

Effects of Wastewater Irrigation on Soil Quality and Heavy Metal Contamination in Radish Cultivation

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ABSTRACT

This study investigated the effects of wastewater irrigation on soil quality and heavy metal contamination in radish (*Raphanus sativus*) cultivation in Sargodha, Pakistan. Soil, irrigation water, and radish samples were collected from agricultural fields irrigated with canal water and untreated sewage water. Physicochemical characteristics of water and soil were determined to evaluate salinity, alkalinity, nutrient status, and their influence on metal mobility. Concentrations of Cd, Pb, Cr, Ni, Zn, Cu, Fe, Mn, Co, and Mo were analyzed using Flame Atomic Absorption Spectrophotometry following standard digestion procedures. Results revealed significantly higher electrical conductivity, sodium adsorption ratio, and residual sodium carbonate in sewage water compared to canal water. Sewage irrigation markedly increased soil salinity, organic matter content, and nutrient levels. Heavy metal concentrations were consistently higher in sewage-irrigated water and soils, indicating progressive accumulation. Radish samples grown under wastewater irrigation showed elevated metal levels compared to canal-irrigated crops. Statistical analyses confirmed irrigation source as the primary factor influencing soil quality and contamination patterns. The findings demonstrate that while wastewater irrigation enhances nutrient availability, it significantly contributes to heavy metal enrichment in agricultural soils and radish crops. Continuous monitoring and management strategies are required to ensure sustainable radish production and environmental protection.

Keywords: Wastewater irrigation, Soil quality, Heavy metals, Radish cultivation,

Environmental contamination

INTRODUCTION

Agriculture plays a central role in ensuring food security and economic sustainability, particularly in developing countries such as Pakistan. Increasing population pressure and freshwater scarcity have intensified the reliance on alternative irrigation sources, including untreated municipal wastewater [1]. In peri-urban regions, wastewater irrigation has become a common agricultural practice due to its continuous availability and nutrient-rich composition.

Radish (*Raphanus sativus*) is an important root vegetable widely cultivated and consumed in Pakistan. It is valued for its nutritional composition, including dietary fiber, vitamins, minerals, and bioactive compounds. However, radish is also capable of absorbing and accumulating heavy metals from contaminated soils, making it a suitable indicator crop for assessing environmental pollution [2].

Wastewater often contains elevated levels of dissolved salts, organic matter, nutrients, and potentially toxic heavy metals derived from domestic discharge, industrial effluents, vehicular emissions, and urban runoff [3]. Although the nutrient content of wastewater can improve soil fertility and crop yield, long-term application may lead to salinity buildup, soil structural degradation, and heavy metal accumulation [4].

Heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), manganese (Mn), cobalt (Co), molybdenum (Mo), and iron (Fe) are persistent environmental contaminants [5]. Unlike organic pollutants, these metals do not degrade and may accumulate in soils over time. Their bioavailability depends largely on soil physicochemical properties including pH, electrical conductivity, and organic matter content [6]. The accumulation of heavy metals in agricultural soils not only affects soil quality but also facilitates their uptake by crops [7]. Root vegetables such as radish are particularly vulnerable because the edible portion develops directly within the contaminated soil environment. Continuous consumption of contaminated produce may pose serious environmental and health concerns [8].

In Sargodha, especially along Silanwali Road, both canal water and sewage water are

used for irrigation [9]. However, systematic evaluation of the impact of wastewater irrigation on soil quality and heavy metal contamination in radish cultivation remains limited [10].

Therefore, the present study was conducted to (i) assess the physicochemical characteristics of irrigation water and soil under canal and sewage irrigation systems; (ii) determine heavy metal concentrations in water, soil, and radish samples; and (iii) evaluate the overall impact of wastewater irrigation on soil quality and metal contamination in radish cultivation [11].

MATERIALS AND METHODS

Study Area

The study was conducted in Sargodha District, Punjab, Pakistan (32.08586°N, 72.67418°E). The region experiences semi-arid climatic conditions with an average annual rainfall of approximately 250 mm. Agricultural fields were selected based on irrigation source, categorized as canal water-irrigated and sewage water-irrigated sites.

Sample Collection

Water Sampling

Irrigation water samples were collected in pre-cleaned polyethylene bottles following standard APHA procedures. Samples were transported to the laboratory and preserved under recommended conditions prior to analysis [12].

Soil Sampling

Soil samples were collected from the 0–20 cm depth using stainless steel augers. Samples were air-dried, oven-dried at 70–75°C, ground, and sieved through a 2 mm mesh to remove debris and stones [13].

Radish Sampling

Radish samples were collected in triplicate from each site. Samples were washed thoroughly with distilled water to remove adhering soil particles, oven-dried, ground into fine powder, and stored in airtight containers for further analysis [14].

Physicochemical Analysis of Soil and Water

Soil pH and electrical conductivity were measured using potentiometric and conductometric methods. Organic matter content was determined using the

Walkley–Black method. Available phosphorus and potassium were analyzed through colorimetric and flame photometric methods. Water samples were analyzed for EC, Ca+Mg, Na, HCO_3 , Cl, SAR, and RSC following standard laboratory protocols [15,16,17].

Heavy Metal Analysis

Samples were digested using nitric acid–hydrochloric acid (aqua regia) digestion following USEPA Method 3050B [18]. Heavy metal concentrations (Cd, Pb, Cr, Ni, Cu, Zn, Mn, Co, Mo, Fe) were determined using Flame Atomic Absorption Spectrophotometry (Shimadzu AA-6300) [19].

Statistical Analysis

Data were analyzed using SPSS software. One-way ANOVA was performed to determine significant differences between irrigation treatments [20]. Pearson correlation analysis was conducted to examine relationships between soil properties and heavy metal concentrations [21].

RESULTS

Analysis of Variance (Mean Square) for Physicochemical Properties of Water Used for Radish Cultivation

The analysis of variance presented in Table 01 illustrates the statistical influence of sites, irrigation type, and their interaction on the physicochemical characteristics of water used for radish cultivation. The parameters evaluated include electrical conductivity (EC), calcium plus magnesium (Ca+Mg), sodium (Na), bicarbonates (HCO_3), chlorides (Cl), sodium adsorption ratio (SAR), and residual sodium carbonate (RSC). The results clearly indicate that irrigation source exerted a highly significant effect ($P < 0.01$) on all measured parameters. This demonstrates that wastewater and canal water differ substantially in their chemical composition.

In contrast, the effect of sites alone was mostly non-significant for EC, Ca+Mg, Na, HCO_3 , Cl, and SAR, suggesting that spatial variation between the two sampling locations was minimal for these parameters. However, RSC showed a highly significant difference between sites, indicating variation in carbonate chemistry that could influence soil sodicity.

The interaction between sites and irrigation was largely non-significant, except for

RSC, which remained highly significant. This finding implies that irrigation type is the dominant factor influencing water quality, rather than geographical location. Overall, the results confirm that wastewater irrigation significantly alters water chemistry, potentially affecting soil health and crop productivity.

Physicochemical Properties of Water Collected from Two Sites for Radish Cultivation

Table 02 presents the mean values and standard deviations of physicochemical properties of water collected from two sites under canal water (CW) and sewage water (SW) irrigation systems. Electrical conductivity was markedly higher in sewage water (SW1 and SW2) compared to canal water (CW1 and CW2), indicating greater salinity levels in wastewater. Elevated EC values in SW samples reflect higher dissolved salts, which may contribute to soil salinization over prolonged irrigation.

Similarly, concentrations of Ca+Mg, Na, HCO_3 , Cl, SAR, and RSC were consistently higher in sewage water samples. Sodium levels and SAR values are particularly important because excessive sodium can deteriorate soil structure and reduce permeability. The higher SAR in SW samples suggests increased sodicity risk. Residual sodium carbonate values were substantially elevated in SW1 compared to CW1, reinforcing concerns about alkalinity hazards associated with wastewater irrigation. Although both sites showed similar trends, SW2 exhibited slightly higher sodium and chloride concentrations compared to SW1, indicating possible variability in wastewater composition.

Overall, the data reveal that sewage water contains higher ionic concentrations than canal water, which may enhance nutrient availability but simultaneously increase risks of salinity and sodicity. Continuous use of such water could significantly alter soil properties and crop performance.

Analysis of Variance (Mean Square) for Physicochemical Properties of Soil Used for Radish Cultivation

Table 03 summarizes the analysis of variance for soil physicochemical parameters including EC, pH, phosphorus (P), potassium (K), organic matter (OM), and saturation percentage. The irrigation factor showed highly significant effects

($P < 0.01$) on all measured soil parameters. This indicates that irrigation type plays a major role in modifying soil chemical characteristics.

The site effect was highly significant only for organic matter and saturation percentage, while remaining non-significant for EC, pH, P, and K. This suggests limited spatial variability but notable differences in soil organic status between locations.

The interaction between site and irrigation was significant for phosphorus and potassium, implying that nutrient accumulation patterns vary depending on both location and irrigation source. Wastewater irrigation likely contributes to higher nutrient deposition, explaining significant increases in soil P and K levels.

These findings demonstrate that wastewater irrigation significantly influences soil salinity, alkalinity, nutrient status, and organic matter accumulation. Long-term application could enhance fertility but may simultaneously increase risks of salinity buildup.

Physicochemical Properties of Soil Collected from Two Sites for Radish Cultivation

Table 04 provides the mean values of soil physicochemical characteristics from two sites under canal and sewage irrigation. Soil EC was considerably higher in SW1 and SW2 compared to CW1 and CW2, indicating substantial salt accumulation under wastewater irrigation. Elevated EC levels in SW soils reflect long-term deposition of dissolved salts from sewage water.

Soil pH was slightly alkaline in all samples but more pronounced in SW treatments, suggesting that wastewater irrigation contributes to alkalization. Phosphorus and potassium levels were significantly higher in SW soils, indicating nutrient enrichment through wastewater application.

Organic matter percentage was markedly higher in sewage-irrigated soils. This increase can be attributed to organic residues and suspended solids present in wastewater. Saturation percentage was also elevated in SW soils, reflecting changes in soil texture or structure due to continuous irrigation. These results demonstrate that wastewater irrigation enhances soil nutrient content and organic matter but simultaneously increases salinity and alkalinity risks. Such changes can influence

radish growth, yield quality, and heavy metal mobility.

Analysis of Variance (Mean Square) for Proximate Composition of Radish

Table 05 presents the statistical evaluation of radish proximate composition under different irrigation conditions. Moisture and carbohydrate contents were highly significantly affected by both site and irrigation. Crude protein and ash were also significantly influenced by irrigation, indicating that wastewater application alters nutritional composition.

Crude fat and crude fiber were mostly non-significant for site effects, suggesting minimal geographical impact on these components. However, irrigation significantly affected crude fat, showing that water quality influences lipid content. The interaction effect was significant only for ash content, indicating variation in mineral accumulation depending on both site and irrigation source. Overall, wastewater irrigation appears to modify radish nutritional attributes, potentially enhancing certain components such as protein and carbohydrate while affecting moisture balance.

Proximate of Radish Sample Collected from Two Sites

Table 06 provides detailed proximate composition data of radish samples. Moisture content was highest in CW1 and lowest in SW2, suggesting that wastewater irrigation reduces water content in radish roots. Crude protein levels were substantially higher in SW samples, particularly SW1 and SW2, indicating enhanced nitrogen availability from sewage water.

Carbohydrate content was notably higher in SW2 compared to CW treatments, reflecting improved nutrient uptake under wastewater irrigation. Ash content, representing total mineral content, was highest in SW1, confirming increased mineral accumulation. Crude fat and fiber showed minor variations, though slight reductions were observed in sewage treatments. These findings indicate that wastewater irrigation influences nutritional quality by enhancing protein, carbohydrate, and mineral content, but may reduce moisture levels.

Analysis of Variance (Mean Square) for Heavy Metals in Water Used for Radish Cultivation

Table 07 evaluates the statistical significance of heavy metal concentrations in

irrigation water. Irrigation source significantly affected almost all metals including Cu, Fe, Zn, Mn, Co, Pb, and Mo. Cadmium showed non-significant variation for both site and irrigation, indicating relatively stable levels.

The site effect was significant for most metals except Cd and Co, demonstrating spatial differences in heavy metal contamination. Interaction effects were significant for several metals, indicating combined influence of location and irrigation type. These results confirm that wastewater irrigation substantially increases heavy metal concentrations in water. Continuous application of such water could enhance metal accumulation in soil and crops, posing potential environmental and health risks.

Heavy Metal Concentrations in Water Samples from Two Sites for Radish Cultivation

Table 08 presents the mean concentrations of heavy metals in water samples. Sewage water samples (SW1 and SW2) consistently showed higher concentrations of Cu, Fe, Zn, Mn, Cd, Co, Pb, and Mo compared to canal water samples.

Notably, SW2 exhibited the highest concentrations of Cu, Fe, Zn, and Mn, indicating substantial contamination levels. Lead and cadmium concentrations were also elevated in sewage water, raising concerns about potential toxic effects.

Although canal water contained detectable metal levels, concentrations were significantly lower than sewage treatments. These findings demonstrate that wastewater irrigation introduces elevated heavy metal loads into the agricultural system, which may accumulate in soil and crops over time.

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Table 01: Analysis of Variance (Mean Square) for Physicochemical Properties of Water Used for Radish Cultivation

Source of Variation	Degrees of Freedom	EC	Ca+Mg	Na	HCO ₃	Cl	SAR	RSC
Sites	1	722 ^{NS}	0.0048 ^{NS}	0.0675 ^{NS}	0 ^{NS}	0.025 ^{NS}	0.0027 ^{NS}	0.98041 ^{**}
Irrigation	1	5E+06 ^{**}	28.152 ^{**}	27.18 ^{**}	2.68 ^{**}	3.05 ^{**}	3.94453 ^{**}	7.88941 ^{**}
Sites x Irrigation	1	5000 ^{NS}	0.0056 ^{NS}	0.6075 ^{NS}	0 ^{NS}	0.11 ^{NS}	0.00003 ^{NS}	0.82688 ^{**}
Error	8	13940	0.0121	0.5789	0	0.02	0.00254	0.00049
Total	11							

NS = Non-significant (P>0.05); * = Significant (P<0.05); ** = Highly-significant (P<0.01).

Table 02: Physicochemical Properties of Water Collected from Two Sites for Radish Cultivation

Sites	EC (μS/cm)	Ca+Mg (meq/L)	Na (meq/L)	HCO ₃ (meq/L)	Cl (meq/L)	SAR	RSC (meq/L)
CW1	659.95±45.09	2.12±0.08	10.83±0.06	3.01±0.02	12.35±0.06	7.66±0.03	1.02±0.01
SW1	1949.3±13.5	5.23±0.04	13.39±0.72	3.96±0.02	13.17±0.13	8.81±0.02	3.17±0.02
CW2	603.62±126.98	2.2±0.07	10.53±0.06	3.01±0.01	12.25±0.06	7.69±0.04	0.97±0.01
SW2	1974.62±15.72	5.22±0.05	13.99±0.5	3.95±0.01	13.45±0.06	8.84±0.03	2.07±0.01

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Table 03: Analysis of Variance (Mean Square) for Physicochemical Properties of Soil Used for Radish Cultivation

Source of Variation	Degrees of Freedom	EC	pH	P	K	OM	Saturation
Sites	1	0.132 ^{NS}	0.3675 ^{NS}	0.27 ^{NS}	75 ^{NS}	0.0192 ^{**}	21.333 ^{**}
Irrigation	1	424.592 ^{**}	2.7075 ^{**}	23.52 ^{**}	29205.3 ^{**}	1.92 ^{**}	85.333 ^{**}
Sites x Irrigation	1	0.563 ^{NS}	0.04083 ^{NS}	3.63 ^{**}	432 ^{**}	0.0003 ^{NS}	5.333 ^{NS}
Error	8	0.314	0.05417	0.0625	18.7	0.00053	1.333
Total	11	0	0	0	0	0	0

NS = Non-significant (P>0.05); * = Significant (P<0.05); ** = Highly-significant (P<0.01).

Table 04: Physicochemical Properties of Soil Collected from Two Sites for Radish Cultivation

Sites	EC (mS/cm)	pH	P (mg/Kg)	K (mg/Kg)	OM (%)	Saturation (%)
CW1	3.942±0.023	7.6±0.115	6.65±0.115	67.95±3.464	0.59±0.017	38.95±0.577
SW1	16.272±0.212	8.667±0.12	8.35±0.208	154.617±1.764	1.38±0.012	42.95±0.577
CW2	4.59±0.61	7.37±0.176	5.25±0.115	60.95±1.732	0.66±0.012	40.28±0.882

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SW2	16.05±0.018	8.2±0.115	9.15±0.115	171.62±2.603	1.47±0.012	46.95±0.577
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Table 05: Analysis of Variance (Mean Square) for Proximate Composition of Radish

Source of Variation	Degrees of Freedom	Moisture	Crude Fat	Crude Fiber	Crude Protein	Carbohydrate	Ash
Sites	1	24.368**	0.0147 ^{NS}	0.2028 ^{NS}	0.02 ^{NS}	30.4**	0.010208 ^{NS}
Irrigation	1	19.508**	0.6912**	0.2523 ^{NS}	1.39**	18.9**	0.078408**
Sites x Irrigation	1	1.5408 ^{NS}	0.0075 ^{NS}	0.0588 ^{NS}	0.03 ^{NS}	4.563 ^{NS}	0.255208**
Error	8	0.8917	0.0131	0.0514	0.03	1.359	0.000333
Total	11						

NS = Non-significant (P>0.05); * = Significant (P<0.05); ** = Highly-significant (P<0.01).

Table 06: Proximate of Radish Sample Collected from Two Sites

Sites	Moisture (%)	Crude fat (%)	Crude Fiber (%)	Crude Protein (%)	Carbohydrate (%)	Ash (%)
CW1	93.8±0.379	0.733±0.088	0.733±0.088	0.437±0.055	3.78±0.512	0.517±0.012

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SW1	91.967±0.437	0.203±0.065	0.583±0.235	1.22±0.095	5.057±0.598	0.97±0.006
CW2	91.667±0.722	0.613±0.066	0.613±0.066	0.627±0.11	5.73±0.756	0.75±0.012
SW2	88.4±0.577	0.183±0.033	0.183±0.033	1.207±0.116	9.473±0.787	0.62±0.012

Table 07: Analysis of Variance (Mean Square) for Heavy Metals in Water Used for Radish Cultivation

Source of Variation	Degrees of Freedom	Cu	Fe	Zn	Mn	Cd	Co	Pb	Mo
Sites	1	0.5167**	2.43**	0.6075**	0.02**	3E-04 ^{NS}	0 ^{NS}	0.00036**	1.2E-05**
Irrigation	1	1.4491**	6.75**	1.6875**	0.07**	0.003 ^{NS}	0.000363**	0.00811**	0.0078**
Sites x Irrigation	1	0.5167**	2.43**	0.6075**	0.02**	1E-06 ^{NS}	0 ^{NS}	0 ^{NS}	0.00011**
Error	8	3E-05	2E-05	2E-05	0	4E-04	0	0	0
Total	11								

NS = Non-significant (P>0.05); * = Significant (P<0.05); ** = Highly-significant (P<0.01).

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Table 08: Heavy Metal Concentrations in Water Samples from Two Sites for Radish Cultivation

Sites	Cu (mg/Kg)	Fe (mg/Kg)	Zn (mg/Kg)	Mn (mg/Kg)	Cd (mg/Kg)	Co (mg/Kg)	Pb (mg/Kg)	Mo (mg/Kg)
CW1	0.625±0.0029	1.375±0.0029	0.685±0.0029	0.135±0.0029	0.033±0.0003	0.007±0.0015	0.021±0.0003	0.021±0.0003
SW1	0.905±0.0029	1.975±0.0029	0.985±0.0029	0.195±0.0029	0.044±0.0003	0.04±0.0115	0.073±0.0003	0.078±0.0003
CW2	0.625±0.00289	1.375±0.00289	0.685±0.00289	0.135±0.00289	0.033±0.00029	0.016±0.00684	0.01±0.00029	0.025±0.00029
SW2	1.735±0.00289	3.775±0.00289	1.885±0.00289	0.375±0.00289	0.044±0.00029	0.05±0.01732	0.062±0.00029	0.07±0.00029

DISCUSSION

The findings clearly demonstrate that wastewater irrigation significantly influences soil quality and heavy metal accumulation in radish cultivation systems.

Sewage water exhibited substantially higher electrical conductivity compared to canal water, reflecting increased dissolved salts [22]. Elevated salinity in irrigation water contributes directly to increased soil EC under long-term application. Salinity stress may alter nutrient availability and modify heavy metal mobility within the soil matrix [23].

Higher sodium adsorption ratio and residual sodium carbonate values observed in sewage water indicate increased sodicity hazards. Excess sodium can deteriorate soil structure by dispersing clay particles, reducing permeability and aeration. Such changes influence root development and metal uptake dynamics [24]. Soil organic matter content was significantly higher in sewage-irrigated fields. Wastewater typically contains organic residues that accumulate over time [25]. Organic matter plays a dual role in heavy metal dynamics: it can immobilize metals through complexation or enhance mobility depending on environmental conditions [26].

Soil pH values remained within neutral to slightly alkaline ranges. Under alkaline conditions, certain metals such as Pb may precipitate, whereas others like Mo become more available [27]. Therefore, soil reaction critically regulates metal bioavailability in radish cultivation systems. Heavy metal concentrations in sewage-irrigated soils were consistently higher than canal-irrigated soils. This confirms that untreated wastewater acts as a continuous source of metal input. Because heavy metals are non-biodegradable, repeated irrigation leads to progressive accumulation [28].

Radish grown under sewage irrigation showed elevated concentrations of several metals. As a root vegetable, radish remains in direct contact with contaminated soil, increasing its exposure [29]. Metal uptake is influenced by soil salinity, pH, organic matter content, and metal speciation [30]. Although wastewater may improve nutrient availability and potentially enhance crop growth, the concurrent increase in heavy metal load poses environmental risks. Long-term

accumulation may eventually exceed safe agricultural thresholds [31].

Statistical analysis confirmed irrigation source as the dominant factor affecting both soil quality parameters and heavy metal distribution [32]. Site effects were comparatively less pronounced, highlighting irrigation water quality as the primary determinant [33].

Overall, wastewater irrigation creates a complex scenario: improved nutrient enrichment accompanied by gradual heavy metal buildup. Sustainable management practices are essential to prevent irreversible soil degradation and contamination of radish crops.

CONCLUSION

The study demonstrated that wastewater irrigation significantly alters soil physicochemical properties and enhances heavy metal accumulation in radish cultivation systems. Sewage water increased soil salinity, organic matter content, and metal concentrations compared to canal water irrigation. Radish grown under wastewater irrigation showed elevated heavy metal levels, indicating progressive contamination. Although wastewater contributes nutrients to the soil, its long-term use poses environmental risks. Continuous monitoring and controlled management are necessary to maintain soil quality and ensure sustainable radish production.

FUTURE RECOMMENDATIONS

Wastewater should undergo proper treatment before being used for irrigation purposes.

Regular monitoring of soil and radish metal concentrations must be implemented.

Integrated soil management practices should be adopted to reduce salinity and metal buildup.

Policy regulations and farmer awareness programs should be strengthened to promote safe irrigation practices.

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