

Impact of Organic Wastes and Irrigation Water Quality on Copper and Cobalt Dynamics in Soil and Their Phytoremediation by Statice (*Limonium sinuatum* L.)

Afrah Mohsen Ali¹ Sabah Latif Assi²

^{1,2} Department of Soil and Water Techniques, Al-Mussaib Technical College, Al-Furat Al-Awsat Technical University, Iraq). E-mail afrah.mohsen.tcm94@student.atu.edu.iq

Received (12/01/2026), Received in revised form (18/03/2026)
Accepted (22/05/2026), Available online (30/09/2026)

FJIAS 2026, 2(3): 1-14

Abstract.

*This study was conducted during the 2025–2026 agricultural season under a shade net at Al-Imam Agricultural Nursery, Al-Imam Subdistrict, Al-Mahawil District, Babil Governorate, Iraq, to evaluate the effects of organic wastes, irrigation water sources, and statice cultivation (*Limonium sinuatum* L.) on copper and cobalt concentrations in soil and their accumulation in plant tissues. The experiment was conducted as a $3 \times 3 \times 2$ factorial experiment arranged in a completely randomized design (CRD) with three replications. The studied factors included organic wastes (no addition, sewage sludge at 100 t ha^{-1} , and poultry manure at 40 t ha^{-1}), irrigation water sources (river water, well water, and sewage water), and cultivation (with or without statice). Copper and cobalt concentrations were determined in the soil and in the shoots and roots of statice plants. The results showed that sewage sludge produced the highest mean soil concentrations of copper and cobalt, reaching 8.33 and 5.35 mg kg^{-1} soil, respectively, whereas the no-addition treatment recorded the lowest means. Sewage water also resulted in the highest mean soil concentrations of copper and cobalt, reaching 8.39 and 5.48 mg kg^{-1} soil, respectively. Statice cultivation reduced soil copper concentration from 9.68 to 4.30 mg kg^{-1} and soil cobalt concentration from 5.22 to 4.21 mg kg^{-1} compared with non-cultivated soil. In plant tissues, the combined application of sewage sludge and sewage water resulted in the highest copper and cobalt concentrations in both shoots and roots. These findings indicate that sewage sludge and sewage water were the major sources contributing to copper and cobalt accumulation in the soil, while statice demonstrated a clear capacity to absorb these elements and reduce their concentrations in the soil.*

Keywords: organic wastes; sewage water; copper; cobalt; statice; phytoremediation.

1. INTRODUCTION

Heavy metals are of considerable environmental concern because of their persistence, limited biodegradability, potential bioavailability, and tendency to accumulate in soils and plant tissues, thereby posing potential risks to ecosystems and human health. In agricultural soils, their environmental significance depends not only on their total concentrations but also on their mobility, bioavailability, and potential transfer through the soil–plant system.

Therefore, understanding the behavior of individual metals under different soil management conditions is essential for assessing contamination and developing appropriate remediation strategies [1, 2].

Organic wastes, including sewage sludge and poultry manure, are commonly applied to agricultural soils to improve soil fertility, increase organic matter content, and supply essential plant nutrients. However, these materials may also contribute to the accumulation of heavy metals, particularly when applied at high rates or repeatedly over time. Their effects on soil depend largely on their chemical composition, degree of stabilization, application rate, and metal content. Sewage sludge is of particular concern because it may contain potentially harmful elements that can accumulate in soil following land application [3, 4].

The quality and source of irrigation water can also influence the accumulation of heavy metals in agricultural soils. Prolonged irrigation with water containing elevated concentrations of dissolved salts and potentially toxic elements, particularly untreated sewage water, may increase the accumulation and mobility of heavy metals in the soil. The extent of this effect depends on water quality, irrigation duration, soil properties, and the concentrations of contaminants present in the irrigation water [5, 6].

Copper (Cu) is an essential micronutrient required for several physiological and biochemical processes in plants; however, excessive concentrations may become toxic. Its mobility and availability in soil are influenced by several factors, including soil reaction, organic matter content, clay minerals, and metal oxides [7]. Cobalt (Co) is a naturally occurring trace element in soils, but elevated concentrations may adversely affect soil organisms, plant growth, and environmental quality [8, 9]. Therefore, the behavior of Cu and Co in the soil–plant system is influenced by both their sources of input and the ability of plants to absorb, accumulate, and translocate these elements within their tissues.

Statice (*Limonium sinuatum* L.) is an ornamental plant that may have potential value in phytoremediation studies because, as a non-food crop, its cultivation may reduce concerns associated with the transfer of accumulated metals into the human food chain. Previous research has demonstrated the ability of *L. sinuatum* to accumulate heavy metals such as lead and cadmium, suggesting its potential application in the remediation of metal-contaminated soils [10]. In addition, *L. sinuatum* has shown considerable tolerance to abiotic stress, particularly salinity, which may support its establishment under adverse soil conditions [11].

Therefore, the present study aimed to evaluate the effects of organic wastes and irrigation water sources on copper and cobalt concentrations in soil and to assess their uptake and accumulation in the shoots and roots of statics.

2. MATERIALS AND METHODS

2.1 Experimental site

The pot experiment was conducted during the 2025–2026 agricultural season at Al-Imam Agricultural Nursery, Al-Imam Subdistrict, Al-Mahawil District, Babil Governorate, Iraq, located at 32.665017° N and 44.527820° E.

2.2 Preparation of the growing medium

The experimental area under the shade net was thoroughly cleaned, and all plant residues and weeds were removed. The ground was then covered with a nylon sheet followed by a layer of sand to minimize weed growth and insect infestation. The soil was air-dried, crushed, sieved, and subsequently placed in the experimental pots according to the requirements of the experiment.

2.3 Experimental design and treatments

completely randomized design (CRD) with three replications, resulting in 18 treatment combinations and 54 experimental units. The experiment included three factors. The first factor was organic waste application at three levels: no addition, sewage sludge at 100 t ha⁻¹ applied before planting, and poultry manure at 40 t ha⁻¹. The second factor was irrigation water source at three levels: river water, well water, and sewage water. The third factor was cultivation, represented by soil cultivated with statics and non-cultivated soil. The experimental treatments were arranged according to all possible factorial combinations of the three factors.

2.4 Organic wastes and irrigation water

Sewage sludge was collected from the wastewater treatment station in the Al-Maamiriya area, Babil Governorate. The sludge was placed in polyethylene bags, air-dried, ground, and passed through a 4-mm sieve before application. Poultry manure was obtained from local poultry farms, air-dried, ground, and sieved before use. Three irrigation water sources were used in the experiment: river water, well water, and sewage water, according to the assigned experimental treatments.

2.5 Determination of heavy metals in soil

For the determination of copper (Cu) and cobalt (Co) in soil, 1 g of air-dried soil previously passed through a 2-mm sieve was transferred into a 50-mL Pyrex flask. Five milliliters of concentrated nitric acid (HNO_3) were added, and the samples were left for 24 h. The samples were then heated on a hot plate at 80°C for 1 h and allowed to cool. Subsequently, 5 mL of concentrated perchloric acid (HClO_4) were added, and the samples were heated on a hot plate at 180°C for 2–3 h until the digest changed from dark brown to a clear, colorless solution. The digests were filtered through Whatman No. 42 filter paper, and the final volume was adjusted to 10 mL with distilled water. Copper and cobalt concentrations were then determined using an atomic absorption spectrophotometer (AAS) at the appropriate wavelength for each element [12].

2.6 Determination of copper and cobalt in plant tissues

At the end of the growing season, plant samples were collected separately from the shoots and roots of static plants in each experimental unit. The samples were washed first with tap water and then with distilled water, oven-dried at 65°C for 48 h until a constant weight was obtained, and ground using an electric grinder. The ground samples were thoroughly homogenized, passed through a 0.5-mm sieve, and stored in plastic containers until analysis.

For the determination of copper (Cu) and cobalt (Co), 0.5 g of the dried and ground plant sample was transferred into a 250-mL Pyrex flask. Then, 2.5 mL of concentrated sulfuric acid (H_2SO_4) were added, and the samples were left for 24 h. The samples were subsequently heated on a hot plate at 80°C for 1 h and allowed to cool. Thereafter, 2.5 mL of concentrated perchloric acid (HClO_4) were added, and digestion was continued at 180°C for 2–3 h until a clear, colorless solution was obtained. The digests were filtered through Whatman No. 42 filter paper, and the final volume was adjusted to 50 mL with distilled water. Copper and cobalt concentrations were determined using an atomic absorption spectrophotometer (AAS) [13].

2.7 Statistical analysis

The experimental data were subjected to analysis of variance (ANOVA) using GenStat software according to the factorial completely randomized design. Treatment means were compared using the least significant difference (LSD) test at the 5% probability level.

3.RESULTS AND DISCUSSION

3.1 Total copper concentration in soil (mg kg^{-1} soil)

Table (1) shows significant differences in total soil copper concentration among the studied factors. Among the organic waste treatments, sewage sludge recorded the highest mean copper concentration (8.33 mg kg^{-1} soil), followed by poultry manure (7.61 mg kg^{-1} soil), whereas the no-addition treatment recorded the lowest mean (5.03 mg kg^{-1} soil). Regarding irrigation water sources, sewage water produced the highest mean copper concentration (8.39 mg kg^{-1} soil), followed by well water (6.53 mg kg^{-1} soil), while river water recorded the lowest mean (6.04 mg kg^{-1} soil). Cultivation also had a significant effect on soil copper concentration, as non-cultivated soil recorded a mean of 9.68 mg kg^{-1} soil, compared with 4.30 mg kg^{-1} soil in soil cultivated with static.

The triple interaction among cultivation, organic waste, and irrigation water source showed significant differences in soil copper concentration. The highest value (13.53 mg kg^{-1} soil) was recorded in non-cultivated soil treated with sewage sludge and irrigated with sewage water, whereas the lowest value (3.11 mg kg^{-1} soil) was recorded in soil cultivated with static, receiving no organic waste addition, and irrigated with river water.

The increase in soil copper concentration following sewage sludge application may be attributed to the input of copper and other trace elements contained in the sludge, particularly when such materials are applied at relatively high rates or repeatedly over time [14]. Similarly, the higher copper concentration recorded under sewage water irrigation may be associated with the presence of copper and other dissolved constituents in wastewater, which can accumulate in soil with continued irrigation [6]. In contrast, the reduction in soil copper concentration under static cultivation may be related to plant uptake and the ability of the root system to absorb and regulate copper through sequestration and controlled translocation within plant tissues. Plants employ several physiological and molecular mechanisms to regulate copper uptake, transport, and detoxification under elevated copper availability [15].

Table(1). Effect of organic wastes, irrigation water sources, and static cultivation on total copper concentration in soil (mg kg^{-1} soil).

Mean	Irrigation water			Organic waste	Cultivation
	Sewage	Well	River		
6.38	9.94	4.64	4.57	No addition	Non-cultivated
11.95	13.53	11.90	10.42	Sewage sludge	

10.69	12.74	10.13	9.21	Poultry manure	Cultivated
3.68	4.50	3.41	3.11	No addition	
4.70	4.95	4.63	4.52	Sewage sludge	
4.53	4.67	4.49	4.42	Poultry manure	
0.034	0.059			LSD 0.05	
Mean	Irrigation water x cultivation			Cultivation	
9.68	12.07	8.89	8.07	Non-cultivated	
4.30	4.71	4.18	4.02	Cultivated	
0.020	0.034			LSD	
Mean	Organic waste x irrigation water			Organic waste	
5.03	7.22	4.03	3.84	No addition	
8.33	9.24	8.27	7.47	Sewage sludge	
7.61	8.71	7.31	6.82	Poultry manure	
0.024	0.04			LSD	
	8.39	6.53	6.04	Mean	
	0.024			LSD	

For the interaction between cultivation and irrigation water source, the highest mean copper concentration (12.07 mg kg⁻¹ soil) was recorded in non-cultivated soil irrigated with sewage water, whereas the lowest mean (4.02 mg kg⁻¹ soil) was recorded in static-cultivated soil irrigated with river water. Regarding the interaction between organic waste and irrigation water source, sewage sludge combined with sewage water recorded the highest mean copper concentration (9.24 mg kg⁻¹ soil), whereas the no-addition treatment combined with river water recorded the lowest mean (3.84 mg kg⁻¹ soil). Furthermore, the interaction between cultivation and organic waste showed that non-cultivated soil treated with sewage sludge recorded the highest mean copper concentration (11.95 mg kg⁻¹ soil), while cultivated soil without organic waste addition recorded the lowest mean (3.68 mg kg⁻¹ soil).

3.2 Total cobalt concentration in soil (mg kg⁻¹ soil)

Table (2) shows significant differences in total soil cobalt concentration among the studied factors. Among the organic waste treatments, sewage sludge recorded the highest mean cobalt concentration (5.35 mg kg⁻¹ soil), followed by poultry manure (5.04 mg kg⁻¹ soil), whereas the no-addition treatment recorded the lowest mean (3.76 mg kg⁻¹ soil). Regarding irrigation water sources, sewage water produced the highest mean cobalt concentration (5.48 mg kg⁻¹ soil), followed by well water (4.46 mg kg⁻¹ soil), while river water recorded the lowest mean (4.20 mg kg⁻¹ soil). Cultivation also significantly affected soil cobalt concentration, as non-cultivated soil recorded a mean of 5.22 mg kg⁻¹ soil, compared with 4.21 mg kg⁻¹ soil in soil cultivated with static.

The triple interaction among cultivation, organic waste, and irrigation water source showed significant differences in soil cobalt concentration. The highest value (6.83 mg kg⁻¹ soil) was recorded in non-cultivated soil treated with sewage sludge and irrigated with sewage water, whereas the lowest value (2.82 mg kg⁻¹ soil) was recorded in soil cultivated with static, receiving no organic waste addition, and irrigated with river water.

The increase in soil cobalt concentration following sewage sludge application may be attributed to the direct input of cobalt and other heavy metals contained in the sludge. Sewage sludge has been reported to contain cobalt among the measured heavy metals, supporting its potential role as a direct source of cobalt accumulation in soil [16]. Similarly, the higher cobalt concentration recorded under sewage water irrigation may be associated with the presence of cobalt and other dissolved constituents in wastewater, which can accumulate in soil with continued irrigation. Higher cobalt accumulation has been reported in soils irrigated with wastewater compared with canal water [17]. In contrast, the lower soil cobalt concentration under static cultivation may be related to plant uptake and rhizosphere-associated processes that contribute to the removal of part of the cobalt from the soil [18].

For the interaction between cultivation and irrigation water source, the highest mean cobalt concentration (5.99 mg kg⁻¹ soil) was recorded in non-cultivated soil irrigated with sewage water, whereas the lowest mean (3.70 mg kg⁻¹ soil) was recorded in static-cultivated soil irrigated with river water. Regarding the interaction between organic waste and irrigation water source, sewage sludge combined with sewage water recorded the highest mean cobalt concentration (6.33 mg kg⁻¹ soil), whereas the no-addition treatment combined with river water recorded the lowest mean (3.32 mg kg⁻¹ soil). Furthermore, the interaction between cultivation and organic waste showed that non-cultivated soil treated with sewage sludge recorded the highest mean cobalt concentration (5.85 mg kg⁻¹ soil), while cultivated soil without organic waste addition recorded the lowest mean (3.26 mg kg⁻¹ soil).

Table 2. Effect of organic wastes, irrigation water sources, and static cultivation on total cobalt concentration in soil (mg kg⁻¹ soil).

Mean	Irrigation water			Organic waste	Cultivation
	Sewage	Well	River		
4.25	4.98	3.97	3.82	No addition	Non-cultivated

5.85	6.83	5.51	5.22	Sewage sludge	
5.55	6.17	5.41	5.05	Poultry manure	
3.26	3.98	2.97	2.82	No addition	Cultivated
4.86	5.83	4.51	4.22	Sewage sludge	
4.52	5.10	4.41	4.07	Poultry manure	
0.006	0.010			LSD 0.05	
Mean	Irrigation water x cultivation			Cultivation	
5.22	5.99	4.96	4.70	Non-cultivated	
4.21	4.97	3.96	3.70	Cultivated	
0.003	0.006			LSD	
Mean	Organic waste x irrigation water			Organic waste	
3.76	4.48	3.47	3.32	No addition	
5.35	6.33	5.01	4.72	Sewage sludge	
5.04	5.64	4.91	4.56	Poultry manure	
0.004	0.01			LSD	
	5.48	4.46	4.20	Mean	
	0.004			LSD	

3.3 Copper concentration in the shoots and roots of static (mg kg⁻¹ dry matter)

Table (3) shows significant differences in copper concentrations in the shoots and roots of static plants as affected by organic waste treatments and irrigation water sources. In the shoots, sewage sludge recorded the highest mean copper concentration (2.89 mg kg⁻¹ dry matter), followed by poultry manure (2.74 mg kg⁻¹ dry matter), whereas the no-addition treatment recorded the lowest mean (2.55 mg kg⁻¹ dry matter). Regarding irrigation water sources, sewage water produced the highest mean copper concentration (4.82 mg kg⁻¹ dry matter), followed by well water (1.88 mg kg⁻¹ dry matter), while river water recorded the lowest mean (1.48 mg kg⁻¹ dry matter). The interaction between organic waste and irrigation water source showed that sewage sludge combined with sewage water recorded the highest copper concentration in the shoots (5.04 mg kg⁻¹ dry matter), whereas the no-addition treatment combined with river water recorded the lowest concentration (1.35 mg kg⁻¹ dry matter).

In the roots, sewage sludge also recorded the highest mean copper concentration (2.79 mg kg⁻¹ dry matter), followed by poultry manure (2.62 mg kg⁻¹ dry matter), whereas the no-

addition treatment recorded the lowest mean (2.45 mg kg^{-1} dry matter). Sewage water resulted in the highest mean copper concentration in the roots (4.76 mg kg^{-1} dry matter), followed by well water (1.74 mg kg^{-1} dry matter), while river water recorded the lowest mean (1.36 mg kg^{-1} dry matter). The highest copper concentration in the roots (4.99 mg kg^{-1} dry matter) was recorded under the combination of sewage sludge and sewage water, whereas the lowest concentration (1.23 mg kg^{-1} dry matter) was recorded under the no-addition treatment irrigated with river water.

Overall, copper concentrations in the shoots were slightly higher than those in the roots in most treatments, indicating that a portion of the absorbed copper was translocated from the roots to the aboveground tissues. The increased copper accumulation in plant tissues under sewage sludge application may be attributed to the greater availability of copper in soil resulting from this organic source [19]. Similarly, the higher copper concentrations observed under sewage water irrigation may be associated with the input of copper and other dissolved constituents through irrigation water, leading to increased copper availability in soil and subsequent uptake by the plant. Previous studies have shown that irrigation with non-conventional water resources can enhance copper accumulation in soils and plant tissues [19]. The relatively higher copper concentrations observed in the shoots may also be related to physiological and molecular mechanisms regulating copper uptake, sequestration, transport, and detoxification within plant tissues [20].

Table 3. Effect of organic wastes and irrigation water sources on copper concentration in the shoots and roots of static (mg kg⁻¹ dry matter).

Shoot system				
Mean	Irrigation water			Organic waste
	Sewage	Well	River	
2.55	4.61	1.70	1.35	No addition
2.89	5.04	2.05	1.58	Sewage sludge
2.74	4.81	1.89	1.52	Poultry manure
0.021	0.036			LSD _{0.05}
	4.82	1.88	1.48	Irrigation water
	0.021			LSD _{0.05}
Root system				
Mean	Irrigation water			Organic waste
	Sewage	Well	River	
2.45	4.55	1.56	1.23	No addition

2.79	4.99	1.92	1.46	Sewage sludge
2.62	4.75	1.74	1.38	Poultry manure
0.016	0.028			LSD _{0.05}
	4.76	1.74	1.36	Irrigation water
	0.016			LSD _{0.05}

3.4 Cobalt concentration in the shoots and roots of static (mg kg⁻¹ dry matter)

The data presented in Table (4) show significant differences in cobalt concentrations in the shoots and roots of static plants as affected by organic waste treatments and irrigation water sources. In the shoots, sewage sludge recorded the highest mean cobalt concentration (2.96 mg kg⁻¹ dry matter), followed by poultry manure (2.71 mg kg⁻¹ dry matter), whereas the no-addition treatment recorded the lowest mean (2.13 mg kg⁻¹ dry matter). Regarding irrigation water sources, sewage water produced the highest mean cobalt concentration (5.00 mg kg⁻¹ dry matter), followed by well water (1.46 mg kg⁻¹ dry matter), while river water recorded the lowest mean (1.33 mg kg⁻¹ dry matter). The interaction between organic waste and irrigation water source showed that sewage sludge combined with sewage water recorded the highest cobalt concentration in the shoots (5.78 mg kg⁻¹ dry matter), whereas the no-addition treatment combined with river water recorded the lowest concentration (1.12 mg kg⁻¹ dry matter).

In the roots, sewage sludge also recorded the highest mean cobalt concentration (2.85 mg kg⁻¹ dry matter), followed by poultry manure (2.56 mg kg⁻¹ dry matter), whereas the no-addition treatment recorded the lowest mean (2.00 mg kg⁻¹ dry matter). Sewage water resulted in the highest mean cobalt concentration in the roots (5.00 mg kg⁻¹ dry matter), followed by well water (1.26 mg kg⁻¹ dry matter), while river water recorded the lowest mean (1.15 mg kg⁻¹ dry matter). The highest cobalt concentration in the roots (5.85 mg kg⁻¹ dry matter) was recorded under the combination of sewage sludge and sewage water, whereas the lowest concentration (0.95 mg kg⁻¹ dry matter) was recorded under the no-addition treatment irrigated with river water.

Overall, cobalt was accumulated in both the shoots and roots of static, with relatively small differences between the two plant parts depending on the treatment. Shoot cobalt concentrations were higher than root concentrations in several treatments, indicating that a portion of the absorbed cobalt was translocated from the roots to the aboveground tissues.

However, under the sewage sludge and sewage water combination, the maximum cobalt concentration in the roots (5.85 mg kg^{-1} dry matter) slightly exceeded that recorded in the shoots (5.78 mg kg^{-1} dry matter). The increased cobalt accumulation under sewage sludge application and sewage water irrigation may be attributed to the direct contribution of cobalt from these sources and its increased availability in the soil solution [21, 22].

Table 4. Effect of organic wastes and irrigation water sources on cobalt concentration in the shoots and roots of static (mg kg⁻¹ dry matter).

Shoot system				
Mean	Irrigation water			Organic waste
	Sewage	Well	River	
2.13	4.08	1.20	1.12	No addition
2.96	5.78	1.63	1.46	Sewage sludge
2.71	5.15	1.56	1.41	Poultry manure
0.021	0.037			LSD _{0.05}
	5.00	1.46	1.33	Irrigation water
	0.021			LSD _{0.05}
Root system				
Mean	Irrigation water			Organic waste
	Sewage	Well	River	
2.00	4.02	1.02	0.95	No addition
2.85	5.85	1.42	1.28	Sewage sludge
2.56	5.12	1.35	1.22	Poultry manure
0.020	0.034			LSD _{0.05}
	5.00	1.26	1.15	Irrigation water
	0.020			LSD _{0.05}

4. Conclusions

- Sewage sludge increased copper and cobalt concentrations in soil compared with the no-addition and poultry manure treatments, indicating that sewage sludge was the organic waste most strongly associated with the accumulation of these two elements in soil.
- Sewage water was the irrigation source that resulted in the highest mean concentrations of copper and cobalt in soil compared with well water and river water.
- Cultivation with static reduced copper and cobalt concentrations in soil compared with non-cultivated soil, indicating the ability of the plant to remove part of these elements from the soil through uptake.

- The combination of sewage sludge and sewage water resulted in the highest accumulation of copper and cobalt in the shoots and roots of statice, indicating that increased concentrations of these elements in the soil were associated with greater plant uptake.
- Copper and cobalt were translocated from the roots to the shoots, with shoot concentrations exceeding root concentrations in several treatments, indicating the ability of statice to absorb and translocate these elements within plant tissues.

5. Recommendations

- Sewage sludge and sewage water should be analyzed for copper, cobalt, and other heavy metals before being used for agricultural purposes.
- Untreated sewage water should not be recommended for irrigation without appropriate treatment and periodic monitoring of heavy metal accumulation in soil.
- Statice may be considered a promising plant for further phytoremediation studies in soils containing elevated concentrations of copper and cobalt, provided that the harvested biomass is properly removed and managed.
- Further studies should evaluate phytoremediation indices, including the bioconcentration factor (BCF), biological accumulation coefficient (BAC), and translocation factor (TF), to better determine the potential of statice for phytoextraction or phytostabilization of copper and cobalt.
- Lower application rates of sewage sludge and treated wastewater should be evaluated to identify levels that provide beneficial effects on soil while minimizing the accumulation of copper and cobalt.

REFERENCES

- [1] Tangahu, B. V., Sheikh Abdullah, S. R., Basri, H., Idris, M., Anuar, N., & Mukhlisin, M. (2011). A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *International Journal of Chemical Engineering*, 2011, 939161.
- [2] Pouresmaieli, M., Ataei, M., Forouzandeh, P., Azizollahi, P., & Mahmoudifard, M. (2022). Recent progress on sustainable phytoremediation of heavy metals from soil. *Journal of Environmental Chemical Engineering*, 10(5), 108482.

- [3] Nunes, N., Ragonezi, C., Gouveia, C. S. S., & Pinheiro de Carvalho, M. Â. A. (2021). Review of sewage sludge as a soil amendment in relation to current international guidelines: A heavy metal perspective. *Sustainability*, 13(4), 2317.
- [4] Ondrasek, G., Bubalo Kovačić, M., Reljić, M., Školjarev, D., Stipičević, S., Smoljo, I., Matthies, R., Samardžija, P., Savić, R., Shahid, M. S., & Horvatinec Isaković, J. (2025). From hazardous waste to valuable resource: Trends in sewage sludge composition and reuse challenges at Croatia's largest wastewater treatment plant. *Energy Nexus*, 20, 100593.
- [5] Alnaimy, M. A., Shahin, S. A., Vranayova, Z., Zelenakova, M., & Abdel-Hamed, E. M. W. (2021). Long-term impact of wastewater irrigation on soil pollution and degradation: A case study from Egypt. *Water*, 13(16), 2245.
- [6] Natasha, Shahid, M., Khalid, S., Murtaza, B., Bibi, I., Rashid, M. I., Al-Wabel, M. I., Niazi, N. K., & Dumat, C. (2022). Accumulation pattern and risk assessment of potentially toxic elements in selected wastewater-irrigated soils and plants in Vehari, Pakistan. *Environmental Research*, 214, 113853.
- [7] Pikula, D. (2023). Effect of the degree of soil contamination with Cd, Zn, Cu, and Pb on their mobility in the soil profile in a microplot experiment. In *Heavy Metals*. IntechOpen.
- [8] Cappuyns, V., & Mallaerts, T. (2014). Background values of cobalt in soils and factors controlling its concentrations. *Journal of Geochemical Exploration*, 147, 42–50.
- [9] Kosiorek, M., & Wyszowski, M. (2019). Effect of cobalt on the environment and living organisms—A review. *Environmental Monitoring and Assessment*, 191(12), 1–17.
- [10] Sheikh-Assadi, M., Khandan-Mirkohi, A., Alemardan, A., & Moreno-Jiménez, E. (2015). Mycorrhizal *Limonium sinuatum* (L.) Mill. enhances accumulation of lead and cadmium. *International Journal of Phytoremediation*, 17(6), 556–562.
- [11] Xu, X., Zhou, Y., Mi, P., Wang, B., & Yuan, F. (2021). Salt-tolerance screening in *Limonium sinuatum* varieties with different flower colors. *Scientific Reports*, 11, 14562.
- [12] Page, A. L., Miller, R. H., & Keeney, D. R. (Eds.). (1982). *Methods of soil analysis. Part 2: Chemical and microbiological properties* (2nd ed.). American Society of Agronomy.
- [13] Jones, J. B. (2001). *Laboratory guide for conducting soil tests and plant analysis*. CRC Press.
- [14] Reichman, S. M., Gu, Z., Dassanayake, K. B., Kaudal, B. B., Szokovski, L., Leonard, J. S., Coutts, A., & Surapaneni, A. (2025). Effects of multiple annual biosolids applications on the soil concentrations of metals, organochlorine pesticides and polychlorinated biphenyls in a field trial in Victoria, Australia. *Waste Management*, 201, 114777.

-
- [15] Chen, G., Li, J., Han, H., Du, R., & Wang, X. (2022). Physiological and molecular mechanisms of plant responses to copper stress. *International Journal of Molecular Sciences*, 23(21), 12950.
- [16] Dass, A., et al. (2026). Sewage water and sludge co-implementation effects on soil properties and green chili in Typic Haplustalf of southern India. *Frontiers in Agronomy*. <https://doi.org/10.3389/fagro.2026.1718217>
- [17] Khan, Z. I., Shahid, M., Ashfaq, A., Ahmad, K., Fatima, S., Bashir, S., Noorka, I. R., Ashraf, M. I., Memona, H., Seleiman, M. F., Alotaibi, M., & Ali, N. (2025). Assessing heavy metal bioaccumulation in radish and soil under wastewater and canal water irrigation. *Annals of Agricultural Sciences*, 70(1), 100388.
- [18] Siunova, T. V., Filonov, A. E., Gorovtsov, A. V., Akhmetov, L. I., Ivanov, F. D., Rajput, V. D., Minkina, T. M., Sushkova, S. N., Wong, M. H., & Biswas, J. K. (2025). Potential of nickel and cobalt resistant microorganisms for effective phytoremediation of heavy metal contaminated soils. *Discover Environment*, 3, 99.
- [19] Khan, Z. I., Hussain, M. I., Zafar, A., Ahmad, K., Ashraf, M. A., Alrashidi, A. A., Alhaithloul, H. A. S., Alghanem, S. M., & others. (2022). Ecological risk assessment and bioaccumulation of trace element, copper, in wheat varieties irrigated with non-conventional water resources in a semi-arid tropics. *Agricultural Water Management*, 274, 107899.
- [20] Xu, E., Li, Q., Lin, J., Luo, M., Pan, L., Feng, M., Ding, Y., Zhang, K., Li, C., Bao, Y., Jiang, H., & Xu, Q. (2024). Molecular mechanisms of plant responses to copper. *International Journal of Molecular Sciences*, 25(13), 6993.
- [21] Khan, Z. I., Ahmad, T., Safdar, H., Nadeem, M., Ahmad, K., Bashir, H., Ugulu, I., Dogan, Y., & Ashfaq, A. (2020). Accumulation of cobalt in soils and forages irrigated with city effluent. *Egyptian Journal of Botany*, 60(3), 855–863.
- [22] Huang, H., Yamaji, N., Huang, S., & Ma, J. F. (2025). Uptake and accumulation of cobalt is mediated by OsNramp5 in rice. *Plant, Cell & Environment*, 48(1), 3–14.