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Ensuring Sustainable Agricultural Practices: Treated Wastewater Quality and Its Impact on Groundwater for Irrigation in Oman

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Abstract The utilization of treated wastewater (TWW) for agricultural irrigation can enhance soil properties and fertility for better crop growth. However, toxic chemicals in TWW, if exceeding permissible limits, pose environmental and health risks. This study aims to evaluate the quality of treated wastewater (TWW) and groundwater used for irrigation in alfalfa and date palm fields, focusing on specific ion toxicity, salinity, heavy metal concentrations, and other water quality parameters. Water samples were collected from four plantation sites in the Ibra and Alqabil provinces during the summer and winter seasons of 2020 and 2021. The samples were analyzed for electrical conductivity (EC), pH, total dissolved solids (TDS), carbonate, bicarbonate, and the presence of arsenic (As), cadmium (Cd), cobalt (Co), boron (B), lead (Pb), nickel (Ni), copper (Cu), iron (Fe), zinc (Zn), manganese (Mn), and chromium (Cr). The findings reveal that both TWW and groundwater in the sampled sites exhibited salinity levels detrimental to sensitive crops. Trace element concentrations generally adhered to permissible limits as defined by FAO and Oman standards, except for boron, which exceeded allowable limits by up to 40% in groundwater when compared to the control site. Notably, cobalt (Co), arsenic (As), and cadmium (Cd) were undetectable in all water samples. Additionally, groundwater samples taken in close proximity to sewage treatment plants (STPs) displayed a 37% increase in EC, TDS, and heavy metal concentrations. This suggests that groundwater, like TWW, may contain undesirable salts and heavy metals that could compromise water quality. This research underscores the importance of monitoring and assessing the quality of both treated wastewater and groundwater used for irrigation. While these water sources hold potential benefits for agriculture, they also carry the risk of negatively impacting soil and crop health due to salinity and the presence of certain contaminants. This study provides critical insights into the safe use

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of TWW and groundwater in agricultural practices, highlighting areas for improvement in water treatment and management strategies to ensure sustainable agricultural productivity.

Keywords Physicochemical assessment · Environmental sustainability · Human health risks · Heavy metal contamination · Water quality analysis

1 Introduction

The utilization of treated wastewater has emerged as a pragmatic approach to sustain agriculture, particularly in irrigating various crops such as palm trees, citrus plants, and forage crops in Oman. However, the compounding impacts of climate change have initiated a cascade of challenges, notably the degradation of groundwater quality due to the infiltration of seawater into the aquifers. This infiltration has resulted in a complex phenomenon of groundwater salinization, rendering the soil unsuitable for cultivation and posing significant impediments to agricultural productivity (A. Ahmed & Askri, 2016; Jiang et al., 2023).

Recent initiatives, exemplified by the expansion of the One Million Date Palm Trees Project across several governorates in Oman, signify strategic efforts aimed at bolstering agricultural resilience amidst climatic upheavals (Batarseh et al., 2021; Qiu et al., 2023). Under stringent governmental regulations, this project has undergone augmentation to encompass not only date palm cultivation but also the incorporation of fruit and forage crops, all reliant on sophisticated irrigation systems. Such expansions have been pivotal in aiding farmers' adaptation to the multifaceted challenges posed by the changing climate (Cetin et al., 2022b; Cetin and Jawed, 2024). However, this laudable endeavor has triggered an unanticipated consequence: a surge in farmers' quest for alternative water sources to sustain these tree crops. Consequently, the demand for freshwater in plantation agriculture has experienced a dramatic threefold increase, perpetuating a palpable disparity between water consumption and its availability.

This pressing demand for water has driven the proliferation of a system where treated wastewater, sourced from sewage treatment plants (STPs), is conveyed to adjacent farms through an extensive network of plastic pipelines. These pipelines facilitate the transfer of treated wastewater from its origin at the STPs to the targeted plantations, serving as a daily ritual that spans across diverse governorates within the country (Cesur et al., 2022; Cetin et al., 2022a; Cicek et al., 2022). This innovative yet intricate system exemplifies the evolving strategies adopted by farmers and policymakers to address the growing water scarcity issues while simultaneously ensuring the sustenance of agricultural practices in the face of escalating climatic challenges (Cetin and Jawed, 2021; Cetin et al., 2023).

The utilization of treated wastewater for irrigation purposes is a critical practice in mitigating water scarcity in agriculture (Aisha, 2023; Ali & Üçüncü, 2023). However, the quality of irrigation water, particularly in terms of dissolved salts and trace contaminants, holds substantial significance in its impact on crops and soil health. Numerous studies have underscored the pivotal role of water quality in irrigated agriculture. Reports assessing treated wastewater and groundwater quality for irrigation have highlighted the implications of dissolved salts and trace contaminants on water quality (Nguyen & Huynh, 2023; Han et al., 2024), emphasizing their profound effects on crops and soil properties (Kadyampakeni et al., 2017; Zaman et al., 2018).

The consequences of poor water quality on irrigated crops are multifaceted and far-reaching. High salt accumulation in the root zone due to irrigation with water containing dissolved salts can impede plant growth and decrease soil permeability, primarily through excessive sodium or calcium leaching. Additionally, the presence of pathogens or contaminants in irrigation water poses direct threats to plant health, rendering water unsuitable for agricultural use (Bharti et al., 2020; Zhang et al., 2021). Studies conducted on water quality in Oman have also delved into the impact of treated wastewater on heavy metal levels and their translocation within the soil–plant system. Investigations have explored heavy metal accumulation in soil, its uptake by plants, and subsequent accumulation in fruits, shedding light on potential risks associated with using treated wastewater for irrigation purposes (Al-Musharafi et al., 2013; Batarseh et al., 2021; Murad, 2014; Pal & Mahato, 2016).

Amidst these considerations, the adherence to established water quality standards, such as those outlined by the Food and Agriculture Organization (FAO) for irrigation, holds critical importance. These standards encompass social, economic, and environmental components essential for ensuring sustainable agricultural practices in Oman. However, uncertainties persist regarding the potential impact of treated water, especially concerning heavy metal contamination, on the food chain and its implications for human and animal health. Furthermore, the long-term sustainability of date palm plantation agriculture, reliant on alternative water sources such as treated wastewater and groundwater, necessitates empirical evidence to substantiate their viability (Hu et al., 2023; Sukri et al., 2023).

The objective of this study is to evaluate the quality of treated wastewater (TWW) and groundwater utilized for irrigation in alfalfa and date palm fields, specifically focusing on assessing specific ion toxicity, salinity levels, heavy metal concentrations, and various other water quality parameters. By collecting water samples from four plantation sites in the Ibra and Alqabil provinces across different seasons, this research aims to provide comprehensive insights into the suitability of these water sources for agricultural practices. The novelty of this study lies in its examination of both treated wastewater and groundwater, shedding light on potential risks associated with their use in irrigation, including elevated salinity levels and the presence of contaminants such as boron. The implications of this research are significant for ensuring sustainable and safe agricultural practices in Oman. By highlighting areas of concern and potential improvement in water treatment and management strategies, this study contributes valuable insights towards safeguarding soil and crop health while maximizing agricultural productivity. Ultimately, this research underscores the importance of rigorous monitoring and assessment of water quality in agricultural irrigation practices, emphasizing the need for proactive measures to mitigate environmental and health risks associated with irrigation water contamination.

2 Material and Methods

2.1 Study Area

Ibra and Alqabil provinces, nestled amidst encircling mountains approximately 150 km from Muscat governorate, exhibit a distinct hot and arid climate. The annual average temperature is 25.8 °C, with scant rainfall averaging around 105 mm per year. September is the driest month, while June experiences the highest temperatures, averaging 32.0 °C, and January records the lowest at 18.9 °C. The agricultural landscape in these regions supports a variety of crops, including palm trees, citrus fruits, alfalfa, sorghum, wheat, and lettuce. Agriculture relies heavily on the Afalaj systems and groundwater reservoirs for irrigation. The field study encompasses four distinct sites within the region, each employing specific irrigation practices and water sources (Fig. 1). Site 1: Exclusively uses groundwater (GW) for irrigation and is situated approximately 5 km away from Sites 2, 3, and 4. Site 2: Relies on treated wastewater (TWW) for irrigation. Site 3: Employs a mixed water source comprising treated wastewater and groundwater (TWW and GW) (Table 1). Site 4: Located near the Ibra Sewage Treatment Plant (STP), uses groundwater (GW) for irrigation (Fig. 2).

These farms predominantly use traditional irrigation systems, where water channels traverse from collection basins to the agricultural plots. Farmers must obtain requisite permissions to access treated wastewater directly from the sewage treatment plant for irrigation. The treated wastewater undergoes comprehensive tertiary treatment to eliminate organic and inorganic compounds, pathogens, easily sedimentable solids, and non-settleable materials. This process aims to produce effluents with minimal concentrations of contaminants suitable for irrigating various trees and crops, except for vegetables. The Haya Water Company, now known as Nama Water Services, operates the water treatment plant with a

Fig. 1 Water collection basin

Table 1 The geographical coordinates of the farm sites and their water sources

Farm No	Site No	Geographical Locations		Water sources
		Northing	Easting	
Farm No. 1	Site 1	22° 43′ 15.1"	58° 36′ 11.1"	GWC (Control site)
Farm No. 2		22° 49′ 52.2"	58° 25′ 47.2"	
Farm No. 3		22° 50′ 8.6	58° 24′ 21.4	
Farm No.4	Site 2	22° 43′ 40.6"	58° 32′ 5.6"	TWW (Treated wastewater)
		22° 43′ 39.2"	58° 32′ 4.8"	
Farm No. 5		22°44′21.16"	58°31′46.04"	
Farm No. 6		22°44′9.11"	58°32′3.45"	
Farm No. 7	Site 3	22° 44′ 17.7”	58° 31′ 57.5"	MW (TWW + GW)
Farm No. 8		22° 44′ 8.1"	58° 31′ 56.0"	MW (TWW + GW)
Farm No. 9		22°44′6.21"	58°32′1.02"	MW (TWW + GW)
Farm No. 10	Site 4	22° 43′ 50.4"	58° 32′ 23.6"	GWN (near STP)
Farm No. 11		22° 43′ 43.6"	58° 32′ 24.3"	GWN (near STP)
Farm No. 12		22°43′35.08"	58°32′14.76"	GWN (near STP)

capacity to process 1879 m^3/day, treating 1685 m^3/day of water intended for the city's use. This treatment process ensures that the effluents meet specified standards, facilitating their safe and sustainable use in agricultural irrigation within the region.

2.2 Sample Collection and Analytical Methods

Sample Collection Water samples were collected twice annually, in January and July, over the course of 2020 and 2021, from four sites in Ibra and Alqabil provinces. To minimize contamination, polyethylene bottles used for sample collection were pre-cleaned by washing with distilled water, soaked in 10% nitric acid (HNO_3) for 24 h, and rinsed thrice with distilled water.

Water Quality Parameters Fifteen water quality parameters were analyzed to assess the suitability of treated wastewater (TWW) and groundwater (GW) for irrigation. These parameters included salinity, electrical conductivity (EC), total dissolved solids (TDS), sodium (Na), chloride (Cl), boron (B), lead (Pb), chromium (Cr), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), pH, calcium (Ca), magnesium (Mg), and other trace elements.

Field Measurements In the field, water temperature, pH, EC, and TDS were measured using a portable meter (Hanna HI991301) with a glass electrode calibrated using standard buffer solutions. For each field season, 100 ml of water samples were collected in six replicates (three for EC, pH, TDS, and other elements, and three for heavy metal analysis).

Sample Preservation and Heavy Metal Analysis To prevent microbial utilization, 1 ml of HNO_3 was added to each sample immediately after collection, and samples were refrigerated at 4 °C. Heavy metals were quantified using the EPA 3015A method. Specifically, 45 ml of each water sample was digested with 4 ml of HNO_3 and 1 ml of HCl in a microwave digestion system at 170 ± 5 °C and 1200 Watts (Zhao et al., 2024). After digestion, samples were filtered using Whatman grade 42 filters, diluted to 50 ml with deionized water, and stored at 4 °C until analysis.

Carbonate and Bicarbonate Determination Carbonate and bicarbonate ions were determined by titration against sulfuric acid (H_2SO_4) using phenolphthalein and methyl orange indicators, following ICARDA standard methods (Zhu et al., 2024).

Calcium and Magnesium Determination Calcium (Ca) and magnesium (Mg) were determined by titration with disodium EDTA (0.01 N). For calcium, NaOH (4 N) and ammonium purpurate were used as indicators. For combined calcium and magnesium (Ca + Mg), an ammonium chloride-ammonium hydroxide buffer solution and eriochrome black

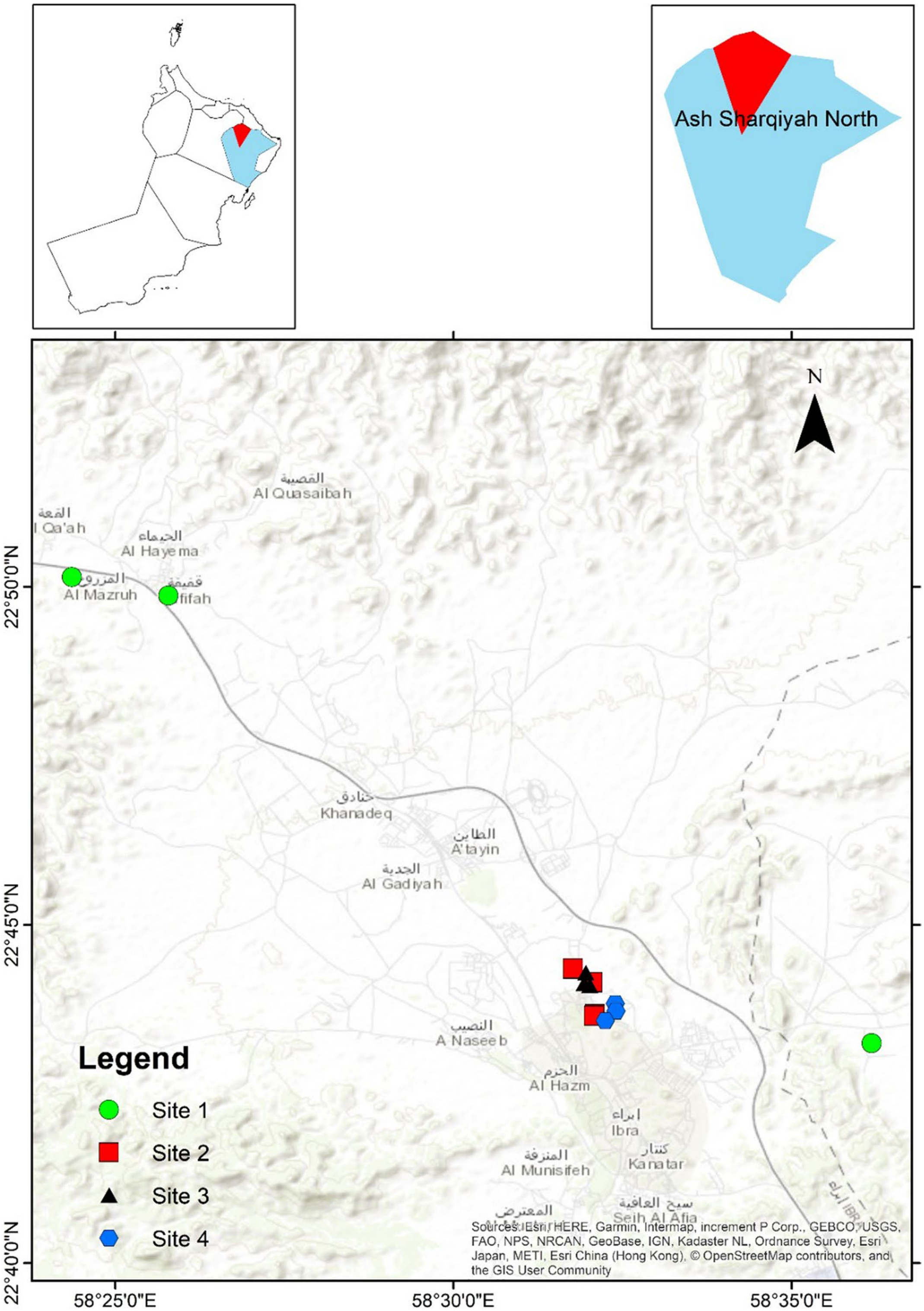

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Fig. 2 Map of the study area

T indicator were used (Dai et al., 2024b; Zhu et al., 2024).

Trace Element Analysis Trace elements were analyzed using an inductively coupled plasma optical emission spectrometer (ICP-OES) according to the method described by Bulska and Ruszczyńska (2017a, b).

Phosphorus, Chloride, Carbonate, and Bicarbonate Analysis Phosphorus, chloride, carbonate, and bicarbonate concentrations were analyzed using titrimetric methods as outlined by Chapman and Pratt, (1982).

The rationale behind the selection of specific parameters for assessment in this study is fundamental to understanding the environmental dynamics and potential risks associated with heavy metal contamination in agricultural settings. The chosen parameters were carefully selected based on their relevance to water quality and their known associations with heavy metal concentrations in previous research. Additionally, these parameters are commonly used indicators of environmental health and are widely recognized in scientific literature and regulatory frameworks. While the authors may have considered other sets of parameters, the selected ones were deemed most pertinent for several reasons. Firstly, parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), and total hardness (TH) are fundamental indicators of water quality and can provide insights into the overall chemical composition and suitability of water for irrigation purposes. These parameters can also influence the mobility and bioavailability of heavy metals in soil and water systems.

Furthermore, the inclusion of specific heavy metals such as copper (Cu), chromium (Cr), nickel (Ni), manganese (Mn), iron (Fe), zinc (Zn), and lead (Pb) is crucial due to their known toxicological effects and potential risks to human health and the environment. These metals are commonly found in wastewater effluents and are often monitored closely in environmental assessments due to their widespread occurrence and detrimental impacts on ecosystems. Sensitivity analysis of these parameters on the results is essential to understand their relative importance and potential interactions. By systematically varying the values of each parameter and observing their effects on heavy metal concentrations, researchers can assess which factors have the most significant influence on the outcomes. Sensitivity analysis can also help identify potential confounding variables or sources of uncertainty in the data, allowing for more robust interpretations and conclusions.

2.3 Statistical Analysis Methods

Software and Tools Mathematical, statistical, and data analyses were performed using Microsoft Office Excel (2016 version) and the agricolae package in R programming software (version 3.3.0) for Windows. IBM SPSS version 25 was utilized to calculate Pearson correlation coefficients.

Design and Replication A randomized complete block design (RCBD) with three replicates was employed for data analysis. Each replicate consisted of three farm plots per site, with a date palm stand density of 10,000 stands per hectare, separated from other sites by at least 5 km. This design helps in minimizing variability and improving the reliability of the results.

Multivariate Statistical Analysis Multivariate statistical techniques were applied to identify possible changes and patterns in water quality. These techniques are valuable in understanding the complex relationships between multiple water quality parameters.

Correlation Analysis Pearson correlation coefficient was used to assess the relationships and influences among physicochemical properties and heavy metals in the treated wastewater and groundwater samples. This statistical method helps in determining the strength and direction of linear relationships between variables.

Mean Comparison Duncan's multiple range test (DMRT) was used for comparing means at a significance level of $p < 0.05$. This post-hoc test helps in identifying significant differences between treatment means, thereby providing a clearer understanding of the impact of different water sources on the measured parameters. By integrating these statistical methods, the study ensures a robust analysis of the data, providing insights into the quality and suitability of treated wastewater and groundwater for agricultural irrigation.

3 Results and Discussion

The treated wastewater (TWW) and groundwater (GW) samples from all the plantation sites were analyzed for various quality parameters including pH, temperature, electrical conductivity (EC), bicarbonate (HCO3-), carbonate (CO3-2), chloride (Cl-), total dissolved solids (TDS), and sodium adsorption ratio (SAR).

3.1 pH Analysis

The pH of irrigation water exhibited significant variability ($p < 0.05$) across different water sources and seasons. Notably, the highest average pH values were observed in groundwater close to the well (GWC) at 7.82, followed by 7.73 in groundwater near the nursery (GWN), 7.67 in mixed water (MW), and 7.64 in treated wastewater (TWW). Statistical analysis using Duncan's test revealed no significant difference ($\alpha = 0.05$) in mean pH values between TWW, MW, and GWN, as well as between GWN and GWC (Fig. 3). However, the highest average pH values occurred during the summer of 2020 (7.79) and the winter of 2021 (7.75), suggesting a tendency towards neutral alkalinity. This aligns with findings by Zhu et al., (2024), attributing natural alkalinity to CO2 dissolution in the atmosphere or carbonate rocks like limestone and dolomite. Notably, the predominance of bicarbonate (HCO3-) as the primary carbonate component supports these findings, corroborated by studies by Ahmed and Askri, (2016) and Yi et al., (2022). Moreover, pH values of irrigation water sources within date palm farms adhered to Omani standards (pH = 6—9) for treated wastewater effluent reuse and discharge, as well as WHO and FAO standards (6—8.5).

3.2 Electrical Conductivity (EC) Assessment

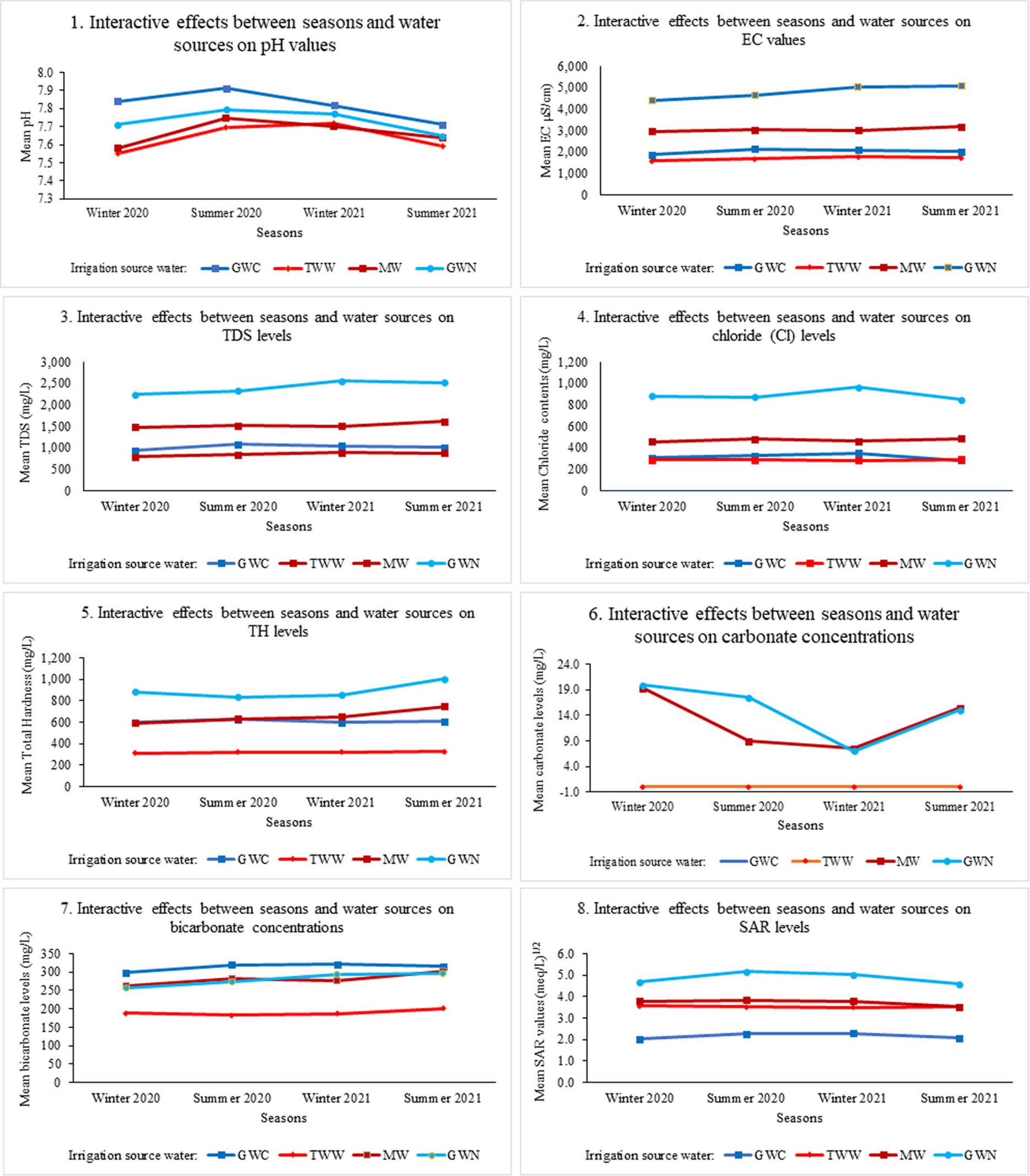
EC values demonstrated significant variation across different water sources, with groundwater samples near the sewage treatment plant (STP) exhibiting the highest average EC (4791.94 μS/cm), while treated wastewater had the lowest (1689.5 μS/cm). No significant difference ($p < 0.05$) was found between the average EC values of GWC and TWW. Seasonal variations were observed, with EC values in winters (averaging between 2702.56 μS/cm and 2983.08 μS/cm) notably lower than those in summers, indicating an annual difference of approximately 870 μS/cm (Table 2). High salt content in water with elevated EC levels can lead to soil degradation and pose toxicity risks to plants, as highlighted by Li et al., (2023). Furthermore, livestock may experience water balance disruptions due to excessive salinity, echoing the findings of Hu et al., (2023). Evaluation against established standards revealed that a substantial portion of the samples were slightly to moderately saline, underscoring the unsuitability of treated wastewater for animal consumption and its adherence to Omani standards for treated wastewater effluents (2000 μS/cm).

3.3 Total Dissolved Solids (TDS) Analysis

TDS levels exhibited significant variability across different water sources and seasons. The highest average TDS values were recorded in groundwater near the well (GWN) at 2412.50 mg/L, followed by mixed water (MW), groundwater near the nursery (GWC), and treated wastewater (TWW) (Table 3). Evaluation against established standards revealed that a majority of samples were slightly to moderately suitable for irrigation, although a significant portion of groundwater near the nursery (GWN) was deemed unsuitable. These findings align with Omani standards for Wastewater Reuse and Discharge (Class A) and Hu et al.'s classification (2023), emphasizing the importance of monitoring TDS levels for sustainable agricultural practices.

3.4 Total Hardness (TH) Assessment

TH levels varied significantly across irrigation water sources, with groundwater near the nursery (GWN) exhibiting the highest average TH (893.64 mg/L) and groundwater near the well (GWC) the lowest (321.01 mg/L) (Table 4). No significant differences in TH were observed between GWC and MW,


1. Interactive effects between seasons and water sources on pH values

2. Interactive effects between seasons and water sources on EC values

3. Interactive effects between seasons and water sources on TDS levels

4. Interactive effects between seasons and water sources on chloride (Cl) levels

5. Interactive effects between seasons and water sources on TH levels

6. Interactive effects between seasons and water sources on carbonate concentrations

7. Interactive effects between seasons and water sources on bicarbonate concentrations

8. Interactive effects between seasons and water sources on SAR levels

Fig. 3 The interaction plots between irrigation sources and seasonal variation for water quality properties on date palm plantation(ADD Q)

Table 2 Classification of irrigation according to (Dai et al., 2024a) based on EC

Classification		EC (µS/cm)	GWC		TWW		MW		GWN		Total	
			No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples
Type I	non-saline	< 0.700	0	0	0	0	0	0		0	0	0
Type II	slightly saline	700 -2000	15	41.7	36	100	0	0	0	0	51	35.4
Type III	moderately saline	2000 > EC < 10,000	21	58.3	0	0	36	100	36	1000	93	64.6
Type IV	highly saline	10,000—25,000	0	0	0	0	0	0	0	0	0	0

Table 3 Classification of irrigation water based on TDS

Classification	TDS	GWC		TWW		MW		GWN		Total	
		No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples
Preferred for irrigation	< 450 mg/L	0	0	0	0	0	0	0	0	0	0
Slight to moderate	450—2000 mg/L	36	100	36	100	36	100	6	16.7	114	79.2
High (unsuitable for irrigation)	> 2000 mg/L	0	0	0	0	0	0	30	83.3	30	20.8

Table 4 The Total hardness classification of the sampled sites

Irrigation water sources	Soft	Moderately Hard	Hard		Very		Hard	
	TH < 75 $CaCO_3$		75 < TH < 150 $CaCO_3$		150 < TH < 300 mg $CaCO_3$		TH > 300 mg/L $CaCO_3$	
	No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples
GWC	0	0	0	0	0	0	36	100
TWW	0	0	0	0	0	0	36	100
MW	0	0	0	0	0	0	36	100
GWN	0	0	0	0	0	0	36	100

suggesting a mitigating effect of treated wastewater on total hardness (Fig. 3). Seasonal variations were non-significant, with average TH values remaining relatively stable across different seasons. Evaluation against WHO and Omani standards revealed that a substantial portion of samples fell within permissible limits, emphasizing the importance of TH monitoring for water quality management in agricultural practices (Table 5).

3.5 Classification of Water Samples

Classification of water samples based on salinity revealed variations across different sources and locations. Groundwater samples near the control site exhibited freshwater characteristics, while treated wastewater samples were categorized as fresh to brackish. Groundwater near the sewage treatment plant (STP) and mixed water samples fell within the brackish water category, with a portion of groundwater near the STP categorized as saltwater. These classifications underscore the heterogeneous nature of water sources and highlight the importance of tailored management strategies for sustainable agricultural practices.

3.6 Carbonate and Bicarbonate Concentrations

Carbonates and bicarbonates in water play pivotal roles in determining calcium and magnesium levels and the water's acidity. The presence of these compounds is primarily attributed to carbonate weathering and carbonic acid dissolution in aquifers. In our study, significant variations ($p < 0.05$) in carbonate concentrations were observed across different irrigation water sources and seasons. While treated wastewater and control site groundwater showed negligible carbonate content, concentrations ranged from 5.79 to 29.45 mg/L in mixed water and 0 to 38.3 mg/L in groundwater near nurseries. Conversely, bicarbonate concentrations exhibited significant seasonal variations ($p < 0.05$) and interactive effects with irrigation water sources. Concentrations ranged from 183 to 365.7 mg/L in winter 2020, 175.68 to 378.27 mg/L in summer 2020, 159.82 to 383.08 mg/L in winter 2021, and 186.66 to 381.69 mg/L in summer 2021. These findings align with previous research by Al Hadidi et al., (2021) and Nagaraju et al., (2016) and underscore the dynamic nature of carbonate and bicarbonate levels in groundwater.

3.7 Trace Element Analysis

Iron **(Fe)** Iron is crucial for plant growth and metabolism, and its concentration varied significantly across irrigation water sources. Average concentrations were 0.09 mg/L in mixed water, 0.088 mg/L in groundwater near nurseries, and 0.084 mg/L in treated wastewater, with the lowest concentration recorded in groundwater near wells (0.061 mg/L) (Fig. 4). Interactive effects among irrigation water sources and seasons were significant. While seasonal fluctuations were observed across sites, treated wastewater fell below Omani standards (1 mg/L) for wastewater reuse and discharge (Class A) and FAO standards for irrigation water. However, concentrations in

Table 5 Classification of irrigation according to (Sawyer, 1960), cited by (Shen et al., 2023) based on total hardness

Classification		GWC		TWW		MW		GWN		Total	
		No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples
Fresh	≤ 150 mg/L	12	33.3	0	0	0	0	0	0	12	9.09
Fresh—brackish	150 – 300 mg/L	0	0	36	100	0	0	0	0	36	36.36
Brackish	300—1000	24	66.7	0	0	36	100	24	66.7	84	54.55
Brackish—salt	1000 – 10,000	0	0	0	0	0	0	0	0	0	0
Salt	10,000 – 20,000	0	0	0	0	0	0	12	33.3	12	0
Hypersaline	$> 20{,}000$	0	0	0	0	0	0	0	0	0	0

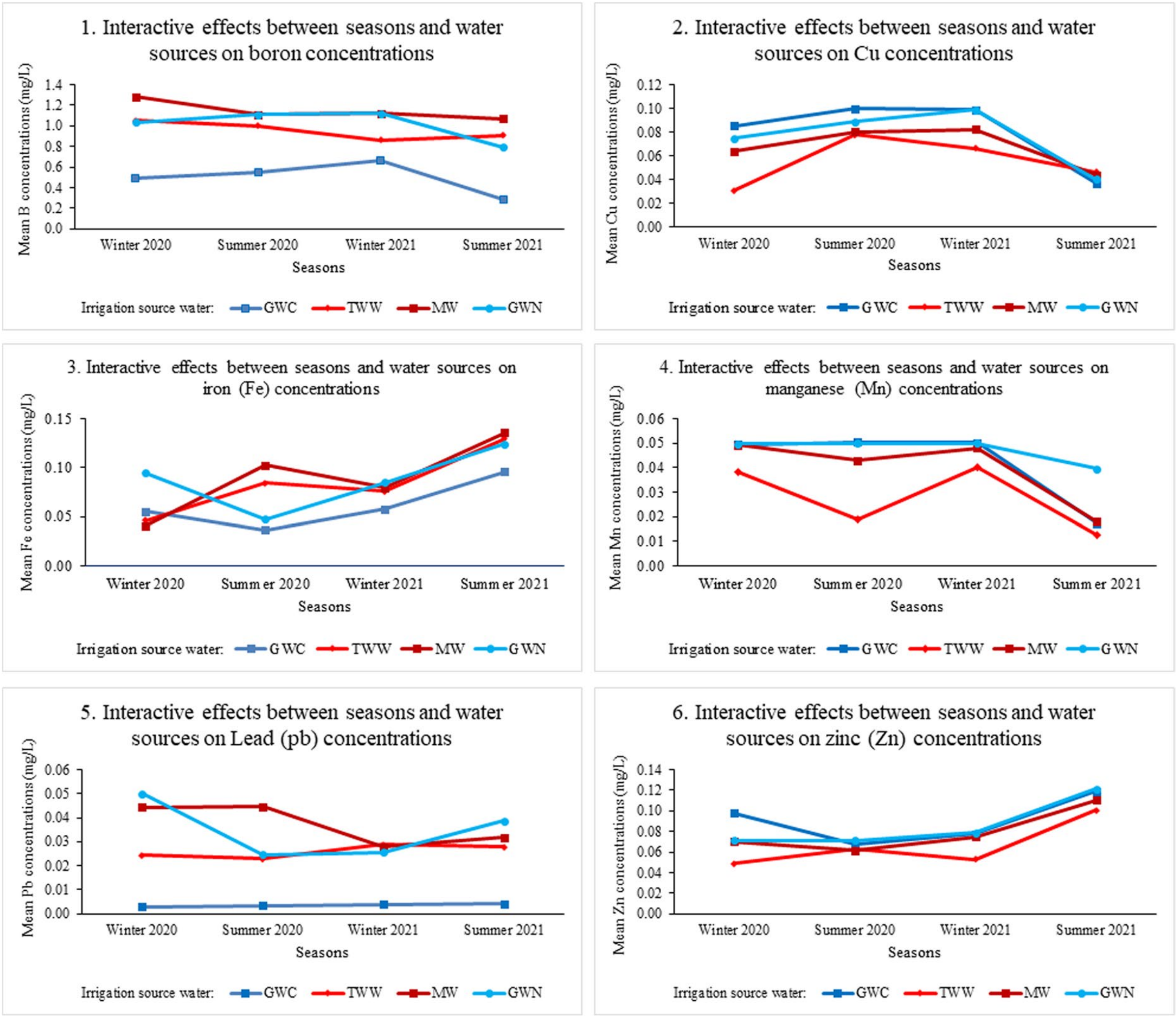


Fig. 4 **a-f** The interaction plots for heavy metals found in water between irrigation sources and seasonal variation in date-palm plantation

other sources remained within FAO's recommended limits (5.0 mg/L), consistent with findings by Hu et al., (2023).

Zinc (Zn) Zinc, an essential micronutrient for plants and animals, exhibited significant variability across irrigation water sources and seasons. Average concentrations ranged from 0.07 to 0.09 mg/L, with the highest levels observed in groundwater near wells and the sewage treatment plant. Interactive effects between zinc concentrations and water sources were notable, with fluctuations observed across seasons. Despite these variations, concentrations remained below Omani standards for wastewater reuse and discharge (Class A) and FAO standards for irrigation water. Our findings are consistent with previous studies by Yi et al., (2022), Yin et al., (2023), and Kinuthia et al., (2020), highlighting the importance of monitoring trace element levels in irrigation water.

Lead (Pb) Lead, a non-essential trace metal, showed concentrations below FAO's permissible limits (5 mg/L) across irrigation water sources and seasons. Average concentrations ranged from 0.004 to 0.04 mg/L, with the highest levels observed in mixed water and the lowest in groundwater near wells. No significant interactive effects were observed between lead concentrations and water sources. Despite variations, treated wastewater concentrations remained lower than those reported for Salala STP, while other sources remained within acceptable limits. These findings align with previous research by Baawain et al., (2013) and Wen et al., (2024), underscoring the importance of maintaining lead levels within safe thresholds for agricultural practices.

Boron (B) Boron, essential for plant growth albeit in small quantities, exhibited significant variation across irrigation water sources. The highest average concentration was found in groundwater near nurseries (GWN) at 1.15 mg/L, followed by mixed water (MW) and treated wastewater (TWW) at 1.02 mg/L and 0.96 mg/L, respectively. Groundwater near wells (GWC) showed the lowest concentration at 0.50 mg/L. While TWW and GWN showed non-significant variations in boron content, significant interactive effects were observed between boron concentrations and seasons. For instance, in the GWC site, boron concentration increased from 0.50 mg/L in winter 2020 to 0.54 mg/L in summer 2020, then decreased to 0.29 mg/L in summer 2021. Similarly, in TWW, concentrations decreased from 1.06 mg/L in winter 2020 to 1.0 mg/L in summer 2020 but increased from 0.87 mg/L in winter 2021 to 0.91 mg/L in summer 2021. The boron values across all sources, except for groundwater near control sites, exceeded Omani wastewater standards (Class A) of 0.5 mg/L and FAO permissible limits of 0.75 mg/L for boron in reclaimed water for irrigation (Fig. 4). This higher concentration could be attributed to water–rock interactions common in arid regions, allowing for boron accumulation. Other sources include municipal wastewater, industrial effluents, and agricultural chemicals. Attention to boron-rich sources like TWW, MW, and GWN is crucial, particularly for boron-sensitive crops like citrus.

Copper (Cu) Copper concentrations varied considerably across irrigation water sources, with significant differences observed. The highest average concentration was found in groundwater near control sites and sewage treatment plants (GWC and GWN) at 0.08 mg/L, followed by mixed water (MW) at 0.07 mg/L. There were no significant differences between Cu concentrations in GWN and GWC. Interactive effects between different water sources and seasons were notable, with fluctuations observed. Despite these variations, concentrations in treated wastewater remained below Omani standards for wastewater reuse and discharge and FAO permissible limits.

Manganese (Mn) Manganese, an essential trace element, exhibited significant variation across irrigation water sources. The highest average concentration was observed in groundwater near nurseries (GWN) at 0.05 mg/L, followed by groundwater near wells (GWC) and mixed water (MW) at 0.04 mg/L. The lowest concentration was found in treated wastewater (TWW) at 0.03 mg/L. These values exceeded previously reported levels but remained below Omani standards for wastewater reuse and discharge and FAO permissible limits (Fig. 4). Significant interactive effects were observed between manganese concentrations and seasons, indicating seasonal fluctuations across all sources. Monitoring manganese levels is crucial for maintaining water quality standards in agricultural practices.

3.8 Correlation Analysis of Irrigation Water Properties and Heavy Metals

The correlation analysis conducted using Pearson's correlation coefficient revealed insightful relationships among various irrigation water properties and heavy metals, shedding light on potential pollution sources and their impacts (Table 6). Strong positive correlations were observed between electrical conductivity (EC), total dissolved solids (TDS), and total hardness (TH), indicating a shared dependence on common causal factors (Luo et al., 2022). Furthermore, moderate positive correlations were found between carbonate ions (CO3-2) with TDS, TH, and boron (B); manganese (Mn) with lead (Pb) and copper (Cu); and weak positive correlations between pH with bicarbonate (HCO3-) and Cu; EC with Mn, HCO3-, and B; TDS with Mn and B; zinc (Zn) with iron (Fe), and Zn with TH, HCO3-, CO3-2 with TH; and HCO3- with Mn and TH. Conversely, moderate negative correlations were observed between Zn with Pb; Fe with Mn and Pb; as well as weak negative correlations between Zn with B and Mn; and Fe with Mn and Cu. These findings align with previous research by Kumar et al., (2012) and Venkatesh et al., (2009), corroborating the complex interplay between various water properties and heavy metal concentrations.

Table 6 Person's correlation matrix for different parameters in irrigation water sources

Parameters	pH	EC	TDS	Zn	Pb	Ni	Fe	Mn	Cr	Cu	B	Total Hardness (TH)	CO3	HCO3
pH	1													
EC	0.058	1												
TDS	0.058	0.998**	1											
Zn	0.004	0.145	0.143	1										
Pb	0.298**	0.126	0.126	-0.533**	1									
Ni	-0.428**	0.288	0.284	0.247	-0.623**	1								
Fe	-0.245**	0.195*	0.201*	0.388**	-0.620**	-0.268	1							
Mn	0.282**	0.342**	0.343**	-0.379**	0.566**	0.480**	-0.554**	1						
Cr	0.384*	0.278	0.283	0.314	-0.329	-0.110	0.202	0.483**	1					
Cu	0.429**	0.117	0.121	-0.283**	0.780**	-0.248	-0.402**	0.595**	0.008	1				
B	-0.230**	0.368**	0.374**	-0.358**	0.450**	-0.418*	0.116	0.138	0.162	0.053	1			
Total Hardness (TH)	0.019	0.779**	0.782**	0.332**	0.075	0.358*	0.117	0.335**	0.048	0.154	0.035	1		
CO3	0.139	0.671**	0.669**	0.078	0.060	-0.379*	0.102	0.212*	0.577**	-0.034	0.457**	0.420**	1	
HCO3	0.322**	0.347**	0.345**	0.322**	-0.074	0.156	0.042	0.285**	0.238	0.246**	-0.134	0.397**	0.152	1

**. Correlation is significant at the 0.01 level (2-tailed)

*. Correlation is significant at the 0.05 level (2-tailed)

The soil pH emerged as a critical parameter affecting plant uptake, with trace element-related toxicities predominantly reported in acidic soils (Bojórquez-Quintal et al., 2017). The prevalence of bicarbonate ions may be attributed to the dissolution of carbonate minerals such as calcite and dolomite, as reported by Hu et al., (2022). Similarly, the values of TDS and EC were primarily influenced by the concentrations of prevalent cations (Na, Ca, and Mg) and anions (Cl and HCO3), consistent with findings by Al-Kalbani et al., (2017), Lan et al., (2022), Jahin et al., (2020), Naik et al., (2019), and Pal et al., (2021). These correlations underscore the intricate relationship between water chemistry parameters and heavy metal concentrations, emphasizing the need for comprehensive monitoring and management strategies to safeguard agricultural sustainability and environmental health.

4 Conclusion

The assessment conducted in this study revealed an escalation in heavy metal pollutants within the soil surrounding plantation sites neighboring the Ibra water treatment facilities. Particularly, parameters such as pH, Total Hardness, and Electrical Conductivity exhibited moderate risk indications in the groundwater adjacent to the sampled plantation sites closer to the treated wastewater plant. This rise in contamination levels can be attributed to a combination of anthropogenic factors stemming from urbanization and gradual deposition resulting from natural weathering processes over time. Furthermore, the study highlighted a moderately low-risk exposure scenario across all plantation sites concerning trace elements, including Cu, Cr, Ni, Mn, Fe, Zn, and Pb, with concentrations below the prescribed FAO standards for water pollution. Multivariate statistical methods elucidated that the biogeochemical origins for Cu, Mn, Fe, Co, and Ni did not significantly contribute to escalating risks, except in the case of Boron. The heightened presence of Boron in plantation sites near treatment plants surpassed permissible thresholds outlined by Omani and FAO standards, primarily originating from rock material weathering, atmospheric deposition, and anthropogenic sources.

The research underscores the critical need for continuous and periodic monitoring of heavy metal concentrations in groundwater, treated wastewater, and mixed water within the vicinity of Ibra and Al-Qabil provinces to manage and mitigate potential risks associated with heavy metal contamination. Particularly, vigilance targeting elements such as B, Zn, and Pb is imperative to prevent their unchecked escalation. Additionally, advocating for the use of organic fertilizers and biological pest control emerges as pivotal strategies for plantation owners to enhance sustainability, reducing reliance on synthetic fertilizers and pesticides and minimizing potential environmental repercussions.

In terms of future directions, several avenues for research and action are warranted. Firstly, longitudinal studies are essential to monitor temporal variations in heavy metal concentrations and evaluate the effectiveness of mitigation measures over time. Understanding how these concentrations fluctuate seasonally and annually can inform more targeted and efficient management strategies. Additionally, investigating the specific sources and pathways of heavy metal contamination is crucial for implementing effective remediation measures. By pinpointing the origins of contamination, such as industrial activities or agricultural runoff, tailored solutions can be developed to address these issues at their root. Furthermore, exploring alternative wastewater treatment methods and assessing their efficacy in reducing heavy metal concentrations in treated effluents can provide sustainable solutions to minimize contamination risks. Assessing the long-term ecological impacts of heavy metal contamination on soil health, plant growth, and biodiversity is also paramount. This holistic approach can guide ecosystem restoration efforts and ensure the preservation of environmental integrity. Lastly, integrating community engagement and stakeholder participation is essential to foster awareness and promote sustainable practices in agricultural and wastewater management. Collaboration between researchers, policymakers, industry stakeholders, and local communities can lead to more effective policies and practices that safeguard both human health and the environment.

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Declarations

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