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Appraisal of phytotoxicity of heavy metals in radish (*Raphanus sativus* L.) grown in Sargodha district, Pakistan: A quantitative assessment

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Abstract
The freshwater shortage and increased domestic effluents have led the farmers to utilize untreated sewage water for irrigation, owing to population growth and urbanization in Pakistan. Though sewage water contains essential plant nutrients, it is also a foremost source of metal contamination within the food chain. This study aimed to compare heavy metals (Cd, Fe, Mn, Cu, Zn, Pb, Ni, and Cr) contamination in radish (*Raphanus sativus* L.) grown in soils irrigated with sewage water, tube well water, and canal water in Sillanwali and Sargodha of Punjab, Pakistan. The areas were evaluated for heavy metal contamination using soil quality indices, including contamination factor (CF), enrichment factor (EF), bioconcentration factor (BCF), estimated daily intake (EDI), and hazard quotient (HQ), which were duly computed for the collected samples. The physicochemical properties of the soil and water samples were also analyzed. The results indicated that the sewage-irrigated areas are more vulnerable to risk concerning metal contamination than those located along canals. Metal concentrations in sewage-irrigated areas were significantly higher in the edible parts of the vegetables; sewage water contained and transferred more metals than canal water; hence, it poses increased health and ecological risks. Peak concentrations were observed at site SW1 (sewage water, site 1) and were the lowest at site TW2 (tube well water irrigation, site 2). Since all metal index values fell below 1, it shows that all metal concentrations were within permissible limits.

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Introduction

Radish (*Raphanus sativus* L.) is a common root vegetable. It is well known for its normal white edible fleshy hypocotyls, which come in various skin colors, shapes, and sizes. Aside from these cultivars, because of the pigments in the xylem, there are also genotypes with purple and pink hypocotyls (Petropoulos et al., 2019; Swaamy, 2023). Despite being a favorite vegetable worldwide, radish is known for several health benefits (Gamba et al., 2021). For example, it has also been reported as a cancer prevention agent, antidiabetic, and antiatherosclerotic, because of being rich in levels of phenolic compounds, flavonoids, and anthocyanins (Ozaki et al., 2021). During the last few years, much research has been done on the clinical properties of radish, and it has been observed that it has huge amounts of minerals, L-ascorbic acid, and by-products that play a vital part in human well-being (El-Beltagi et al., 2022). For example, plant phenols have been reported to have numerous health advantages and are utilized as anti-atherosclerotic, anti-inflammatory, anti-thrombotic, anti-allergic, anti-carcinogenic, anti-bacterial, and antiviral agents (Duarte et al., 2018; Sun and Shahrajabian, 2023). Radish generally accumulates higher levels of Cd when irrigated with wastewater (El-Beltagi et al., 2023). The utilization of radish as a bioactive substance with clinical and health benefits in diseases such as cardiometabolic problems and hypertension, and as an antioxidant and antimicrobial agent, has become a field of interest for scientists and the medical industry (Manivannan et al., 2019; Khan et al., 2022).

Water is fundamental for economic and social progress, agricultural output, food security, and keeping a balanced biological system (Rehman et al., 2019; Young et al., 2021). Water shortage raises the main pressing issues about the feasible fate of mankind and the preservation of significant environmental capabilities (Rosa et al., 2020; Musie and Gonfa, 2023). On the other hand, water shortages could decrease yields and seriously influence food security around the world (Young et al., 2021).

The agricultural area of Pakistan is confronting the issue of the water management system (Chandio et al., 2020; Ahmad et al., 2023). Roughly 70% of the cultivated land is irrigated. The primary area of agriculture is irrigated by dams, wells, rivers, and channels (Ali et al., 2021). Due to the shortage of fresh water, farmers are compelled to use wastewater with no treatment as an alternative to fresh water, which brings about harmful consequences for crops as well as for individuals who are also liable for heavy metal accumulation in the soil. The potential of plants to take up heavy metals is different, as certain plants gather more heavy metals than others and cause different health problems to individuals through the food chain (Sun et al., 2023).

The untreated wastewater shows shifting levels of trace metals and pollutants, while these water reserves can be utilized after sustainable treatment at a specific level for agriculture. On the other hand, it will open the entryways for heavy metals to go into the soil-plant ecosystem (Farhadkhani et al., 2018; Khan et al., 2022). Long-lasting contaminants can accumulate in the water-soil-plant environment after wastewater discharge and can enter the food web. In any case, long-lasting wastewater supply to agriculture is extremely destructive to the environment, climate, and human prosperity. Trace metals can impact photosynthesis, plant digestion, stomatal opening, and other ecophysiological traits and can moreover impact microbial organizations or cause damage (Batool et al., 2023).

Heavy metals are classified into two major classes: One is useful heavy metals that play an important role in human health and include heavy metals like iron (Fe), zinc (Zn), copper (Cu), molybdenum (Mo), cobalt (Co), or manganese (Mn). The other class of heavy metals includes those that constitute environmental hazards, such as lead (Pb), tin (Sn), mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), and the toxic heavy metals that do not ensure any good in their association with human wellbeing (Dhaliwal et al., 2020). The utilization of heavy metals through polluted consumption can cause different illnesses like thalassemia, dermatitis, and cancer in the human body (Yadav and Pervez, 2024). A body's frameworks directly initiate disability in enzymatic, cardiovascular, reproductive, nervous (peripheral and central), detoxification pathways (kidneys, liver, skin, colon, liver), energy production pathways, endocrine (hormonal), immune, gastrointestinal, urinary framework, and blood circulation systems due to these poisonous compounds (Ahmad et al., 2019).

Heavy metals are available in enormous quantities in the environment due to regular and anthropogenic activities and influence human existence in different ways. Ongoing waste dumping in the environment, particularly heavy metals in soil, is a danger to biotic life (Saha et al., 2022; Abd-Elhalim et al., 2025).

This study aimed to assess the effects of contaminated food crops (radish) and provide guidance for managing future consumption requirements. Specifically, it evaluated heavy metal concentrations in agricultural soils and food crops (radish) irrigated with wastewater and their impacts on human health.

Materials and Methods

Sampling sites

The study was carried out in two tehsils of the Sargodha district in Punjab, Pakistan, i.e., Tehsil Sillanwali and Tehsil Sargodha. At both locations, samples of water, soil, radish crop, and human blood were collected. The sites were irrigated using different water sources, namely sewage water (SW), canal water (CW), and tube-well water (TW). Within the tehsil Sargodha, the following specific locations were selected: TW1: Chak 85 NB (32.0674◦ N, 72.7841◦ E), CW1: Chak 71 NB (32.18 83◦ N, 73.0286◦ E), and SW1: Lahore Road (32.082466◦ N, 72.669128◦ E). In Tehsil Sillanwali, the chosen sites were TW2: Chak 129 NB (31.8249◦ N, 72.5412◦ E), CW2: Chak 121 NB (31.78◦ N, 72.47◦ E), and SW2: Farooka Road (31.887221◦ N, 72.414400◦ E) (**Figure 1**).

Fig. 1: Map of sampling sites

Sample collection

Water samples were collected from two locations at each site, accounting for canal water, groundwater (tube well water), and sewage water. Samples (each, 5 mL) from each source were stored in labeled plastic bottles and placed at room temperature for further analysis. Soil samples were taken from the soils irrigated with canal water, others with groundwater, or sewage water (**Fig. 1**). A total of 18 soil samples (1 kg each) were collected, with three replicates from each location. The soil samples were first air-dried and then oven-dried at 70-75 °C for five days to remove moisture. The soil was then ground to a fine powder, and the samples were kept in polythene bags for analysis. The radish samples were collected from three sites in the study area, with a total of 18 samples and three replicates from each site irrigated with canal, groundwater, and sewage water. The samples were put in polythene containers and washed with distilled water for decontamination. The crop samples were air-dried and subsequently oven-dried at 70-75 °C for three days. After drying, the samples were ground into fine powder and stored for testing.

Sample digestion

Five mL of the water sample was digested with three mL of H_2SO_4 and five mL of H_2O_2 in a digestion chamber for 30 minutes. Then, 2 mL of H_2O_2 was added until the solution was colorless. The sample was then diluted to 50 mL with distilled water and stored in polyethylene bottles. For soil digestion, one g of soil was mixed with 4 mL of H_2SO_4 and 8 mL of H_2O_2 and boiled in a digestion chamber for 30 minutes. The first digestion was carried out, and two mL of H_2O_2 were added until the solution became clear. The sample that had been digested was filtered through Whatman No. 42 filter paper, diluted to a total volume of 50 mL with double-distilled water, and kept in labeled plastic bottles. The sampled radish plants (1 g each) were processed with 2 mL H_2SO_4 and 4 mL of H_2O_2 for 15-30 minutes. The samples were then filtered through Whatman No. 42 paper, diluted to 50 mL with double-distilled water, and stored in marked plastic bottles. The well-prepared samples were subjected to an atomic absorption spectrophotometer (AA 6300 Shimadzu, Japan) for determining the concentrations of different metals.

Pollution indices

Contamination factor (CF)

To determine metal contamination, the contamination factor (CF) was computed. This ratio, defined by the average concentration of metals in comparison to the concentration of metals in organic matter, is useful for assessing the temporal trend of pollution. This is calculated as follows:

$$CF = \frac{\mathrm{C}\ heavy\ metal}{\mathrm{C}\ background}$$

Sivakumar et al. (2016) state that a CF of 1 indicates very little contamination. A CF between 1 and 3 implies some moderate contamination, whereas a CF from 3 to 6 signifies a high level of contamination.

Enrichment factor (EF)

The EF was calculated following Buat-Menard and Chesselet (1979).

$$EF = \frac{(metal\ concentration\ in\ crop/\ concetration\ in\ soil)\ sample}{\left(metal\ concentration\ in \frac{crop}{}\ concetration\ in\ soil\right)\ \mathrm{standard}}$$

Estimated daily intake (EDI)

The assessment and analysis of the possible health impacts of metals were done using estimated daily intake (EDI), target hazard quotient (THQ), estimated cancer risk (ECR), and hazard index (HI). The EDI is given in mg kg^{-1} day^{-1} by the given equation.

$$EDI = (C \times DI \times CF)/BW$$

Where:
C = the concentration of metal in mg kg^{-1}
DI = daily intake
BW = reference body weight
CF = conversion factor

The estimated daily intake (EDI) values were compared with those of provisional tolerable daily intake (PTDI) levels set by JEFCA, so as to ascertain if the recommended daily limits had been exceeded.

Hazard quotient (HQ)

It was quantified following Sharma et al. (2016), using the following equation:

$$HQ = \frac{(D) \times (\mathrm{Cmetal})}{(RfD) \times BO}$$

where:
D = daily food intake (kg day^{-1})
Cmetal = concentration of the metal (mg kg^{-1})
RfD = reference oral dose of the metal (mg kg^{-1} of body weight/day)
BO = body weight (kg)

Bioconcentration factor (BCF)

The bioconcentration factor (BCF) refers to the concentration of metals present in the edible parts of plants after being transferred from the soil. The BCF value was derived from the following equation:

$$\mathrm{BCF} = \frac{\mathrm{MV_{Plant}}}{\mathrm{MV_{Soil}}}$$

MVplant = Metal concentration in the plant
MVsoil = Metal concentration in soil

Results

Water samples (Physicochemical properties)

The data reveal a significant variation in the quality of water from different sites (**Table 1**). All water quality parameters, e.g., electrical conductivity (EC), SAR, RSC, bicarbonates, and inorganic elements such as Na, Ca + Mg, and Cl, listed in **Table 1**, show significant differences concerning the sites. For example, all these parameters were at their lowest at the TW1 location.

Table 1: Physicochemical properties of water samples

Sites	Chloride (mg L^{-1})	EC (dS m^{-1})	Ca^{2+} + Mg^{2+} (meq L^{-1})	Na^{+} (mg L^{-1})	SAR (meq L^{-1})	RSC (meq L^{-1})	Bicarbonates (meq L^{-1})
TW1	0.35±0.01	0.31	2.96±0.17	0.46±0.08	0.25±0.008	0.09±0.01	2.37±0.02
CW1	3.54±0.01	1.25	5.50±0.02	7.06±0.008	4.36±0.01	2.75±0.01	8.46±0.14
SW1	6.19±0.01	1.83	6.66±0.08	11.45±0.01	6.35±0.01	3.25±0.01	9.87±0.01
TW2	0.63±0.08	0.28	2.55±0.01	0.37±0.01	0.34±0.008	0.10±0.01	2.40±0.11
CW2	3.01±0.02	1.53	5.68±0.005	9.72±0.02	5.60±0.11	5.23±0.02	8.88±0.02
SW2	5.75±0.01	1.88	8.47±0.005	10.38±0.03	5.37±0.005	1.46±0.14	9.68±0.02

Metal concentrations in water

The data on metal concentrations in water reveal notable differences across the sites, as shown in **Figure 2 & 3.**

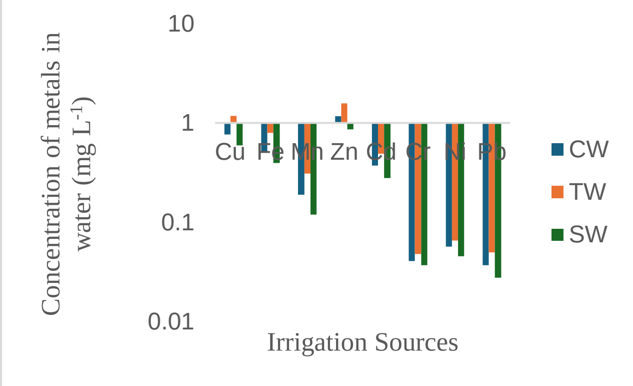

Figure 2: Variation of metal concentration (mg L^{-1}) in water at three different locations of Site 1

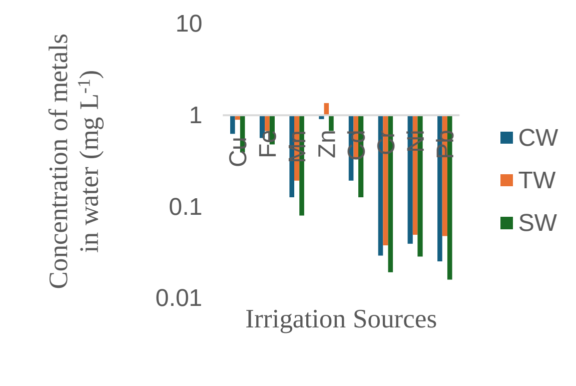

Figure 3: Variation of metal concentration (mg L^{-1}) in water at three different locations of Site 2

Significant differences in metal concentrations across the sites and locations for most of the metals analyzed were observed. Copper, manganese, zinc, cadmium, chromium, nickel, and lead show marked differences between the sites and within the locations. (**Figs. 2 & 3**) However, iron and cadmium were not much higher, which indicates that their concentrations were less influenced by the site or the locations.

Physicochemical properties of soil samples

The following data reveal variations in soil properties across the sites.

Table 2: Physicochemical properties of soil samples

Sites	Potassium (mg kg^{-1} DW)	EC (dS m^{-1})	pH	Saturation percentage	Phosphorus (mg kg^{-1} DW)	Organic matter (%)
TW1	208.66±0.57	2.68±0.01	7.43±0.008	37.28±0.02	11.27±0.02	0.74±0.01
CW1	216.33±1.15	3.67±0.01	8.10±0.02	38.70±0.01	14.79±0.01	0.79±0.01
SW1	405.00±1.76	7.83±0.01	8.87±0.01	35.68±0.02	46.00±1.53	1.24±0.01
TW2	216.66±1.45	2.22±0.01	7.65±0.01	33.32±0.008	7.39±0.01	0.88±0.01
CW2	189.34±1.45	3.73±0.01	7.85±0.01	40.25±0.005	6.92±0.02	1.11±0.01
SW2	425.34±1.45	7.56±0.12	8.36±0.02	37.70±0.11	38.24±0.01	1.26±0.005

Concentrations of different metals in soil samples

Significant variations were recorded in the soil physico-chemical properties of soils of different locations (**Table 2**). Of all locations, SW1 had the highest levels of K and P as well as soil electrical conductivity and pH. The interaction between the sites and locations was significant for most metals, including copper, manganese, zinc, chromium, nickel, and lead, though it is not significant for cadmium (**Figures 4 & 5**). The TW soil had the highest levels of all metals.

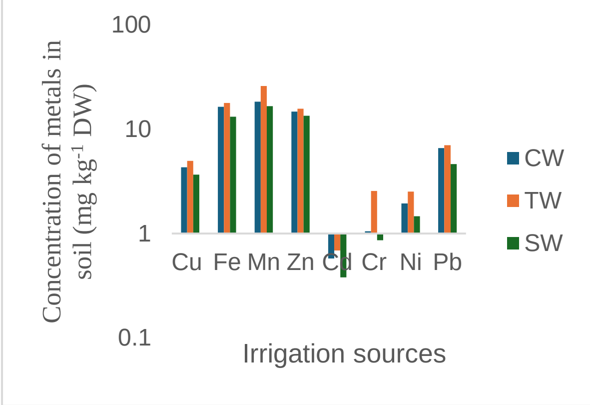

Figure 4: Variation of metal concentrations (mg kg^{-1}) in soil samples from three locations of Site 1

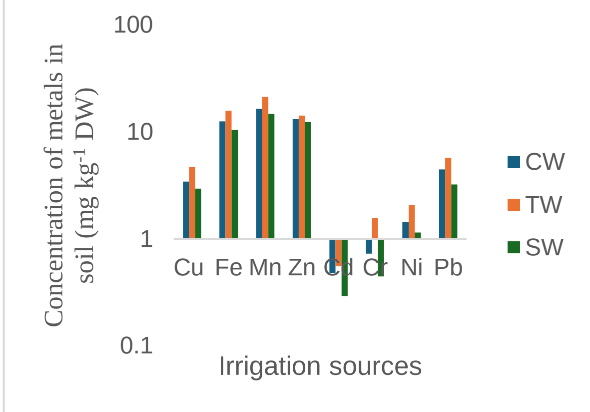

Figure 5: Variation of metal concentrations (mg kg^{-1}) in soil samples from three locations of Site 2

Metal concentrations in radish

The mean concentrations of metals in radish show notable variations across sites (Figs. 6 & 7).

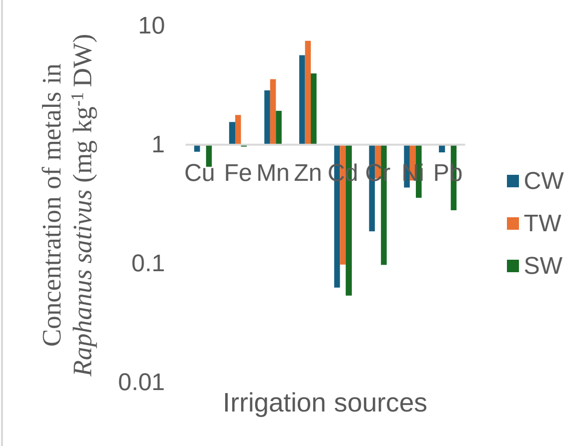

Figure 6: Variation in metal concentrations (mg kg^{-1}) in radish at three different locations of Site 1

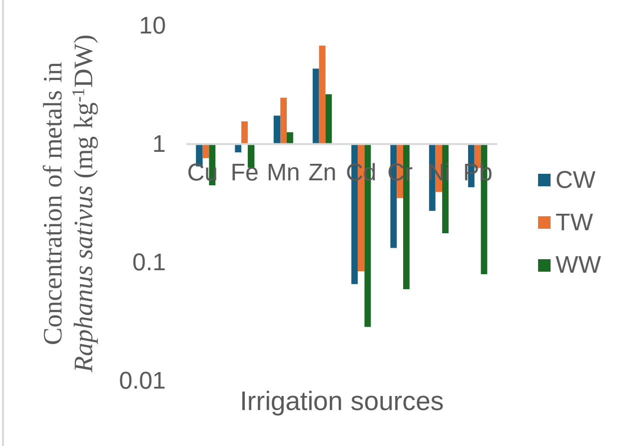

Figure 7: Variation in metal concentrations (mg kg^{-1}) in radish at three different locations of Site 2

The metal concentrations in radish indicate significant differences across the sites and locations for most metals (**Figures 6 & 7**). The interaction between the sites and the locations had been significant for manganese, zinc, cadmium, chromium, nickel, and lead, but not significant for copper. The radish samples collected from the TW site had highest levels of Zn, Mn, and Fe (**Figures 6 & 7**).

Concentrations of metals in blood serum

The mean concentrations of metals in the blood serum exhibited notable variation across the sites. The blood samples collected from the human subjects of the TW site had higher levels of all metals analyzed in the current study than those from the other sites (**Figures 8 & 9**).

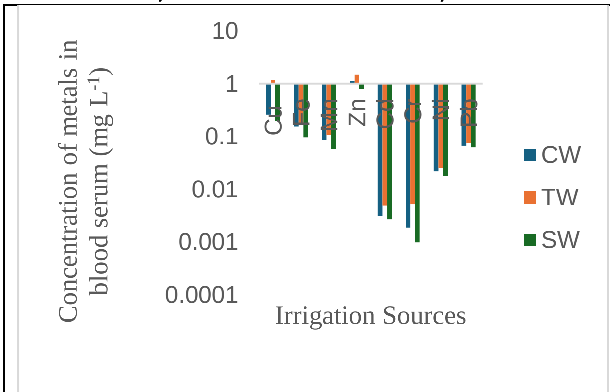

Figure 8: Variation of metal concentrations (mg L^{-1}) in the blood serum at three different locations of Site 1

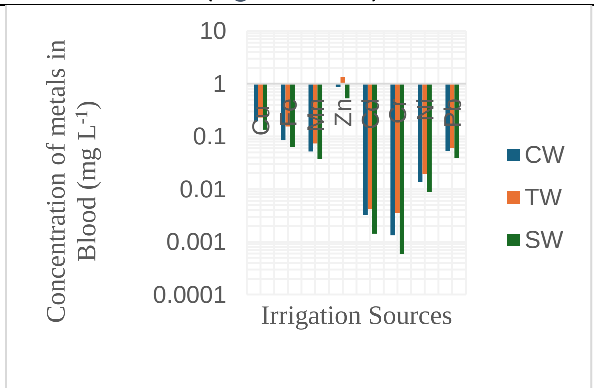

Figure 9: Variation of metal concentrations (mg L^{-1}) in the human blood serum at three different locations of Site 2

Contamination factor of metals in radish

The assessment of the contamination factor (CF) for different metals in radish reveals a significant variation across different sites (**Table 3**). However, the CF for all metals analyzed was significantly higher for the SW1 site compared with those of the other sites (**Table 3**).

Table 3: Contamination factor of metals in *Raphanus sativus*

Sites	Cd	Fe	Mn	Cu	Zn	Pb	Ni	Cr
TW1	0.0055	0.2328	0.0781	0.2842	0.2706	0.1253	0.1543	0.0215
CW1	0.0083	0.2892	0.0866	0.3359	0.2968	0.1792	0.2045	0.0264
SW1	0.0100	0.3157	0.1219	0.3860	0.3150	0.1901	0.2659	0.0643
TW2	0.0042	0.1836	0.0691	0.2281	0.2488	0.0871	0.1210	0.0114
CW2	0.0069	0.2206	0.0772	0.2664	0.2644	0.1203	0.1512	0.0181
SW2	0.0080	0.2770	0.1001	0.3666	0.2855	0.1548	0.2185	0.0359

Enrichment factor of metals in radish

The enrichment factor (EF) for radish metals across different sites shows a notable variability. The EF for Fe, Mn, Pb, and Cr was the highest for the SW1 site, whereas that for Cd was the highest for the SW2 site (**Table 4**). However, the EF for Ni was the highest for the TW1 site.

Table 4: Enrichment factor of metals in radish

Sites	Cd	Fe	Mn	Cu	Zn	Pb	Ni	Cr
TW1	0.5366	0.0094	0.0108	0.0508	0.0468	0.1640	0.1264	0.4445
CW1	0.4133	0.0121	0.0144	0.0575	0.0610	0.3535	0.1168	0.7009
SW1	0.5399	0.0128	0.0127	0.0564	0.0757	0.3783	0.1029	0.7930
TW2	0.3858	0.0078	0.0107	0.0438	0.0339	0.0674	0.0799	0.5276
CW2	0.5198	0.0087	0.0080	0.0539	0.0523	0.2642	0.0989	0.7257
SW2	0.5783	0.0127	0.0099	0.0460	0.0759	0.2971	0.0984	0.8825

Estimated daily intake of metals by humans

The estimated daily intake (EDI) of metals by humans is presented in **Table 5**. The daily intake of Cd, Fe, Mn, Cu, Zn, Pb, Ni, and Cr was the highest for the SW1 site, whereas the lowest daily intake of all these metals was recorded for the TW2 site (**Table 5**).

Table 5: Estimated daily intake (mg/kg/day) by humans through contaminated radish

Sites	Cd	Fe	Mn	Cu	Zn	Pb	Ni	Cr
TW1	0.0020	0.0368	0.0735	0.0248	0.1515	0.0107	0.0136	0.0037
CW1	0.0023	0.0592	0.1091	0.0332	0.2166	0.0330	0.0167	0.0071
SW1	0.0037	0.0680	0.1355	0.0374	0.2852	0.0374	0.0191	0.0197
TW2	0.0010	0.0242	0.0481	0.0172	0.1008	0.0030	0.0067	0.0022
CW2	0.0025	0.0326	0.0666	0.0247	0.1656	0.0165	0.0104	0.0051
SW2	0.0032	0.0594	0.0942	0.0290	0.2592	0.0239	0.0150	0.0133

Hazard quotient for metals in radish

The hazard quotient (HQ) for metals in radish, irrigated with different types of water, is presented in **Table 6**. The HQ of Cd, Fe, Mn, Cu, Zn, Pb, Ni, and Cr was the highest for the SW1 site, whereas it was the lowest for the TW2 site (**Table 6**).

Table 6: Hazard quotient (HQ) of metals in radish

Sites	Cd	Fe	Mn	Cu	Zn	Pb	Ni	Cr
TW1	0.2052	0.5263	0.5254	0.6215	0.5053	0.2677	0.6821	0.0024
CW1	0.2397	0.8469	0.7795	0.8319	0.7220	0.8255	0.8351	0.0047
SW1	0.3748	0.9726	0.9680	0.9371	0.9507	0.9371	0.9562	0.0131
TW2	0.1096	0.3460	0.3442	0.4303	0.3361	0.0765	0.3378	0.0015
CW2	0.2511	0.4662	0.4763	0.6183	0.5520	0.4143	0.5227	0.0034
SW2	0.3238	0.8487	0.6730	0.7267	0.8640	0.5992	0.7522	0.0089

Bioconcentration factor for metals in radish

The bioconcentration factor (BCF) for metals in radish, presented in **Table 7,** shows a significant variation among different locations and sites. The BF of different metals varied from site to site and location to location. Thus, no consistent pattern of BF was observed for different metals at different sites (**Table 7**).

Table 7: Bioconcentration factor of metals in radish

Sites	Cd	Fe	Mn	Cu	Zn	Pb	Ni	Cr
TW1	0.1412	0.0727	0.1155	0.1772	0.2929	0.0603	0.2431	0.1127
CW1	0.1087	0.0941	0.1546	0.2007	0.3816	0.1301	0.2247	0.1777
SW1	0.1420	0.0990	0.1364	0.1967	0.4734	0.1392	0.1979	0.2010
TW2	0.1015	0.0606	0.0865	0.1528	0.2119	0.0248	0.1536	0.1337
CW2	0.1368	0.0679	0.1059	0.1881	0.3274	0.0972	0.1903	0.1840
SW2	0.1522	0.0985	0.1154	0.1606	0.4746	0.1093	0.1893	0.2237

Discussion

Considerable variation in the levels of different metals analyzed in the water samples collected from different locations was recorded in the current study. For example, copper (Cu) levels ranged from the lowest (0.39 mg L^{-1}) at TW2 to the highest (1.18 mg L^{-1}) at SW1. While assessing heavy metal contamination and risk assessment in water, paddy soil, and rice around an electroplating plant, Liu et al. (2011) documented the presence of Cu in water (1.67 mg L^{-1}), which was significantly higher than recorded in our study. Likewise, iron (Fe) concentrations in water in our investigation fluctuated from 0.39 mg L^{-1}at TW1 to 0.79 mg L^{-1}at SW1. While assessing water quality and potential health risk of Manzala lake in Egypt, Khatita et al. (2017) recorded the concentration of Fe (1.98 mg L^{-1}) in water, which is significantly higher than observed in the current discoveries. Moreover, manganese (Mn) levels were minimum at TW1 (0.08 mg L^{-1}) and their highest at SW1 (0.31 mg L^{-1}). Abagale et al. (2013) assessed heavy metal concentration in wastewater from car washing bays used for agriculture in the Tamale metropolis, Ghana, and documented Mn level in contaminated water in the range of 1.073-1.082 mg L^{-1}, being much higher than we documented in our study. In our research trial, zinc (Zn) in water samples ranged from 0.67 mg L^{-1} at TW2 to 1.58 mg L^{-1}at SW1. The water Zn concentrations recorded in the current study are markedly lower than the wastewater Zn values (5.73 mg L^{-1}) found by Maqsood et al. (2022) while appraising zinc metal in meadows and ruminants and their impact on the health of humans. Cadmium (Cd) levels were found to be minimal, showing 0.12 mg L^{-1} at TW2 and the highest (0.49 mg L^{-1}) at SW1. Panhwar et al. (2016) drew a correlation of the levels of cadmium and aluminum in drinking water with those of blood samples of kidney disorder patients, and showed Cd level as 2.36 mg L^{-1}, which is much higher than we documented in our investigation. Chromium (Cr) and Pb concentrations documented in our investigations in water samples collected from different locations were much lower than those reported by Hassan et al. (2013), while assessing heavy metals in wheat plants irrigated with contaminated wastewater.

The levels of different metals in the soil samples collected from different locations are generally much lower or within the permissible limits, as reported in different already published studies. For example, Hassan et al. (2013) noted much higher levels of Cu and Waseem et al. (2014) of Fe in soils than those documented in our study. Moreover, soil Zn levels were also reported to be much higher (Mapanda et al., 2005) than those recorded in our study. However, soil Cd levels recorded in our study tally significantly with what Shan et al. (2025) have recently reported in their study concerning the appraisal of soil Cd levels in Southern China. The levels of soil Cr documented in our study are much lower than those reported elsewhere (Ripin et al., 2014) and Xie et al. (2023). However, Kafeel et al. (2022), while appraising the soil Cr levels in some areas of the Punjab Province, reported lower levels of Cr than those of our findings for copper (Cu), Fe, Zn, and Mn in the radish tissue, which were the lowest at TW2, and the highest at SW1. Cadmium (Cd), Cr, Pb, and Ni concentrations in the radish tissue were the lowest at TW2, and their highest at SW1. The levels of radish Cd, Cr, and Pb observed in the current study are much lower than those recorded in different *Brassica* species (Zunaidi et al., 2024). Earlier, Roychowdhury et al. (2017) showed that *Brassica juncea*, a very common species of the genus *Brassica*, is a potential accumulator of metals such as Cd, Pb, Zn, and Cu.

Analysis of different metals (Cu, Zn, Fe, Mn, Pb, Cd, Cr, and Ni) in the blood serum of humans from different locations was found to be within permissible limits. Thus, these findings do not agree with those of Akbar Jan et al. (2011), who observed that Cu, Zn, and Mn concentrations in the human blood samples collected from the polluted area were considerably higher than those from the non-polluted (control) area. Likewise, Moradi et al. (2016) found high levels of several heavy metals, such as Cd, Pb, Ni, Fe, Co, Cr, Mn, Cu, and Zn in the blood serum samples of patients with multiple sclerosis (MS) disease living in two industrial regions of Isfahan, Iran.

Contamination factors (CF) of different metals (Cu, Fe, Mn, Zn, Cd, Cr, Pb, and Ni) were found to be the lowest at location TW2 and the highest at location SW1. Similar findings have been reported in another study (Islam et al., 2021), in which the authors demonstrated increased values of CF for various metals in samples from metal-polluted sites. Moreover, the CF values for all eight metals analyzed in this study were well below 1, indicating minor contamination (Mohan et al., 2024). Similarly, the enrichment factors (EF) of all eight metals were the highest in the SW1 location and the lowest in the TW2 location. The enrichment factor (EF) is often used to appraise the influence of human and natural activities on metal accumulation in the environment (Han and Gu, 2023). However, an EF value lower than 0.5 specifies that the metal is mobilized, a value within the range 0.5-1.5 shows that the metal has been derived from natural sources, and an EF value over 1.5 indicates that the metal enrichment is attributable to anthropogenic activities (Ustaoğlu et al., 2022). In all cases, the CF values are much lower than the EF value of 0.5, so the mobility of each metal from soil to plant is safe. The estimated daily intake (EDI) of all eight metals was the lowest at the location TW2 and the highest at the location SW1. Haq et al. (2021) also showed a differential pattern of EDI values for vegetable samples collected from industrial and non-industrial areas in Bangladesh. For example, the authors noted higher values of EDI for different metals in the industrial site, but lower values in the non-industrial site.

The metal hazard quotient (HQ) and bioconcentration factor (BCF) of all eight metals were the lowest at TW2 and the highest at SW1. By calculating the hazard quotient (HQ), the potential for non-carcinogenic health impacts from exposure to a metal can be assessed. However, BCF measures the level of metal sharing between an organism (maybe plants) and its surrounding environment (water). However, the BCF value over 1 shows high uptake of a metal by plants (Ba et al., 2024), and this metric can be employed for the phytoremediation potential of plants. In the current study, the BCF values were much below 1, so the phytoremediation potential of radish is quite low as compared to several other species belonging to the family Brassicaceae (Zunaidi et al., 2024). The HQ values of all metals were well below 1, so no potential health risks (Oladeji et al., 2023) can be associated with the use of radish grown in these areas.

Conclusion

The present study is a comprehensive analysis of heavy metal contamination in radish, soil, and water from different irrigation systems in the Sargodha district and Sillanwali tehsil. The results show that even though the concentrations of heavy metals were the highest in radish irrigated with sewage water (SW1) and the lowest in those irrigated with tube well water (TW2), all the metals measured in this study remained within the permissible limits according to the pollution indices. The computed contamination factors (CF), enrichment factors (EF), estimated dietary intake (EDI), hazard quotient (HQ), and bioconcentration factor (BCF) are within the permissible limits, so a little health risk can be expected from the use of this vegetable being grown with irrigation with wastewater.

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Conceptualization and planning of research: KA, ZIK, AA, MI. Conduction of research: MZ. Data collection: MZ. visualization and interpretation: MZ, KA, ZIK, AA, MI, MM, SA. Statistical analysis: MZ, KA, ZIK. Preparation of initial draft: MZ, KA, ZIK, AA, SA, MI, IRN, MM, SA, MIA, SU, RU. Review of initial draft: ZIK, KA, MZ, AA, IRN, SA, MIA, SU, RU. Revisions and corrections: MZ, ZIK, KA, MIA, MM, AA. Proofreading and approval of the final version: All authors.

Permissions and ethical compliance
The Institutional Human Ethics Committee of the University of Sargodha (Approval No.25-A18 IEC UOS) has allowed all the protocols used in this experiment. All experimental methods for this study have followed all the appropriate guidance and regulations, including NRC standards.

Handling of bio-hazardous materials
The authors certify that all experimental materials were handled with great care during collection and experimental procedures. After completion of the study, all materials were properly discarded to minimize/eliminate any types of bio-contamination.

Supplementary material
No supplementary material is included with this manuscript.

Conflict of interest
The authors declare no conflict of interest.

Availability of primary data and materials
As per editorial policy, experimental materials, primary data, or software codes are not submitted to the publisher/Journal management. These are available with the corresponding author (s) and/or with other author(s) as declared by the corresponding author (s) of this manuscript.

Authors' consent
All authors have critically read this manuscript and agreed to publish in IJAaEB.

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It is declared that the authors did not use any AI tools or AI-assisted services in the preparation, analysis, or creation of this manuscript submitted for publication in the International Journal of Applied and Experimental Biology (IJAaEB).

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