



Sustainable agriculture in oman: evaluating treated wastewater irrigation effects on soil quality, heavy metal accumulation, and alfalfa growth

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Abstract

Water scarcity in arid regions like Oman necessitates sustainable irrigation alternatives such as treated wastewater (TWW). This study evaluates the long-term impact of TWW, mixed water, and groundwater irrigation on soil properties, heavy metal accumulation, and alfalfa (*Medicago sativa*) growth in the Ash-Sharqiyah North Governorate. Physicochemical analyses of soils and alfalfa shoots from 12 farms revealed significant site-specific variations in parameters such as pH, electrical conductivity (EC), sodium adsorption ratio (SAR), and organic matter (OM). Soils irrigated with TWW exhibited lower salinity and heavy metal concentrations compared to those near sewage treatment plants (STP) or irrigated solely with groundwater. Nickel (Ni) and chromium (Cr) levels in soils near STP and control sites exceeded FAO/WHO limits, likely due to long term waste water discharge. However, bioaccumulation in alfalfa remained below safety thresholds which suggesting limited plant uptake under current soil conditions. Contamination and enrichment indices confirmed TWW's role in minimizing metal accumulation. Alfalfa showed efficient uptake of nutrients like potassium (K), phosphorus (P), and chloride (Cl), with boron (B) being the only heavy metal with a bioaccumulation factor (BAF) > 1 across all sites. Salinity, organic substance content and lithography were found to be the main factors influencing variance in metal dynamics using PCA analysis. Alfalfa cultivated using TWW irrigation was safe for animal consumption even though the soil had some elevated metal levels. So, prolonged use of TWW may increase metal accumulation, highlighting the importance of long-term monitoring. In order to enhance the adoption of TWW in agriculture, awareness programs for farmers, provision of supportive policies, subsidies and cost-effective treatment technologies are necessary. These measures can build trust and encourage large scale implementation of TWW in water scarce regions.

Keywords Heavy metals · Contamination · Wastewater · Alfalfa · Soil properties · Pollution factor

1 Introduction

One of the biggest problems facing arid and semi-arid areas like Oman is still water scarcity. Oman's climate is extremely dry, its rainfall is unpredictable, and its freshwater supplies are scarce. Since agriculture uses more than 80% of the nation's water, finding alternate irrigation sources is necessary to maintain agricultural production under these restrictions (Odhiambo 2017; McDonnell 2016).

Reusing treated wastewater (TWW) for irrigation is one of the most promising approaches. TWW has several advantages, including being a reliable source of water and frequently high in vital nutrients like potassium, phosphate, and nitrogen, which may lessen the need for artificial fertilizers. (Al-Musharafi et al. 2013; Abdelrahman and Al-Ajmi

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1994). However, Depending on source pollution and treatment effectiveness, it could also have trace levels of heavy metals and other contaminants (Briffa et al. 2020). Because of their persistence, possible toxicity, and ability to bioaccumulate, these pollutants—especially heavy metals like nickel (Ni), chromium (Cr), cadmium (Cd), and lead (Pb)—pose a threat to crop safety as well as soil quality (Jaishankar et al. 2014; Balkhair and Ashraf 2016).

Heavy metals in soil pose major health concerns to humans and the environment because they can interfere with nutrient intake, stunt plant development, and contaminate food chains (Malan and Farrant 1998; Rizvi et al. 2020). Studies conducted in the area have revealed dangerously high concentrations of Cr, Zn, Ni, and Cd in crops that are irrigated with wastewater, raising questions about food safety and long-term soil deterioration (Balkhair and Ashraf 2016; Karanja et al. 2012). Additionally, some soils may affect the mobility and retention of these metals, especially those with an alkaline pH or high in organic matter (Kabata-Pendias 2010; Wuana and Okieimen 2011).

Numerous indices, such as the contamination factor (Cf), pollution load index (PLI), enrichment factor (EF) and bioaccumulation factor (BAF) have been created and extensively used to measure contamination levels and evaluate environmental risk (Hakanson 1980; Ghosh et al. 2019). According to Al-Shali et al. (2024), these metrics provide information on the dynamics of metal buildup in the soil–plant system and aid in differentiating between natural and man-made causes of pollution.

For such evaluations, alfalfa (*Medicago sativa*), a nutrient-rich fodder crop widely grown in Oman, is a very pertinent topic. By selecting alfalfa (*Medicago sativa* L.) as a biological indicator due to its high water demand and sensitivity to irrigation water quality, the study provides valuable insight into long-term impacts under arid conditions. Furthermore, the focus on Ni, Cr, Pb, and Zn—priority metals frequently detected in Omani wastewater effluents and of regulatory concern—adds regional relevance. Being a legume with deep roots, it may interact with and collect soil components over extended periods of time, which makes it a useful bioindicator of soil pollution and health (Prado et al. 2010). Metal uptake by plants occurs primarily through root absorption, facilitated by processes such as ion exchange, diffusion, and chelation. The extent of uptake is strongly influenced by soil characteristics (Iqbal et al. 2023). The long-term effects of TWW on alfalfa farming in Oman, specifically with regard to heavy metal mobility and accumulation patterns, have not, however, been well studied. TWW can provide significant agronomic and environmental benefits when properly treated and monitored but that potential risks must also be managed through stringent treatment standards, regular monitoring, and integrated land management practices. Nickel (Ni), Chromium (Cr), Lead (Pb), and

Zinc (Zn) were specifically investigated because Previous monitoring reports and regional studies have shown that these metals are among the most frequently detected contaminants in treated wastewater effluents in Oman. Ni, Cr, and Pb are toxic even at low concentrations and can accumulate in edible plant parts, posing potential health risks. Zn, while an essential micronutrient, can reach phytotoxic levels under prolonged wastewater irrigation. The long-term effects of irrigation using groundwater, mixed water, and treated wastewater on soil characteristics and alfalfa growth in Oman are assessed in this study. It provides information on how irrigation techniques, environmental health, and sustainable agriculture interact in areas with limited water resources.

2 Materials and methods

2.1 Experimental site and test planning

Date palms, citrus, alfalfa, sorghum, wheat, and vegetables are among the crops that are grown in Ibra, the second-largest city in the Ash-Sharqiyah North Governorate (Al-Shali et al. 2024). Four sites—groundwater control (GWC), treated wastewater (TWW), mixed water (MW), and a location close to the Sewage Treatment Plant (STP)—were the focus of the January 2020 investigation in Ibra and Alqabel. The fields, which are situated at 22°43'N, 58°31'E, and 469 m above sea level, are irrigated traditionally and include date palms supporting alfalfa and lemon trees. Furrow irrigation was conducted at regular intervals with the water requirements of alfalfa. Previously run by the Ministry of Regional Municipalities and Water Resources, the Ibra STP was founded in 2006 and has a planned capacity of 4500 m³/day. At present, it gets up to 1685 m³/day. Treated water is distributed to farms via a pipeline network. Field site coordinates align with those in a prior study (Al-Shali et al. 2024). The fields were chosen based on crop age of more than two years to ensure growth and biomass production. Irrigation history were collected across sites by regular sampling and monitoring.

2.2 Soil sampling and analysis

Soil samples from 12 alfalfa farms were collected using a stainless-steel hand auger, air-dried, crushed, sieved (0.5 mm), and pooled after removing debris. For heavy metal analysis, 100 g of each sample was pulverized and filtered (0.15 mm). Using the USEPA 3051 A method, 0.5 g of soil and blanks (deionized water) were digested with 9 ml HNO₃ and 3 ml HCl at 175 ± 5 °C and 1200 W. After cooling, samples were filtered (Whatman No. 42) and diluted to 50 mL with distilled water and heavy metal concentrations were determined using

ICP-OES. Calcium carbonate content was measured via the calcimeter method, which quantifies CO_2 released from the reaction with HCl (Serrano et al. 2005; Patra et al. 2020). Soil organic matter and organic carbon were estimated using the Loss on Ignition (LOI) method, involving drying at 105°C for 24 h, followed by combustion at 550°C for 3 h (Kumar et al. 2019). Organic carbon was calculated as per Patra et al. (2020). Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) were determined by titration with 0.01N sulfuric acid using phenolphthalein and methyl red indicators. Soil texture was assessed using the hydrometer method, following Mishra et al. (2022). Samples were dispersed in sodium hexametaphosphate, transferred to sedimentation cylinders, and particle size distribution (sand, silt, clay) was calculated. Soil moisture content was measured using the gravimetric method, based on weight loss after drying (Ghosh et al. 2019).

2.3 Plant sampling and analysis

Alfalfa shoot samples were collected during winter from the same 12 farms used for soil sampling, with composite samples taken from multiple locations per site. Heavy metal analysis was performed using microwave digestion with a Milestone Start D, SK-10 high-pressure rotor, following USEPA protocols. Plant moisture content, essential for assessing health and water use efficiency, was determined using the gravimetric method (Kumar et al. 2019). Samples were weighed, oven-dried at 70°C for 48 h until constant weight, cooled in a desiccator, and reweighed to calculate dry weight. Chloride content in soil and plants was analyzed via titration with AgNO_3 using potassium chromate (5%) as an indicator (Sharma et al. 2020).

2.4 Contamination and pollution indices

Several indices are used to evaluate soil contamination and environmental risk. These include the Contamination Factor (Cf), Pollution Load Index (PLI), and Modified Degree of Contamination (mCd) to assess pollutant levels. The Enrichment Factor (EF) and Geo-accumulation Index (Igeo) help identify anthropogenic and historical pollution (Al-Shali et al. 2024). The Bioaccumulation Factor (BAF) and Transfer Factor (TF) assess pollutant uptake and movement in plants, which is vital for food safety in crops for animals. These tools support risk assessments, inform safety thresholds, and promote awareness among farmers (LaBauve et al. 1988).

3 Statistical analysis

Data analysis was conducted using ANOVA in SPSS Statistics 25 to evaluate the effects of cutting time, cultivar, and water type, with means compared using Duncan's Multiple

Range Test ($P \leq 0.05$). Pearson correlation assessed relationships between heavy metals and soil properties, while multi-variate ANOVA examined combined factor effects (Mishra et al. 2022). Principal Component Analysis (PCA) identified key contributors to variation in metal concentrations. Statistical methods followed as per our previous study (Al-Shali et al. 2024).

4 Results

4.1 Soil physico-chemical properties

The physiochemical properties of soil of alfalfa fields irrigated with different water sources is shown in Table 1. Soil pH varied among sites, with the control site showing the highest pH, followed by TWW-irrigated, mixed-water irrigated, and STP-adjacent soils (Fig. 1a). USDA classification indicated that control, MW-, and STP-irrigated soils were predominantly alkaline, while TWW-irrigated soils were evenly distributed between alkaline and moderately alkaline categories. Electrical conductivity (EC) varied significantly across sites, with the highest EC recorded in STP-adjacent soils, followed by MW-irrigated, TWW-irrigated, and control soils (Fig. 1b). These results align with studies linking irrigation sources and sewage proximity to soil salinity, with elevated levels potentially impacting crop productivity.

Whereas the Sodium (Na) levels were highest in mixed-water irrigated soils followed by TWW, STP-adjacent and control, with no significant difference between MW and TWW. Risks such as soil hardening and decreased permeability were indicated by all values exceeding WHO guidelines (Xu et al. 2023). The amounts of chloride (Cl^-) were lowest in areas watered by TWW and greatest in soils next to STP. There were no discernible interaction effects, indicating that the primary determinant of chloride distribution is irrigation water quality. With an average of 22.1–23.3%, calcium carbonate (CaCO_3) concentrations did not significantly differ between sites, suggesting a consistent distribution. The sodium adsorption ratio (SAR) values, on the other hand, varied greatly, with STP-adjacent soils having the highest SAR values. Mixed-water, TWW-irrigated, and control soils were next. Elevated SAR near the STP reflects the influence of high-SAR irrigation water, while lower values at the control site underscore the impact of water quality on sodium dynamics.

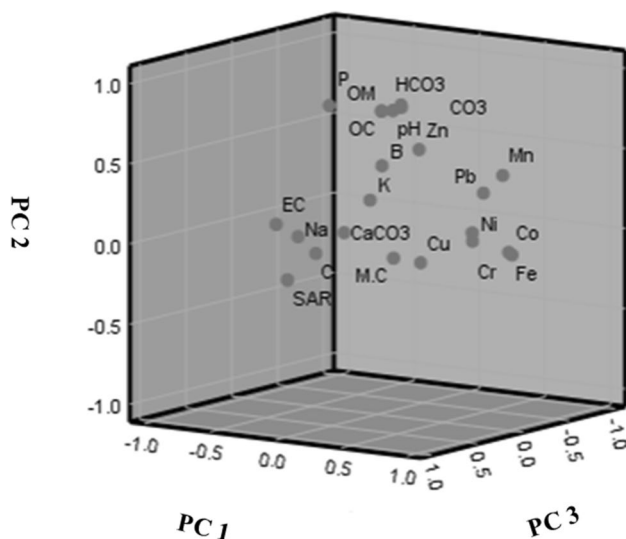
4.2 Heavy metal contamination in soil of Alfalfa sites irrigated with different water sources

The heavy metals and metalloids concentration in soils Alfalfa sites irrigated with different water sources is shown in Table 2. Boron (B) concentrations were highest in control

Table 1 Physico-chemical characteristics of soils at different sites

Parameter	Control Site	TWW-Irrigated Soils	Mixed Water-Irrigated Soils	Soils near STP
pH	8.45 ± 0.16	8.38 ± 0.25	8.35 ± 0.21*	8.34 ± 0.22*
Electrical Conductivity (µS/cm)	1934.81 ± 822.41	2391.92 ± 817.78	3185.53 ± 1073.17*	4850.14 ± 885.17**
Sodium (mg/L)	1605 ± 582.47	2322.50 ± 656.05**	2396.94 ± 665.93**	2003.89 ± 544.19*
Chloride (mg/kg)	297.19 ± 79.77	239.86 ± 78.05*	369.10 ± 79.35*	473.54 ± 93.66**
Potassium (K ⁺) (mg/kg)	1917.22 ± 442.83	1943.19 ± 394.78	1775.78 ± 443.05	1447.50 ± 410.48*
Total Phosphorus (mg/kg)	274.94 ± 129.99	446.33 ± 163.81*	295.67 ± 112.75	366.81 ± 147.05*
Carbonate (mg/L)	41.54 ± 17.94	22.44 ± 13.85**	28.28 ± 15.80*	41.30 ± 17.86
Bicarbonate (mg/L)	312.95 ± 91.07**	—	261.70 ± 91.57*	339.03 ± 106.36
Calcium Carbonate (%)	22.8	22.1	23.3	22.7
SAR (meq/L) ^{1/2}	2.65 ± 0.71	3.59 ± 0.76	4.16 ± 0.90	4.85 ± 0.89
Organic Matter (%)	4.25 ± 0.79	3.67 ± 0.64	3.60 ± 0.79	4.38 ± 0.71
Organic Carbon (%)	2.38 ± 0.45	2.05 ± 0.36	2.02 ± 0.44	2.45 ± 0.40
Moisture Content (%)	15.33 ± 2.99	15.55 ± 3.56	13.60 ± 4.17	13.16 ± 2.96

*statistically significant $p < 0.05$; **highly statistically significant $p < 0.01$

**Fig. 1** Principal component plot in rotated space for the soil physico-chemical characteristics and heavy metals or metalloids in soils of Alfalfa sites

site, followed by STP-adjacent, TWW-irrigated, and MW-irrigated soils. No significant difference was observed between TWW and MW sites, suggesting limited influence of irrigation water. Elevated B levels in the control site may reflect fertilizer or organic input use. Similarly, Cobalt (Co) levels varied significantly, highest in the control site, followed by STP-adjacent, MW, and TWW-irrigated soil. The absence of Cobalt in irrigation water suggests natural or agricultural sources. All values remained below FAO/WHO limits (50 mg/kg). However, Chromium (Cr) concentrations were highest in STP-adjacent soils and the control site, while lower levels were found in MW and TWW-irrigated soils.

No significant differences were observed between control and STP or between TWW and MW sites. Cr levels in control and STP soils exceeded FAO/WHO and EU guidelines, highlighting potential environmental concerns. Copper (Cu), an essential micronutrient for plant, animal, and human health, naturally occurs in soils with concentrations influenced by both geological and anthropogenic factors. In this study, Cu concentrations in alfalfa field soils showed significant site-specific variation. The highest Cu levels were observed in mixed water-irrigated soils, followed by control site soils and TWW-irrigated soils, with the lowest concentration near the sewage treatment plant.

All Cu concentrations were below the FAO/WHO permissible limit of 100 mg/kg (Ogundele and Adio 2015). Iron (Fe) concentrations also varied significantly, with the highest levels in control soils, followed by STP-adjacent soils, mixed water-irrigated soils, and the lowest in TWW-irrigated soils. All Fe contents, in spite of these variations, were much below the FAO/WHO recommendation of 50 g/kg, indicating that irrigation water sources pose no danger (Orhue and Chibuzo 2011). There were noticeable site-specific differences in manganese (Mn) concentrations. Control site soils had the greatest Mn levels, followed by soils next to the sewage treatment plant (STP), soils that were irrigated with TWW, and soils that were irrigated with mixed water. Notwithstanding these variations, all Mn values were still much below the 2000 mg/kg FAO/WHO acceptable limit (Rata et al. 2023). The amounts of nickel (Ni) were lowest in TWW-irrigated soils, followed by mixed water-irrigated soils, control soils, and STP-adjacent soils. Interestingly, all Ni contents were higher than the FAO/WHO-recommended threshold of 50 mg/kg, suggesting possible health and environmental hazards.

Table 2 Heavy Metal Concentrations (Mean $\pm$ SD, mg/kg unless stated) in Alfalfa Field Soils Across Different Irrigation Sites

Metal	Control Site	Near STP	TWW-Irrigated	Mixed Water (MW)	Permissible Limit
Boron (B)	30.25 $\pm$ 11.17**	26.90 $\pm$ 9.43	23.29 $\pm$ 10.74	21.71 $\pm$ 9.57*	25 mg/kg (Brdar-Jokanović, 2020)
Cadmium (Cd)	ND	ND	ND	ND	–
Cobalt (Co)	41.70 $\pm$ 7.15**	31.61 $\pm$ 7.50	23.04 $\pm$ 7.03	23.29 $\pm$ 7.79*	50 mg/kg (FAO/WHO)
Chromium (Cr)	234.88 $\pm$ 40.20*	236.26 $\pm$ 34.85	124.84 $\pm$ 39.42	142.64 $\pm$ 34.62*	100 (FAO/WHO); 150 (EU)
Copper (Cu)	45.92 $\pm$ 7.14	35.37 $\pm$ 6.05*	44.33 $\pm$ 5.28**	47.70 $\pm$ 6.40	100 mg/kg (FAO/WHO)
Iron (Fe) (g/kg)	32.95 $\pm$ 3.67**	26.24 $\pm$ 3.33	19.65 $\pm$ 3.36	20.69 $\pm$ 3.31*	50 g/kg (FAO/WHO)
Manganese (Mn)	470.11 $\pm$ 42.26*	397.01 $\pm$ 55.86	347.91 $\pm$ 41.49	322.20 $\pm$ 52.20*	2000 mg/kg (FAO/WHO)
Nickel (Ni)	680.28 $\pm$ 147.72*	660.92 $\pm$ 100.03	330.72 $\pm$ 139.06	361.57 $\pm$ 124.42*	50 mg/kg (FAO/WHO)
Lead (Pb)	5.73 $\pm$ 0.90**	4.57 $\pm$ 1.15	3.13 $\pm$ 1.12	5.15 $\pm$ 1.07*	100 mg/kg (FAO/WHO)
Zinc (Zn)	42.16 $\pm$ 6.62**	42.05 $\pm$ 9.96	26.51 $\pm$ 9.20*	31.31 $\pm$ 9.73**	300 mg/kg (FAO/WHO)

The acceptable FAO/WHO threshold of 100 mg/kg was maintained despite considerable variation in lead (Pb) readings (Rezaeian and Tohidi Moghadam 2016). Soils at the control site had the highest Pb levels, followed by soils that were mixed water-irrigated, near to STP, and irrigated with TWW. The amounts of zinc (Zn) also differed from site to site, with control soils having the greatest levels, followed closely by STP-adjacent soils, mixed water-irrigated soils, and TWW-irrigated soils having the lowest values.

4.3 Physicochemical properties of Alfalfa shoot cultivated with different irrigation water sources

The moisture content in alfalfa showed no significant differences across irrigation sites. While sodium content varied significantly with the highest levels at the STP site, followed by mixed water, control and the lowest at the TWW site. Chloride content also differed across sites, with the highest in the control site, followed by STP, mixed water, and the lowest in TWW. Potassium and Phosphorus levels were highest in TWW-irrigated alfalfa, followed by mixed water, control, and lowest near STP (Table 3). These findings highlight the influence of irrigation sources on nutrient levels in alfalfa.

4.4 Heavy metal contamination in Alfalfa shoot

The contamination of heavy metals in Alfalfa Shoot irrigated with different water sources is shown in Table 4. In which, Boron (B) concentrations in alfalfa varied across different irrigation sources, with the highest levels in mixed water-irrigated alfalfa/followed by treated wastewater (TWW) and STP-irrigated sites. The lowest concentration was recorded at the control site irrigated with groundwater. No significant differences were observed between STP and TWW-irrigated alfalfa. Cobalt (Co) levels showed slight variations across sites, with the highest average at the control site and lowest Co concentration was found in alfalfa irrigated with TWW. However, no significant differences were detected between STP, TWW and control site values. Chromium (Cr) concentrations remained consistent across all irrigation sources, with values ranging from 0.50 to 0.53 mg/kg, all well below WHO/FAO safety limits (Samantaray et al. 1998; Serrano et al. 2005; Sharma et al. 2020). Copper (Cu) levels varied significantly, with the highest recorded at the control site followed by mixed water-irrigated alfalfa and the lowest at STP-irrigated sites. The TWW-irrigated site also showed Cu deficiency (below 3 mg/kg).

However, Iron (Fe) concentrations were highest in TWW-irrigated alfalfa, followed by mixed water and STP-irrigated sites. The control site had the lowest Fe concentration. All recorded Fe values were below WHO/FAO permissible

Table 3 Nutrient and Moisture Content of Alfalfa shoot Across Different Irrigation Sites

Parameter	Control (Mean $\pm$ SD)	TWW (Mean $\pm$ SD)	Mixed Water (Mean $\pm$ SD)	STP (Mean $\pm$ SD)
Moisture Content (%)	66.44 $\pm$ 3.95	67.14 $\pm$ 3.75	66.03 $\pm$ 4.44	65.60 $\pm$ 4.61
Sodium (mg/kg)	4230.56 $\pm$ 1640.18	3872.22 $\pm$ 1517.44	4391.67 $\pm$ 1272.43	7480.56 $\pm$ 1419.42
Chloride (g/kg)	12.20 $\pm$ 2.13**	9.79 $\pm$ 2.14	11.61 $\pm$ 2.58*	12.64 $\pm$ 2.83**
Potassium (g/kg)	15.13 $\pm$ 2.20	18.22 $\pm$ 2.14**	17.82 $\pm$ 2.17**	14.27 $\pm$ 1.59
Phosphorus (g/kg)	3.53 $\pm$ 4.38	3.73 $\pm$ 5.26**	3.78 $\pm$ 4.07	3.41

Table 4 Heavy Metal Concentrations (Mean $\pm$ SD, mg/kg unless stated) in Alfalfa shoots Across Different Irrigation Sites

Heavy Metal	Control Site (mg/kg)	STP Site (mg/kg)	TWW Site (mg/kg)	Mixed Water Site (mg/kg)	FAO/WHO Limit (mg/kg)
Boron (B)	61.00 $\pm$ 9.48	73.81 $\pm$ 12.27*	78.42 $\pm$ 8.48**	87.44 $\pm$ 10.36	30 (Melsted et al., 1969)
Cobalt (Co)	0.50 $\pm$ 0.07**	0.42 $\pm$ 0.05	0.43 $\pm$ 0.08*	0.50 $\pm$ 0.08	50
Chromium (Cr)	0.53 $\pm$ 0.07	0.50 $\pm$ 0.05	0.50 $\pm$ 0.06	0.52 $\pm$ 0.07	20
Copper (Cu)	4.11 $\pm$ 0.91**	2.04 $\pm$ 0.75	2.49 $\pm$ 0.65*	3.33 $\pm$ 0.65	40
Iron (Fe)	215.66 $\pm$ 67.17	219.78 $\pm$ 61.47**	281.12 $\pm$ 48.28*	241.01 $\pm$ 49.88	425
Manganese (Mn)	21.91 $\pm$ 2.50	20.94 $\pm$ 3.33**	26.89 $\pm$ 3.26*	23.33 $\pm$ 3.04	500
Nickel (Ni)	4.00 $\pm$ 0.85*	4.22 $\pm$ 1.04	2.95 $\pm$ 0.79	3.14 $\pm$ 1.02**	67
Lead (Pb)	0.53 $\pm$ 0.14**	0.41 $\pm$ 0.12*	0.45 $\pm$ 0.16	0.39 $\pm$ 0.11	5
Zinc (Zn)	18.66 $\pm$ 5.31**	16.98 $\pm$ 5.41	8.88 $\pm$ 3.91*	13.49 $\pm$ 5.27*	100

limits (Turekian and Wedepohl 1961; Singh et al. 2010). Manganese (Mn) levels in alfalfa varied across sites, with the highest concentration in alfalfa irrigated with treated wastewater (TWW), followed by mixed water and the control site. The lowest level was recorded near the sewage treatment plant (STP). Differences between the control and mixed water-irrigated sites, as well as between the control and STP sites, were not significant. Mn accumulation was influenced by soil properties rather than irrigation sources, with all values remaining below the FAO/WHO safety threshold of 500 mg/kg.

Nickel (Ni) levels also varied, with the highest concentration near STP, followed by the control site and mixed water-irrigated alfalfa. The lowest level was in TWW-irrigated alfalfa. No significant differences were observed between the STP and control sites or between TWW and mixed water sites. Despite high soil Ni levels, plant uptake remained below the FAO/WHO limit of 67 mg/kg.

Lead (Pb) concentrations were highest at the control site, followed by TWW-irrigated, STP, and mixed water-irrigated alfalfa. Pb levels remained well below FAO/WHO limits (5 mg/kg) and NRC feed safety standards (5–30 mg/kg), indicating minimal contamination risk.

Zinc (Zn) levels were highest at the control site, followed by the STP site (16.98 $\pm$ 5.41 mg/kg) and mixed water-irrigated alfalfa. The lowest concentration was found in TWW-irrigated alfalfa. No significant differences were noted between the control and STP sites. All Zn levels were below the FAO/WHO limit (100 mg/kg), with deficiencies observed across all sites, suggesting the need for supplementation to improve alfalfa growth.

4.5 Correlation analysis of physicochemical properties and heavy metals or metalloids in soils and alfalfa

Pearson correlation analysis revealed strong positive relationships ($R^2 > 0.9$) between organic matter (OM) and organic carbon (OC), along with significant correlations ($p < 0.01$) between carbonate and bicarbonate, and between

zinc (Zn) and both OM and OC. Heavy metals such as cobalt (Co), chromium (Cr), iron (Fe), manganese (Mn), nickel (Ni), and lead (Pb) were also strongly correlated, suggesting common lithological or anthropogenic sources. Moderate correlations between pH and phosphorus (P), carbonate, bicarbonate, OM, and OC indicate pH's influence on metal mobility. Electrical conductivity (EC) was correlated with chloride (Cl), and potassium (K) with calcium carbonate (CaCO_3) and boron (B), reflecting salinity and alkalinity effects on nutrient dynamics. Negative correlations between sodium (Na) and metals like Co and Cr suggest Na may reduce their availability. Principal Component Analysis (PCA) identified five components explaining 79.39% of total variance. These components reflected influences of lithology, carbon cycling, salinity, alkalinity, and soil moisture on soil properties (Table 5, 6).

The correlation analysis (Table 3) revealed significant relationships between soil properties and nutrient uptake in alfalfa. A strong positive correlation ($p < 0.01$) was observed between soil chloride (Cl) and sodium (Na) content in alfalfa. Moderate positive correlations included soil pH with alfalfa moisture content, soil electrical conductivity (EC) with Na in alfalfa, and soil Na with alfalfa potassium (K). Additionally, soil K and phosphorus (P) were linked to higher moisture content in alfalfa, while soil sodium adsorption ratio (SAR) positively correlated with plant Na levels. Other notable associations included soil boron (B) with alfalfa moisture, and soil nickel (Ni) with zinc (Zn) in alfalfa ($p < 0.01$).

Weaker positive correlations were found between soil pH and alfalfa P, soil EC and B, and soil Na with alfalfa P and B. Soil Cl showed links with Cl and chromium (Cr) in alfalfa, while soil P correlated with alfalfa P. Carbonate and bicarbonate in soil were positively associated with alfalfa moisture and Zn. Soil SAR was linked to B in alfalfa, and soil OM and OC correlated with soil B. Additional associations included soil B with Cl, soil cobalt (Co) with alfalfa Zn, and soil Cr with alfalfa Ni. Elements like copper (Cu), iron (Fe), manganese (Mn), Ni, Pb, and Zn in soil showed

Table 5 Pearson correlation matrix between physicochemical properties and Heavy metal in the soils of Alfalfa sites

Parameters	pH	EC	Na	Cl	K	P	CO ₃ ²⁻	HCO ₃ ⁻	CaCO ₃	SAR	OM	OC	M.C	B	Co	Cr	Cu	Fe	Mn	Ni	Pb
EC	-0.124																				
Na	0.135	0.201																			
Cl	-0.096	0.677	0.262																		
K	0.250	-0.211	0.422	-0.004																	
P	0.551	0.211	0.287	-0.073	0.239																
CO ₃ ²⁻	0.622	0.210	-0.055	0.221	0.052	0.486															
HCO ₃ ⁻	0.594	0.121	-0.182	0.131	0.021	0.488	0.839														
CaCO ₃	0.117	0.110	0.357	0.385	0.517	0.074	0.129	0.014													
SAR	-0.224	0.436	0.110	0.497	-0.327	-0.149	-0.126	-0.086	0.101												
OM	0.517	0.295	-0.068	0.285	0.190	0.505	0.726	0.679	0.256	-0.068											
OC	0.517	0.294	-0.068	0.285	0.190	0.505	0.726	0.678	0.256	-0.068	1.000										
M.C	-0.213	-0.297	-0.351	-0.242	0.066	-0.199	-0.195	-0.158	0.004	0.069	-0.176	-0.175									
B	0.429	0.158	0.390	0.322	0.536	0.421	0.474	0.268	0.469	-0.201	0.547	0.547	-0.099								
Co	0.015	-0.330	-0.578	-0.039	-0.316	-0.355	0.168	0.166	-0.205	-0.200	0.092	0.092	-0.013	-0.044							
Cr	-0.028	0.046	-0.533	0.276	-0.395	-0.225	0.357	0.358	-0.073	0.046	0.353	0.352	-0.017	0.098	0.799						
Cu	-0.160	-0.493	0.011	-0.399	0.082	-0.205	-0.283	-0.153	-0.186	-0.244	-0.366	-0.365	0.187	-0.295	0.017	-0.263					
Fe	-0.009	-0.296	-0.475	0.002	-0.162	-0.411	0.227	0.165	-0.046	-0.218	0.141	0.141	0.090	0.101	0.835	0.786	-0.015				
Mn	0.278	-0.266	-0.477	-0.124	-0.160	0.052	0.544	0.512	-0.188	-0.319	0.424	0.424	-0.008	0.187	0.721	0.732	-0.048	0.720			
Ni	0.023	0.053	-0.431	0.097	-0.397	-0.245	0.257	0.239	-0.197	-0.085	0.206	0.206	-0.164	0.037	0.664	0.797	-0.351	0.728	0.692		
Pb	0.128	-0.114	-0.399	0.041	-0.071	-0.013	0.457	0.402	-0.047	-0.190	0.419	0.420	0.136	0.273	0.584	0.685	0.031	0.679	0.769	0.558	
Zn	0.489	0.241	0.148	0.430	0.208	0.309	0.750	0.619	0.333	-0.184	0.706	0.706	-0.373	0.640	0.261	0.464	-0.273	0.399	0.515	0.390	0.554

Table 6 Pearson's correlation coefficient between physicochemical Properties and Heavy Metals or Metalloids in Soils and Alfalfa

Parameters	pH of the soil	EC of the soil	Na ⁺ in the soil	Cl ⁻ in the soil	K ⁺ in the soil	P in the soil	CO ₃ ²⁻ in the soil	HCO ₃ ⁻ in the soil	CaCO ₃ in the soil	SAR in the soil	OM in the soil	OC in the soil	M.C of the soil	B in the soil	Co in the soil	Cr in the soil	Cu in the soil	Fe in the soil	Mn in the soil	Ni in the soil	Pb in the soil	Zn in the soil
Moisture content in alfalfa	0.513	0.080	0.462	0.103	0.587	0.532	0.443	0.337	0.386	-0.230	0.379	0.380	-0.164	0.593	-0.385	-0.318	-0.199	-0.261	0.002	-0.242	0.009	0.428
Na in alfalfa	-0.189	0.621	0.310	0.745	-0.134	-0.090	0.123	-0.021	0.357	0.597	0.156	0.156	-0.149	0.265	-0.042	0.287	-0.452	0.075	-0.046	0.243	0.102	0.325
Cl in alfalfa	-0.066	0.295	0.170	0.494	0.050	-0.090	0.112	-0.027	0.207	0.026	0.155	0.155	-0.193	0.327	0.080	0.241	-0.050	0.173	0.063	0.250	0.117	0.307
K in alfalfa	0.217	-0.221	0.616	-0.172	0.383	0.218	-0.198	-0.327	0.293	0.002	-0.128	-0.128	-0.133	0.215	-0.439	-0.566	0.017	-0.432	-0.418	-0.477	-0.359	-0.145
P in alfalfa	0.432	-0.053	0.472	-0.076	0.428	0.461	0.127	0.068	0.260	-0.194	0.184	0.184	-0.306	0.385	-0.322	-0.370	-0.183	-0.297	-0.210	-0.261	-0.183	0.176
B in alfalfa	-0.159	0.383	0.318	0.075	-0.210	0.077	-0.177	-0.247	-0.148	0.395	-0.264	-0.263	-0.143	-0.257	-0.520	-0.453	0.080	-0.667	-0.534	-0.425	-0.435	-0.385
Co in alfalfa	-0.099	-0.201	-0.109	-0.019	0.015	-0.301	-0.084	-0.110	-0.145	-0.312	-0.194	-0.195	-0.049	-0.010	0.286	0.154	0.242	0.298	0.115	0.127	0.097	0.040
Cr in alfalfa	-0.327	-0.012	0.212	0.304	0.220	-0.467	-0.265	-0.358	0.265	-0.031	-0.137	-0.137	-0.186	0.063	0.056	-0.024	0.101	0.107	-0.128	-0.026	-0.110	0.020
Cu in alfalfa	0.128	-0.322	0.146	-0.127	0.418	-0.196	0.032	-0.039	0.220	-0.456	-0.027	-0.026	0.017	0.272	0.050	-0.152	0.450	0.201	0.117	0.004	0.135	0.175
Fe in alfalfa	-0.180	-0.142	0.087	-0.225	-0.074	-0.237	-0.448	-0.448	-0.150	0.084	-0.447	-0.447	0.023	-0.374	-0.120	-0.309	0.116	-0.258	-0.312	-0.213	-0.262	-0.450
Mn in alfalfa	-0.059	-0.156	0.127	-0.403	0.114	0.178	-0.418	-0.447	-0.139	-0.094	-0.296	-0.296	0.126	-0.033	-0.265	-0.439	0.038	-0.348	-0.331	-0.323	-0.299	-0.478
Ni in alfalfa	0.194	0.259	-0.110	0.276	-0.113	-0.108	0.258	0.151	0.003	-0.053	0.241	0.241	-0.270	0.168	0.284	0.365	-0.476	0.364	0.269	0.495	0.310	0.436
Pb in alfalfa	0.205	-0.166	0.030	-0.206	0.263	-0.016	0.041	-0.003	-0.094	-0.247	0.010	0.010	0.004	0.117	-0.009	-0.127	-0.073	0.025	0.098	0.151	0.068	0.007
Zn in alfalfa	0.093	0.071	-0.591	0.001	-0.372	-0.086	0.333	0.431	-0.168	0.038	0.320	0.320	0.169	-0.141	0.400	0.528	-0.015	0.461	0.491	0.543	0.447	0.178

various positive correlations ($p < 0.01$) with Ni, Zn, moisture, Na, and Cl in alfalfa.

In contrast, moderate negative correlations were found between soil Na and alfalfa Zn, as well as between Co, Mn, and Fe in soil and alfalfa B. A significant negative correlation was also observed between soil Cr and alfalfa K ($p < 0.01$) (Figs 2, 3, 4, 5 and 6).

4.6 Evaluation of pollution indices

Boron (B) contamination remained low ($C_f < 1$) at all sites. Cobalt (Co) and chromium (Cr) showed moderate contamination, while copper (Cu) ranged from moderate at the control and mixed water sites to low by 2021, except at the mixed site, where it stayed moderate. The sewage treatment plant (STP) site consistently had low Cu levels. Nickel

(Ni) showed the highest contamination, with very high levels ($C_f \geq 6$) at the control and STP sites, and high levels ($3 \leq C_f < 6$) at the TWW and mixed sites, though levels declined over time—likely due to leaching or plant uptake. Overall, the control site had the highest metal accumulation. Boron peaked at the control site (0.30) and was lowest at the mixed site (0.22). Co and Cr were highest at the control (2.19) and STP sites (2.63), respectively. Fe, Mn, Pb, and Zn were also most concentrated at the control site, and lowest at the TWW site, showing irrigation source impacts.

However, while pollutant concentrations remain within safe thresholds, continuous monitoring is crucial, especially in arid regions like Oman, where evaporation rates are high and salts or metals can accumulate over time (Zayed and Terry 2003; Xu et al. 2023). Long-term application of TWW could lead to subtle shifts in soil chemistry,

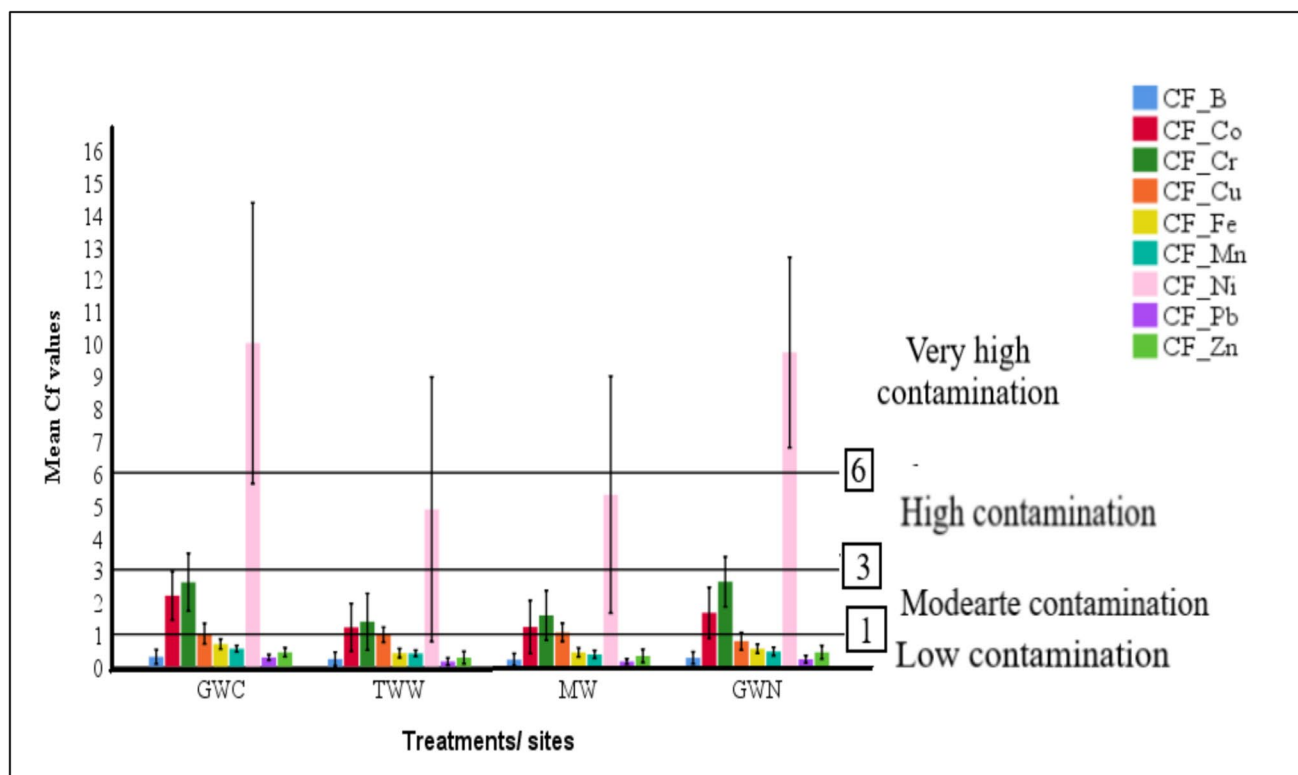


Fig. 2 Contamination factor ($Cf \pm Std. dev$) for heavy metals in the soil of Alfalfa at different sites

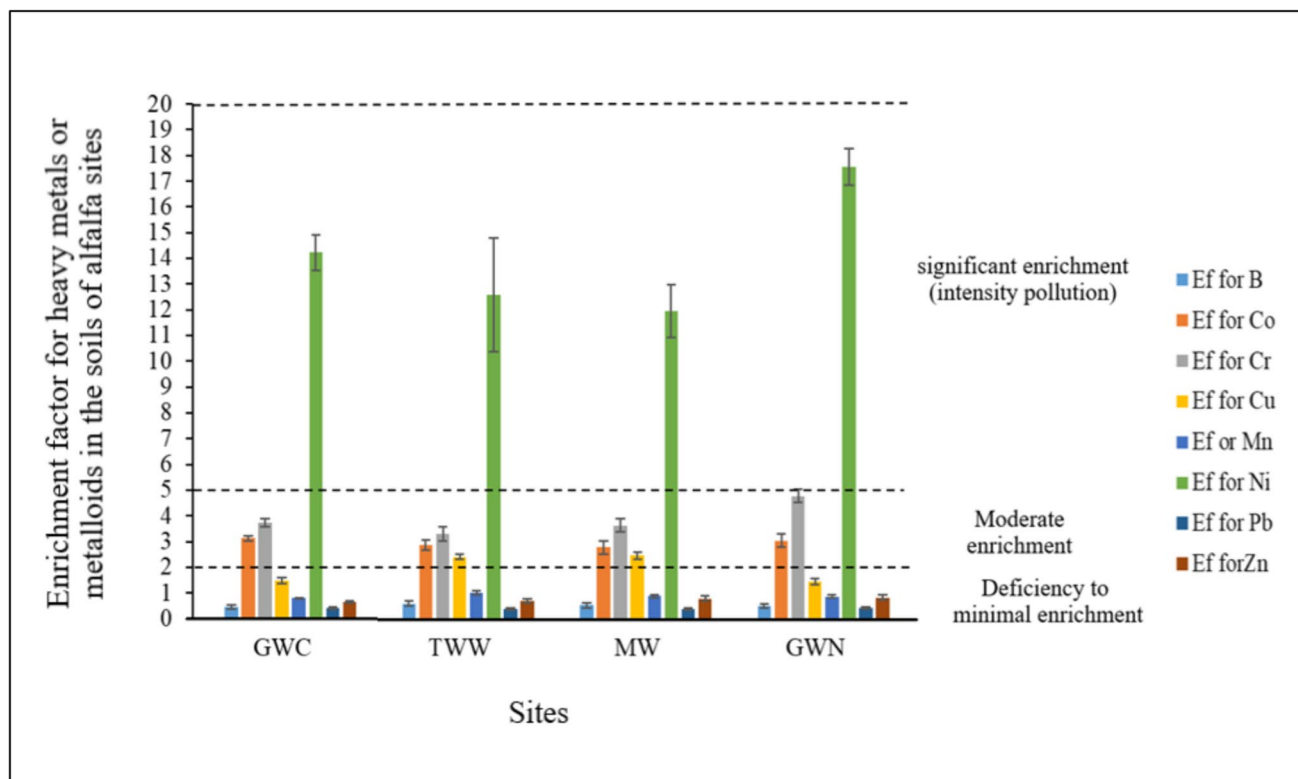


Fig. 3 The Enrichment Factor (EF) for Heavy Metals in Soil of Alfalfa Fields Irrigated with Different Irrigation Water Sources

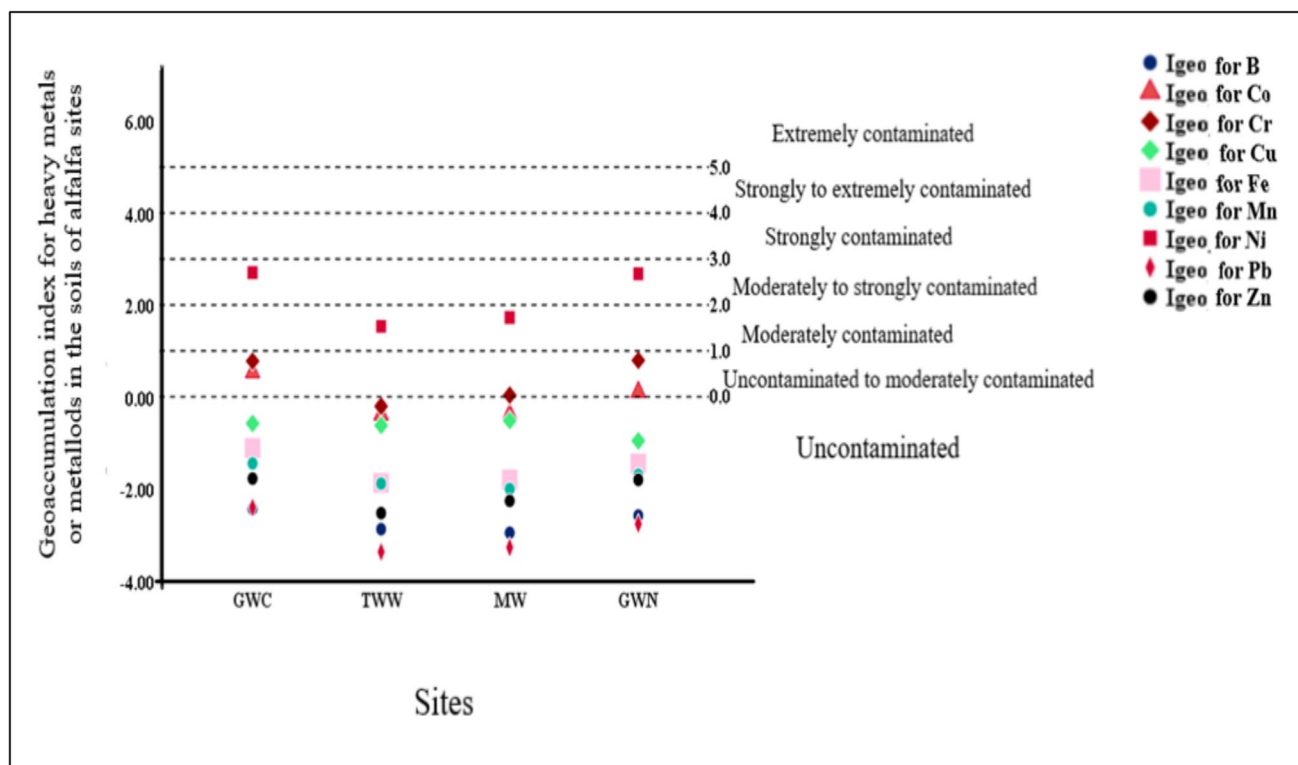
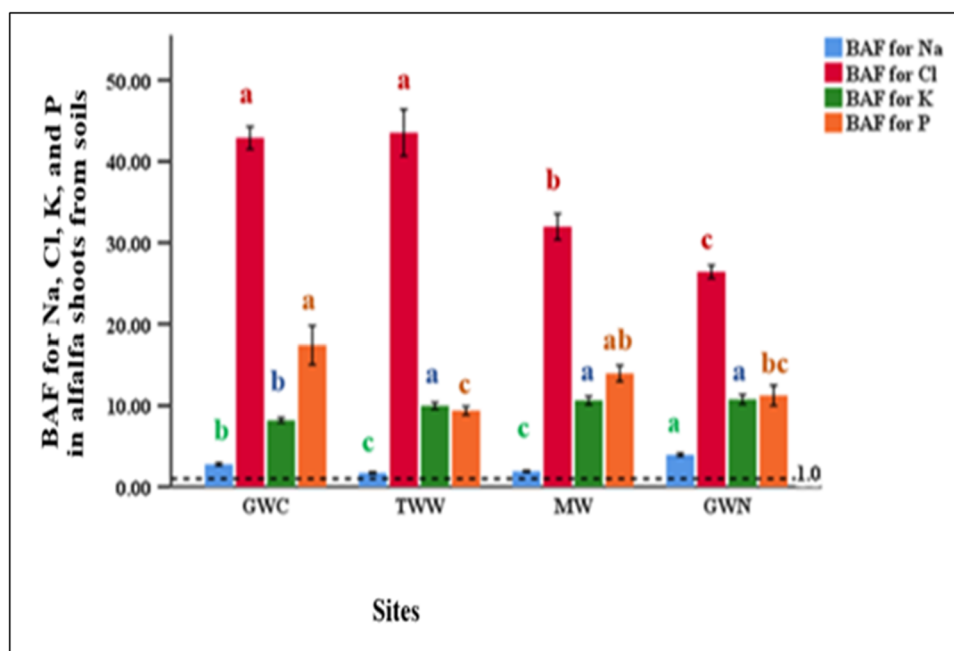


Fig. 4 Geoaccumulation index (Igeo) plot for the detected heavy metals/metal in soils of Alfalfa sites irrigated with different water sources

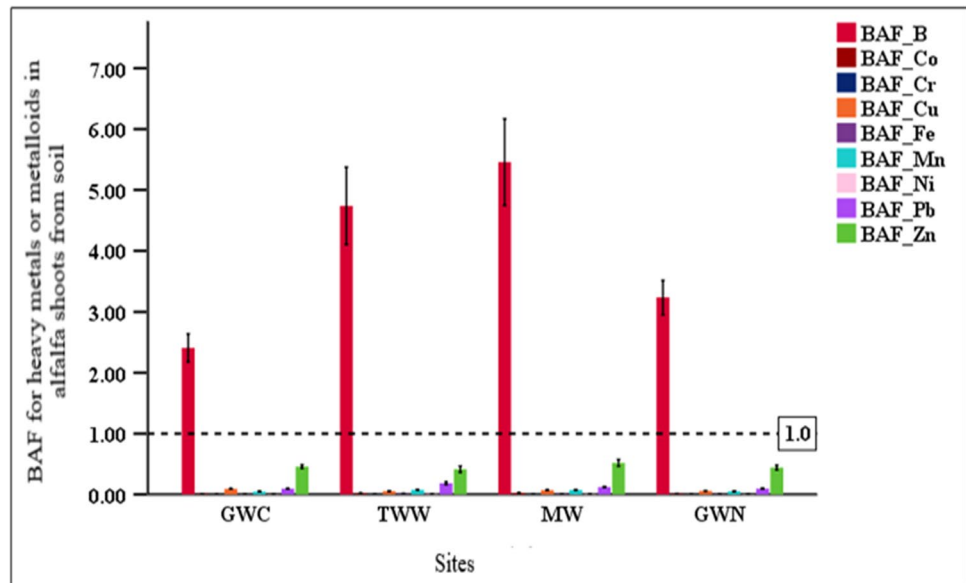
Fig. 5 Bioaccumulation factors for Na, Cl, K and P from soil to Alfalfa shoots



potentially impacting soil microbial activity, pH balance, and nutrient availability. Alfalfa (*Medicago sativa*), the plant used in this study, is a key forage crop in Oman, supporting the country's growing dairy and livestock sectors. The

results indicate no adverse plant responses to the treated wastewater irrigation in terms of growth performance, biomass yield, or visual signs of stress, suggesting that TWW can be a viable water resource for forage production.

Fig. 6 Bioaccumulation factor of detected heavy metals in alfalfa shoots from soils of studied sites



The enrichment factor (EF) for Pb, B, Co, Mn, Cr, Cu, Ni, and Zn was calculated using Fe as the reference element, with Cd excluded due to its absence. EF values for B, Mn, Cr, Pb, and Zn indicated minimal enrichment ($EF \leq 2$) at all sites and time points. Copper (Cu) showed moderate enrichment at the mixed water and TWW sites, while remaining minimally enriched at the control and STP sites. Nickel (Ni) displayed significant enrichment ($5 < EF \leq 20$) across all sites, peaking at the STP and control sites, suggesting inputs from fertilizers, atmospheric deposition, or native soil content. The geoaccumulation index (Igeo) for B, Cu, Mn, Fe, Pb, and Zn was ≤ 0 , indicating no contamination. Co showed minimal contamination at the control and STP sites but none at the TWW and mixed sites. Cr exhibited slight contamination at the STP and control sites. Ni posed the highest risk, with Igeo values indicating moderate to strong contamination, especially at the control (2.70) and STP (2.68) sites.

The bioaccumulation factor (BAF) for sodium (Na), chloride (Cl), potassium (K), and phosphorus (P) in alfalfa varied significantly across sites ($p < 0.05$), reflecting the influence of soil properties and irrigation types. Na BAF was highest at the STP site, followed by the control and mixed water sites, and lowest at the TWW site, indicating increased Na uptake in high-salinity areas. Cl BAF peaked at the TWW site, likely due to lower soil Cl levels, promoting greater plant absorption. For K, the highest BAF was observed at the STP site, with progressively lower values at the mixed water, TWW, and control sites, suggesting efficient K uptake, especially in saline conditions. P accumulation was greatest at the control site, followed by mixed water and STP sites, and lowest at the TWW site, likely due to favorable soil pH and organic matter at the control site. Overall, Cl showed the

highest BAF across all sites, with alfalfa favoring Cl over Na uptake.

The bioaccumulation factor (BAF) for heavy metals and metalloids in alfalfa varied significantly across sites ($p < 0.05$) (Fig. 5.17). Boron (B) was the only element with a BAF > 1 , indicating significant uptake, while all other metals had BAF values below 1, classifying alfalfa as a metal-excluder. The highest BAF for B was recorded at the mixed water-irrigated site, followed by the TWW site (and the STP site, with the lowest at the control site. (This suggests greater boron availability in mixed and TWW-irrigated soils. Metal accumulation patterns varied across sites. At the control and STP sites, the order was $B > Zn > Pb > Cu > Mn > Co > Fe > Ni > Cr$, whereas at the TWW and mixed water sites, it was $B > Zn > Pb > Mn > Cu > Co > Fe > Ni > Cr$. Heavy metal accumulation in plants is influenced by soil characteristics (pH, organic matter, CEC, texture), plant species-specific uptake mechanisms, environmental conditions (temperature, moisture, light), and agricultural practices such as irrigation and fertilization. Factors like competing ions, metal speciation, and mycorrhizal associations also play a role in determining metal bioavailability and uptake efficiency.

5 Discussion

Sustainable agriculture in arid regions such as Oman faces unique challenges, particularly concerning water scarcity, soil degradation, and the need to maintain high crop productivity. As Oman is classified among the most water-stressed countries globally, the exploration of alternative water sources for irrigation is not only a priority but a necessity. One increasingly adopted solution is the use

of treated wastewater (TWW) for irrigation. This practice offers both environmental and agricultural benefits, including the conservation of freshwater resources and the recycling of nutrients present in wastewater. However, it also raises critical concerns regarding soil quality, potential heavy metal accumulation, and its influence on crop growth, especially for sensitive forage crops like alfalfa (*Medicago sativa*), which is widely grown in Oman for livestock feed. Evaluating the long-term effects of TWW irrigation on these parameters is essential to ensure the sustainability and safety of agricultural systems (Al-Shali et al. 2024). Research conducted in Oman and other arid regions has shown that treated wastewater can enhance soil fertility due to its higher organic matter, nitrogen, and phosphorus content compared to freshwater. These nutrients can significantly boost alfalfa growth and yield, making TWW a viable option for increasing forage production in water-limited environments. Nonetheless, the presence of trace elements and heavy metals such as cadmium (Cd), lead (Pb), nickel (Ni), and chromium (Cr) in treated wastewater presents potential risks. While modern wastewater treatment processes can reduce these contaminants to permissible levels, their repeated application over time may lead to gradual accumulation in the soil, altering its chemical properties and potentially posing phytotoxic or ecotoxic risks. Studies in Oman indicate that heavy metal concentrations in soils irrigated with TWW generally remain below international safety thresholds, particularly when tertiary treatment and proper monitoring are implemented. Yet, the long-term impact on soil microbiology and structural integrity must be considered, as these subtle changes may influence nutrient cycling, water retention, and overall soil health. Additionally, alfalfa's uptake of certain heavy metals could affect its nutritional quality and safety as livestock feed. Research suggests that while alfalfa does accumulate some metals under TWW irrigation, most concentrations remain within acceptable ranges for animal consumption, especially when managed properly with periodic soil testing and crop monitoring. Furthermore, the efficiency of metal uptake is influenced by multiple factors including soil pH, organic matter content, irrigation frequency, and the duration of TWW use. The alkaline nature of Omani soils may help immobilize certain metals, reducing their bioavailability and uptake by plants. Nonetheless, a cautious approach is required, involving the integration of best management practices such as alternating TWW with freshwater, using phytoremediation species in rotation, or employing soil amendments like biochar to immobilize metals. Moreover, beyond the chemical implications, TWW irrigation can influence physical soil properties. Improvements in soil moisture content and organic matter can enhance root development and biomass production in alfalfa, contributing to higher forage yields. However, the potential for salinity build-up due to repeated

TWW use must also be addressed. Salt-sensitive crops like alfalfa can experience reduced growth and yield under elevated salinity levels, which can arise from the accumulation of sodium and chloride ions commonly found in treated wastewater. Salinity management through proper leaching practices, soil conditioning, and careful selection of salt-tolerant crop varieties can mitigate these risks. Overall, the strategic use of treated wastewater for irrigation in Oman aligns with national sustainability goals and global efforts to promote circular water use in agriculture. With climate change intensifying water scarcity in the region, the reuse of treated effluent represents a practical adaptation strategy that supports both food security and environmental conservation (Wanjala et al. 2019). However, ensuring the long-term sustainability of this practice necessitates continuous monitoring of soil and plant parameters, adoption of advanced wastewater treatment technologies, and the development of clear regulatory frameworks. Public awareness and farmer training are also vital to successful implementation, as misconceptions about wastewater reuse can hinder its acceptance. In conclusion, while the use of treated wastewater for irrigating alfalfa in Oman shows promise in terms of enhancing soil fertility and crop productivity, it requires a carefully balanced approach that addresses potential risks of heavy metal accumulation and soil degradation. Through integrated soil–water–plant management and robust environmental monitoring, Oman can harness the benefits of treated wastewater irrigation to support sustainable agriculture, improve water resource efficiency, and contribute to national food and fodder security in an environmentally responsible manner.

Although all soils showed Ni concentrations above the FAO/WHO permissible limit, this enrichment is unlikely to be solely due to treated wastewater (TWW) irrigation. Previous studies in arid regions, including Oman, indicate that Ni may originate from multiple sources like agricultural inputs and anthropogenic activities. Therefore, the elevated Ni levels observed in our study likely result from a combination of natural soil characteristics and long-term agricultural practices, with TWW contributing only partially.

The uptake of Pb and Cr by alfalfa was relatively low. The limited accumulation of these metals is primarily attributed to their low mobility and bioavailability in soil rather than to complete plant resistance. Specifically, Pb and Cr tend to strongly adsorb to soil particles, particularly in soils with higher clay content and organic matter, and they readily precipitate as insoluble compounds under neutral to alkaline pH conditions, which restricts their transfer into plant roots. In addition, plants such as alfalfa possess selective uptake mechanisms that favour essential nutrients over non-essential or toxic elements, further reducing Pb and Cr translocation into above-ground tissues.

6 Conclusion

This study shows that treated wastewater (TWW) and mixed water irrigation can reduce soil salinity and heavy metal accumulation compared to groundwater, supporting safer agricultural use when properly managed. Although soils near the sewage treatment plant (STP) showed elevated levels of chromium and nickel, alfalfa remained within FAO/WHO safety limits for animal consumption. Alfalfa effectively excluded harmful metals like Pb, Ni, and Cr. Regular monitoring, especially for Ni, is essential. Principal factors influencing soil properties include lithology, salinity, and human activity. Continued assessment and adaptive land management are vital to maintaining soil health and ensuring sustainable agricultural productivity. Treated wastewater irrigation showed a positive effect on soil properties, enhancing nutrient levels and improving alfalfa growth and yield. Theoretically, our findings contribute to a better understanding of how treated wastewater (TWW) interacts with soil properties to influence heavy metal mobility and plant uptake. Methodologically, the study demonstrates the utility of using alfalfa as a biological indicator crop and highlights the importance of applying standardized indices to assess contamination and risk. This approach supports sustainable agricultural practices, especially in water-scarce regions of Oman. Continuous monitoring of heavy metal concentrations in both soil and plants is crucial to prevent toxicity. Future research should focus on identifying plant varieties with higher tolerance to metal accumulation or incorporating soil amendments to reduce metal uptake.

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Data availability The datasets generated for this study are available on request to the all authors.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Conflict of interest Authors do not have any conflict of interest.

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