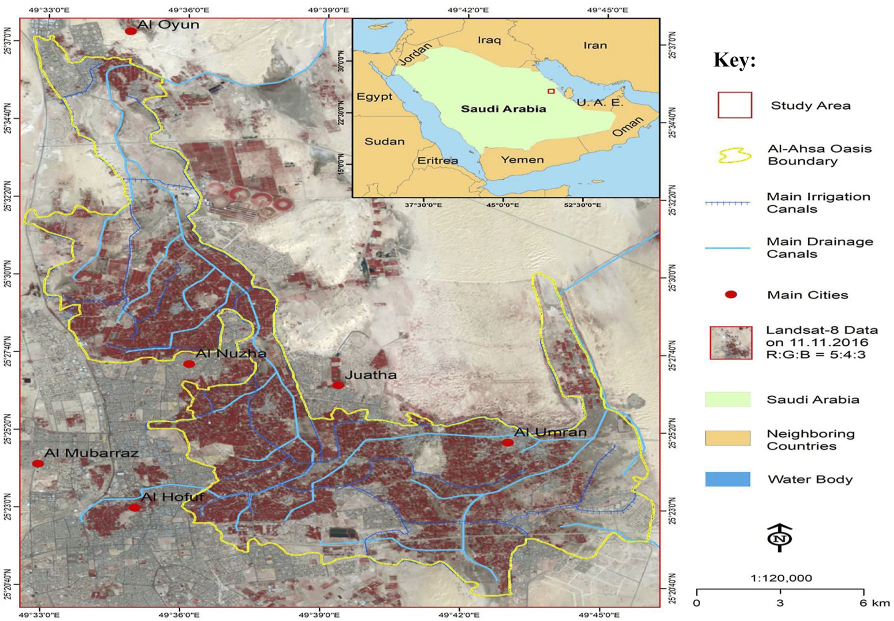

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Figure 1. Location of the study area

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

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

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:

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

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.

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

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

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

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

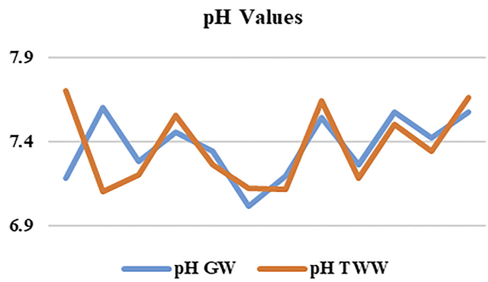

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Figure 2. Fluctuation of soil pH as affected by groundwater (GW) and treated wastewater (TWW)

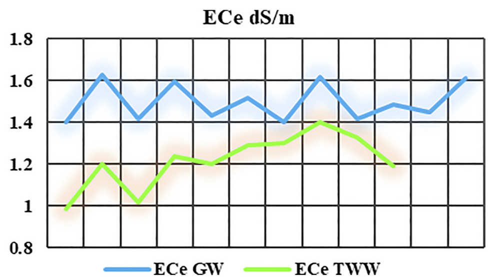

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Figure 3. Soil ECe as affected by groundwater (GW) and treated wastewater (TWW)

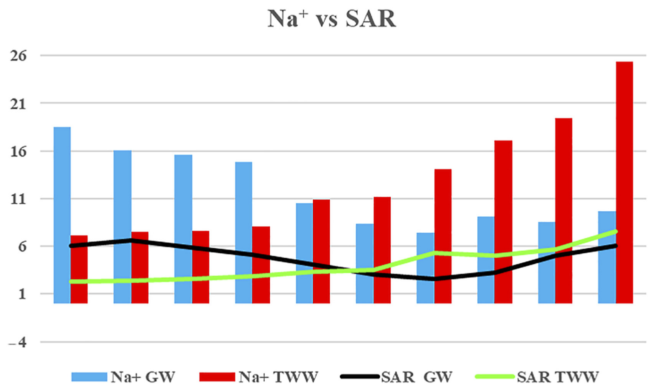

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Figure 4. Na^+ meq/L and SAR as affected by groundwater (GW) and treated wastewater (TWW)

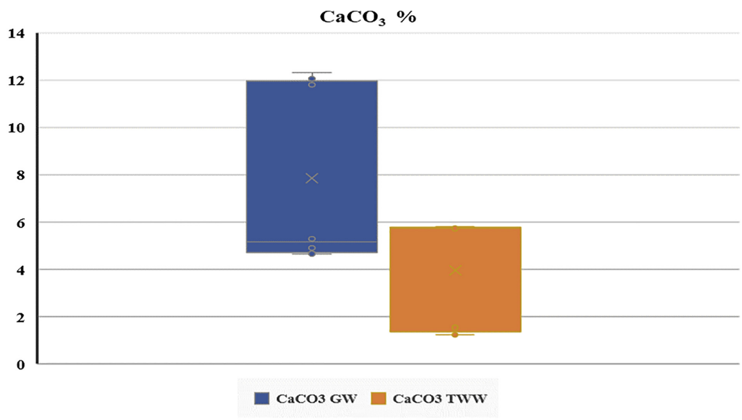

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Figure 5.
Calcium carbonate ($CaCO_3$%) as affected by groundwater (GW) and treated wastewater (TWW)

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.

References

Abdel-Fattah, M. K. (2015). Potential use of halophytes in combination with gypsum to reclaim and restore saline-sodic soils in Egypt. *Malaysian Journal of Soil Science*, *19*, 131–139.

Abdelhamid, M., Eldardiry, E., & El-Hady, M. A. (2013). Ameliorate salinity effect through sulphur application and its effect on some soil and plant characters under different water quantities. *Agricultural Science*, *4*, 39–47. doi: 10.4236/as.2013.41007.

Abhayawickrama, B., Gimhani, D., Kottearachchi, N., Herath, V., Liyanage, D., & Senadheera, P. (2020). In Silico identification of QTL-based polymorphic genes as salt-responsive potential candidates through mapping with two reference genomes in rice. *Plants*, *9*, 233. doi: 10.3390/plants9020233.

Abegunrin, T. P., Awe, G. O., Idowu, D. O., & Adejumobi, M. A. (2016). Impact of wastewater irrigation on soil physicochemical properties, growth and water use pattern of two indigenous vegetables in southwest Nigeria. *Catena*, *139*, 167–178.

Adil, M., Samia, H., Sakher, M., El Hafed, K., Naima, K., Kawther, L., Tidjani, B., Abdesselam, B., Bensalah, L.M`h., Yamina, K., & Amor, H. (2015). Date Palm (Phoenix dactylifera L.) irrigation water requirements as affected by salinity in Oued Righ Conditions, North Eastern Sahara, Algeria. *Asian Journal of Crop Science*, *7*, 174–185. doi:10.3923/ajcs.2015.174.185.

Ahmed, K., Qadir, G., Jami, A. R., Saqib, A. I., Nawaz, M. Q., Kamal, M. A., & Haq, E. (2016). Strategies for soil Amelioration using sulphur in salt affected soils. *Cercet. Agron. Mold.*, *49*, 5–16. doi: 10.1515/cerce-2016-0021.

Al Omron, A. M., El-Maghraby, S. E., Nadeem, M. E. A., El-Eter, A. M., & Al-Mohani, H. (2012). Long term effect of irrigation with the treated sewage effluent on some soil properties of Al-Hassa Governorate, Saudi Arabia. *Journal of the Saudi Society of Agricultural Sciences*, *11*(1), 15–18. doi: 10.1016/j.jssas.2011.04.004.

Al-Barrak, K. M. (2000). The weathering of gypsum and calcite and their role in the reclamation of soilsfrom Al-Hassa Oasis, Saudi Arabia. Reading: Dpartment of Soil Science, University of Reading. PhD Thesis. Available from: https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.340030

Al-Barrak, S. A., & Al-Badawi, M. (1988). Properties of some salt affected soil in Al-Hassa. Saudi Arabia. *Arid Soil Research and Rehabilitation*, *2*, 85–95. doi: 10.1080/15324988809381162.

Al-Harb, I. O. A., Hussain, G., & Lafouza, O. (2009). Irrigation water quality evaluation of Al-Mendasah groundwater and drainage water, Al-Madenah Al-Monawarah region, Saudi Arabia. *International Journal of Soil Science*, *4*, 123–141. doi: 10.3923/ijss.2009.123.141.

Al-Hawas, I. A. (1989). Origin and properties of some phyllosilicate minerals in the soils of the Al-Hassa Oasis, Dpartment of Soil Science. University of Reading, Reading. Available from: https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.265107

Al-Saeedi, A. H. (2022). Characterizing physical and hydraulic properties of soils in Al-Ahsa, Kingdom of Saudi Arabia. *Saudi Journal of Biological Sciences*, *29*(5), 3390–3402. doi:10.1016/j.sjbs.2022.01.061.

Al-Zarah, A. I. (2011). Elemental composition of groundwater and spring waters in Al-Ahsa oasis, eastern region Saudi Arabia. *Trends in Applied Sciences Research*, *6*, 1–18.

Ali, S., Ullah, S., Umar, H., Aslam, M. U., Aslam, Z., Akram, M. S., … Zain, R. (2022). Effects of wastewater use on soil Physico-chemical properties and human health status. *International Journal of Pure and Applied Bioscience*, *10*(2), 50–56. doi: 10.18782/2582-2845.8864.

Allbed, A., Kumar, A. L., & Sinha, P. (2018). Soil salinity and vegetation cover change detection from multi-temporal remotely sensed imagery in Al Hassa Oasis in Saudi Arabia. *Geocarto International*, *33*(8), 830–46.

Alnajem, F. A. (2021). Evaluating the degraded agricultural soils at Al-Hassa Oasis, KSA. MSc Thesis. Environment and Natural Resources Dep. Al-Ahsa: King Faisal University.

Anshassi, M., Laux, S. J., & Townsend, T. G. (2019). Approaches to integrate sustainable materials management into waste management planning and policy. *Resources, Conservation and Recycling*, *148*, 55–66.

Bahri, A., Drechsel, P., Raschid-Sally, L., & Redwood, M. (2009). *Wastewater irrigation and health: Assessing and mitigating risk in low-income countries*. London. Routledge.

Baldock, & Skjemstad (2000). Baldock JA, Skjemstad JO. Role of the soil matrix and minerals in protecting natural organic materials against biological attack. *Organic Geochemistry*, *31*(7-8), 697–710. doi: 10.1016/S0146-6380(00)00049-8.

Bashour, I. I., Al-Mashhady, A. S., Devi Prasad, J., Miller, T., & Mazroa, M. (1983). Morphology and composition of some soils under cultivation in Saudi Arabia. *Geoderma*, *29*(4), 327–340. doi: 10.1016/0016-7061(83)90019-8.

Bedbabis, S., Trigui, D., Ahmed, C. B., Clodoveo, M. L., Camposeo, S., Vivaldi, G. A., & Rouina, B. B. (2015). Long-terms effects of irrigation with treated municipal wastewater on soil, yield and olive oil quality. *Agricultural Water Management*, *160*, 14–21. doi: 10.1016/j.agwat.2015.06.023.

Bedbadis, S., Rouina, B., Boukhris, M., & Ferrara, G. (2014). Effect of irrigation with treated wastewater on soil chemical properties and infiltration rate. *Journal of Environmental Management*, *133*, 45–50.

Biro Turk, K. G., & Aljughaiman, A. S. (2020). Land use/land cover assessment as related to soil and irrigation water salinity over an oasis in arid environment. *Open Geosciences*, *12*, 220–231.

Bloom, P., Meter, K., & Crum, J. (1985). Titration method for determination of clay-sized carbonates. *Soil Science Society of America Journal*, *49*, 1070–1073. Available from: https://agris.fao.org/agris-search/search.do?recordID=US8625356.

Capaldi, F. R., Gratão, P. L., Reis, A. R., Lima, L. W., & Azevedo, R. A. (2015). Sulfur metabolism and stress defense responses in plants. *Tropical Plant Biology*, *8*, 60–73. doi: 10.1007/s12042-015-9152-1.

Chávez, A., Rodas, K., Prado, B., Thompson, R., & Jiménez, B. (2012). An evaluation of the effects of changing wastewater irrigation regime for the production of alfalfa (Medicago sativa). *Agricultural Water Management*, *113*, 76–84. doi: 10.1016/j.agwat.2012.06.021.

Chahal, M. K., Gurpal, S. T., Peter, N. -K., & Bielinski, M. S. (2011). Effect of tomato Packinghouse wastewater properties on Phosphorus and cation leaching in a Spodosol. *Journal of Environmental Quality*, *40*(3), 999–1009.

Chapman, R. W. (1974). Calcareous Duricrust in Al-Hasa, Saudi Arabia. *Geological Society of America Bulletin*, *85*, 2. doi: 10.1130/0016-7606(1974)852.0.CO.

Chefetz, B., Ilani, T., Schulz, E., & Chorover, J. (2006). Wastewater dissolved organic matter: Characteristics and sorptive capabilities. *Water Science and Technology*, *53*, 51–57. doi: 10.2166/wst.2006.207.

Chen, W. P., Lu, S. D., Zhang, W. L., Yi, L., & Jiao, W. (2014). Ecological risks and sustainable utilization of reclaimed water and wastewater irrigation. *Acta Ecologica Sinica*, *34*, 163–172.

Chen, L., Chen, X., Yang, X., Bi, P., Ding, X., Huang, X., & Wang, H.E. (2020). Effect of calcium carbonate on the mechanical properties and microstructure of red clay. *Advances in Materials Science and Engineering*, *2020*, 1–8.

de Albuquerque, A., Wagner, W., Carlos, A.V.de A., José, D.N., Vera, L.A.de L., & José W.do S. (2006), "Treated wastewater and nitrogen: Effects on the chemical properties of the soil", In *2006 ASAE Annual Meeting*, American Society of Agricultural and Biological Engineers, p. 1.

DeNicola, E., Aburizaiza, O. S., Siddique, A., Khwaja, H., & Carpenter, D. O. (2015). Climate change and water scarcity: The case of Saudi Arabia. *Annals of Global Health*, *81*, 342–353. doi: 10.1016/j.aogh.2015.08.005.

Du, Z., Zhao, S., She, Y., Zhang, Y., Yuan, J., Rahman, S. U., . . . Li, P. (2022). Effects of different wastewater irrigation on soil properties and vegetable productivity in the north China plain. *Agriculture*, *12*, 1106. doi: 10.3390/agriculture12081106.

Eamrat, R., Lapkratok, S., Mingyai, S., & Shakya, B. M. (2022). Assessment of groundwater quality for irrigation purposes: A case study of Suwannaphum District, roi-et. Thailand. *International Journal of GEOMATE*, *23*(97), 106–114.

Elfanssi, S., Ouazzani, N., & Mandi, L. (2018). Soil properties and agro-physiological responses of alfalfa (Medicago sativa L.) irrigated by treated domestic wastewater. *Agricultural Water Management*, *202*, 231–40.

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 Research*, *144*, 356–364.

Farhadkhani, M., Nikaeen, M., Hadi, M., Gholipour, S., & Yadegarfar, G. (2020). Campylobacter risk for the consumers of wastewater-irrigated vegetables based on field experiments. *Chemosphere*, *251*, 126408. doi: 10.1016/j.chemosphere.2020.126408.

Galavi, M., Jalali, A., Ramroodi, M., Mousavi, S. R., & Galavi, H. (2010). Effects of treated municipal wastewater on soil chemical properties and heavy metal uptake by sorghum (Sorghum bicolor L.). *Journal of Agricultural Science*, *2*, 235–241. doi: 10.5539/jas.v2n3p235.

Ganjegunte, G., Ulery, A., Niu, G., & Wu, Y. (2018). Organic carbon, nutrient, and salt dynamics in saline soil and switchgrass (Panicum virgatum L.) irrigated with treated municipal wastewater. *Land Degradation and Development*, *29*, 80–90. doi: 10.1002/ldr.2841.

García-Carrillo, M., Luna-Ortega, J. G., Gallegos-Robles, M. Á., Preciado-Rangel, P., & Cervantes-Vázquez, M. G. (2020). Impact of wastewater on soil properties and accumulation of heavy metals, *Terra Latinoamericana*, *38*, 907–916, (English abstract). doi: 10.28940/terra.v38i4.556.

Gee, G. W., & Bauder, J. W. (1994). Particle-size analysis. In A. Klute (Ed.), *Methods of Soil Analysis. Part 1, Physical, Mineralogical Methods* (3rd ed.), pp. 377–382). Madison, WI: SSSA and ASA.

Ghernaout, D. (2017). Water reuse (WR): The ultimate and vital solution for water supply issues. *International Journal of Sustainable Development Research*, *3*, 36–46. doi: 10.11648/j.ijsdr.20170304.12.

Ghernaout, D., Elboughdiri, N., & Al Arni, S. (2019). Water reuse (WR): Dares, restrictions, and trends. *Applied Engineering*, *3*, 159–170.

Gibson, R., Durán-Álvarez, J. C., Estrada, K. L., Chávez, A., & JiménezCisneros, B. (2010). Accumulation and leaching potential of some pharmaceuticals and potential endocrine disruptors in soils irrigated with wastewater in the Tula Valley, Mexico. *Chemosphere*, *81*, 1437–1445. doi: 10.1016/j.chemosphere.2010.09.006.

Gross, A., Azulai, N., Oron, G., Nejidat, A., & Ronen, Z. (2005). Environmental impact and health risks associated with grey water irrigation: A case study. *Water Science and Technology*, *52*(8), 161–169.

Hafshejani, N. A., & Jafari, S. (2017). The study of particle size distribution of calcium carbonate and its effects on some soil properties in Khuzestan province. *Iran Agricultural Research*, *36*(2), 71–80.

Hajjami, K., Ennaji, M. M., Fouad, S., Oubrim, N., Khallayoune, K., & Cohen, N. (2012). Assessment of helminths health risk associated with reuse of raw and treated wastewater of the Settat City (Morocco). *Resources and Environment*, *2*, 193–201. doi: 10.5923/j.re.20120205.03.

Hamed, L. M. M., Galal, Y. G. M., Soliman, M. A. E. S., & Emara, E. I. R. (2019). Optimum applications of nitrogen fertilizer and water regime for wheat (Triticum aestivum L.) using N-15 tracer technique under mediterranean environment. *Egyptian Journal of Soil Science*, *59*(1), 41–52.

Hamilton, A. J., Stagnitti, F., Xiong, X., Kreidl, S. L., Benke, K. K., & Maher, P. (2007). Wastewater irrigation: The state of play. *Vadose Zone J*, *6*, 823–840. doi: 10.2136/vzj2007.0026.

Helmke, P. A., & Sparks, D. L. (1996). Lithium, sodium, potassium, rubidium, and cesium. In D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, . . . M. E. Sumner (Eds.), *Methods of Soil Analysis*. doi: 10.2136/sssabookser5.3.c19.

Hidri, Y., Fourti, O., Jedidi, N., & Hassen, A. (2013). Effects of ten years treated wastewater drip irrigation on soil microbiological properties under Mediterranean conditions. *African Journal of Biotechnology*, *12*(39), 5761–5770.

Hong, G., & Chen (2019). Hong S, Gan P, Chen A. Environmental controls on soil pH in planted forest and its response to nitrogen deposition. *Environmental Research*, *172*, 159–165. doi: 10.1016/j.envres.2019.02.020.

Jeong, H., Jang, T., Seong, C., & Park, S. (2014). Assessing nitrogen fertilizer rates and split applications using the DSSAT model for rice irrigated with urban wastewater. *Agricultural Water Management*, *141*, 1–9. doi: 10.1016/j.agwat.2014.04.009.

Kemmitt, S. J., Wright, D., Keith W. T. G., Jones, D. L. (2006). pH regulation of carbon and nitrogen dynamics in two agricultural soils, *Soil Biology and Biochemistry*, *38*(5), 898-911. doi: 10.1016/j.soilbio.2005.08.006.

Khalid, S., Shahid, M., 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. *International Journal of Environmental Research and Public Health*, *15*, 895.

Khan, M. G., Daniel, G., Konjit, M., Thomas, A., & Eyasu, S. S. (2011). Awoke, G. Impact of textile waste water on seed germination and some physiological parameters in pea (Pisum sativum L.), Lentil (Lens esculentum L.) and gram (Cicer arietinum L.). *Asian Journal of Plant Sciences*, *10*, 269. doi: 10.3923/ajps.2011.269.273.

Khan, M. Y. A., ElKashouty, M., & Bob, M. (2020). Impact of rapid urbanization and tourism on the groundwater quality in Al madinah city, Saudi Arabia: A monitoring and modeling approach. *Arabian Journal of Geosciences*, *13*, 1–22. doi: 10.1007/s12517-020-05906-6.

Khlosi, M. (2015). Predicting water retention properties of dryland soils. PhD Thesis, Faculty of Bioscience Engineering, Ghent University, Ghent.

Lado, M., Bar-Tal, A., Azenkot, A., Assouline, S., Ravina, I., Erner, Y., . . . Ben-Hur, M. (2012). Changes in chemical properties of semiarid soils under long-term secondary treated wastewater irrigation. *Soil Science Society of America Journal*, *76*, 1358–1369. doi: 10.2136/sssaj2011.0230.

Liu, Y., Cui, E., Li, Z., Du, Z., Gao, F., & Fan, X. (2018). Effects of irrigating biochar-and pectin-amended soil with treated municipal wastewater and swine wastewater on soil salinity and sodicity. *Journal of Irrigation and Drainage*, *37*, 16–23. (In Chinese with English abstract). doi: 10.13522/j.cnki.ggps.2017.0430.

Loeppert, R. H., & Suarez, D. L. (1996). Carbonate and gypsum. In D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, . . . M. E. Sumner (Eds.), *Methods of Soil Analysis*. doi: 10.2136/sssabookser5.3.c15.

Mahmoud, E. A., Hassanin, M. A., Borham, T. I., & EmanEmara, I. R. (2018). Tolerance of some sugar beet varieties to water stress. *Agricultural Water Management*, *201*, 144–151. doi: 10.1016/j.agwat.2018.01.024.

Muller, K., Duwig, C., Prado, B., Siebe, C., Hidalgo, C., & Etchevers, J. (2012). Impact of long-term wastewater irrigation on sorption and transport of atrazine in Mexican agricultural soils. *Journal of Environmental Science and Health, Part B*, *47*, 30–41. doi: 10.1080/03601234.2012.606416.

Muyen, Z., Moore, G. A., & Wrigley, R. J. (2011). Soil salinity and sodicity e_ects of wastewater irrigation in South East Australia. *Agricultural Water Management*, *99*, 33–41. doi: 10.1016/j.agwat.2011.07.021.

Nelson, D. W., & Sommer, L. E. (1996). Total carbon, organic carbon, and organic matter. In D.L. Sparks, & Page. *Methods of Soil Analysis, Part 3. Chemical Methods*. doi: 10.2136/sssabookser5.3.c34.

Ofori, S., Puškáčová, A., Růžičková, I., & Wanner, J. (2021). Treated wastewater reuse for irrigation: Pros and cons. *Science of the Total Environment*, *760*, 144026. doi: 10.1016/j.scitotenv.2020.144026.

Oubane, M., Khadra, A., Ezzariai, A., Kouisni, L., & Hafidi, M. (2021). Heavy metal accumulation and genotoxic effect of long-term wastewater irrigated peri-urban agricultural soils in semiarid climate. *Agricultural Water Management*, *794*, 148611. doi: 10.1016/j.scitotenv.2021.148611.

Page, A. L., Miller, R. H., & Keeney, D. R. (1982). *Methods of soil analysis, part 2. Chemical and microbiological properties*. Madison, Wisconsin: Amer. Soc. Of Agron. doi: 10.1002/jpln.19851480319.

Pereira, B. F. F. H., He, Z. L., Stoffella, P. J., & Melfi, A. J. (2011). Reclaimed wastewater: E_ects on citrus nutrition. *Agricultural Water Management*, *98*, 1828–1833. doi: 10.1016/j.agwat.2011.06.009.

Pescod, M. B. (1992). *Wastewater treatment and use in agriculture* (Vol. 47). Rome: FAO Irrig. Drain. Pap.

Qadir, M., Ghafoor, A., & Murtaza, G. (2000). Amelioration strategies for saline soils: A review. *Land Degradation and Development*, *11*, 501–521. doi: 10.1002/1099-145X(200011/12)11:63.0.CO;2-S.

Qian, Y. L., & Mecham, B. (2005). Long-term effects of recycled wastewater irrigation on soil chemical properties on golf course fairways. *Agronomy Journal*, *97*, 717–721.

Qiang, X., Sun, J., & Ning, H. (2022). Impact of subsoiling on cultivated horizon construction and grain yield of winter wheat in the North China Plain. *Agriculture*, *12*, 236. doi: 10.3390/agriculture12020236.

Raeisi-Vanani, H., Soltani-Toudeshki, A. R., Shayannejad, M., Ostad-Ali-Askari, K., Ramesh, A., Singh, V. P., & Eslamian, S. (2017). Wastewater and magnetized wastewater effects on soil erosion in furrow irrigation. *International Journal of Research Studies in Agricultural Sciences (IJRSAS)*, *3*, 1–14. doi: 10.20431/2454-6224.0308001.

Rattan, R. K., Datta, S. P., Chhonkar, P. K., Suribabu, K., & Singh, A. K. (2005). Long-term impact of irrigation with wastewater effluents on heavy metal content in soils, crops and groundwater-a case study. *Agriculture Ecosystems and Environmental*, *109*, 310.

Rizzo, L., Gernjak, W., Krzeminski, P., Malato, S., McArdell, C., Perez, J., . . . Fatta-Kassinos, D. (2020). Best available technologies and treatment trains to address current challenges in urban wastewater reuse for irrigation of crops in EU countries. *Science of the Total Environment*, *710*, 136312. doi: 10.1016/j.scitotenv.2019.136312.

Sanchez, N., Martinez-Fernandez, J., Gonzalez-Piqueras, J., Gonzalez-Dugo, M. P., Baroncini-Turrichia, G., Torres, E. . . . Pérez-Gutiérrez, C. (2012). Water balance at plot scale for soil moisture estimation using vegetation parameters. *Agricultural and Forest Meteorology*, *166-167*, 1–9. doi: 10.1016/j.agrformet.2012.07.005.

Sara, H. (2019). A long-term study of the effects of wastewater on some chemical and physical properties of soil. *Journal of Applied Research in Water and Wastewater*, *12*, 156–161. doi: 10.22126/arww.2020.4593.1148.

Sener, E., & Davra, A. (2013). Assessment of groundwater vulnerability based on a modified DRASTIC model, GIS and an analytic hierarchy process (AHP) method: The case of egirdir lake basin (isparta, Turkey). *Hydrogeology Journal*, *21*, 701–14.

Shakir, E., Zahraw, Z., & Al-Obaidy, A. (2017). Environmental and health risks associated with reuse of wastewater for irrigation. Egypt. *J. Pet.*, *26*, 95–102. doi: 10.1016/j.ejpe.2016.01.003.

Singh, A. A. (2021). Review of wastewater irrigation: Environmental implications. *Resources, Conservation and Recycling*, *168*, 105454.

Singh, P. K., Deshbhratar, P. B., & Ramteke, D. S. (2012). Effects of sewage wastewater irrigation on soil properties, crop yield and environment. *Agricultural Water Management*, *103*, 100–104. doi: 10.1016/j.agwat.2011.10.022.

Statistical Analysis System (SAS) (2000). *SAS user's guide*. Cary: SAS Institute. Version 8.1.

Sushil, K. V., Kochar, D., & Vikas & Khokhar, K. (2019). A review on influence of sewage water on soil properties and microbial biomass carbon. *Indian Journal of Pure and Applied Biosciences*, *7*(5), 83–90.

Toze, S. (2006). Reuse of effluent water—benefits and risks. *Agricultural Water Management*, *80*, 147–159. doi: 10.1016/j.agwat.2005.07.010.

Tsigoida, A., & Argyrokastritis, I. (2020). Electrical conductivity, pH and other soil chemical parameters after sub-irrigation with untreated and treated municipal wastewater in two different soils. *Global NEST Journal*, *22*(1), 55–66. doi: 10.30955/gnj.003217.

Uyan, M., & Cay, T. (2013). Spatial analyses of groundwater level differences using geostatistical modeling. *Environ Ecol Stat*, *20*, 633–46.

WHO (2006). *WHO guidelines for the safe use of wasterwater excreta and greywater*. Geneva: World Health Organization.

Xua, J., Wub, L., Changb, A. C., & Zhanga, Y. (2010). Impact of longterm reclaimed wastewater irrigation on agricultural soils: A preliminary assessment. *Journal of Hazardous Materials*, *183*, 780–786.

Yu, J., Wang, Z., Meixner, F. X., Yang, F., Wu, H., & Chen, X. (2010). Biogeochemical characterizations and reclamation strategies of saline sodic soil in Northeastern China. *CLEAN-soil Air Water*, *38*, 1010–1016. doi: 10.1002/clen.201000276.

Zhang, W. -W., Wang, C., Xue, R., & Wang, L. (2019). Effects of salinity on the soil microbial community and soil fertility. *Journal of Integrative Agriculture*, *18*, 1360–1368. doi: 10.1016/S2095-3119(18)62077-5.

Zhao, Z. H., Liu, G. H., Liu, Q. S., Huang, C., Li, H. (2018). Studies on the spatiotemporal variability of river water quality and its relationships with soil and precipitation: A case study of the Mun river basin in Thailand. *International Journal of Environmental Research and Public Health*. 2018a, *15*, 19. doi: 10.3390/ijerph15112466.

Zhou, W., Han, G., Liu, M., Li, X. (2019). Effects of soil pH and texture on soil carbon and nitrogen in soil profiles under different land uses in Mun River Basin, Northeast Thailand. *PeerJ*. Oct 15, *7*, e7880. doi: 10.7717/peerj.7880.

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