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Rahma MEJRI¹, İbrahim ERDAL^{*1}

EFFECTS OF CANOLA-BASED PHYTOREMEDIATION ON HEAVY METAL ACCUMULATION AND GROWTH OF SUBSEQUENT MAIZE IN SEWAGE SLUDGE-AMENDED SOILS

SUMMARY

The agricultural use of sewage sludge offers important benefits for soil fertility but may also increase the risk of heavy metal accumulation in crops. This study investigated the effects of industrial sewage sludge (ISS) and urban sewage sludge (USS) applied at 0, 20, and 40 t ha⁻¹ on heavy metal dynamics and crop performance in a sequential canola-maize cultivation system. In the first stage, canola was grown for phytoremediation purposes in sludge-amended soils. Subsequently, maize was cultivated in both remediated soils (after canola cultivation) and non-remediated soils under greenhouse conditions. Plant dry weight and the concentrations and uptake of Cd, Co, Cr, and Ni were determined. Sewage sludge applications significantly increased canola biomass, while also promoting heavy metal accumulation, particularly for Cr and Ni. Canola cultivation was associated with lower Cd concentration and uptake in the subsequent maize crop, suggesting that Cd availability to maize may have been reduced. In contrast, maize grown in remediated soils exhibited higher Ni and Cr concentrations and uptake than plants grown in non-remediated soils. This pattern may be related to changes in soil–plant interactions following canola cultivation, although the specific processes responsible were not directly measured in this study. Cobalt responses were comparatively limited and depended mainly on soil conditions. Overall, the results suggest that canola-based phytoremediation may reduce Cd transfer to a subsequent crop while maintaining the agronomic benefits of sewage sludge under the conditions tested. However, the contrasting responses of Ni and Cr highlight the element-specific nature of phytoremediation and the need for further investigation of the mechanisms governing metal availability during crop succession.

Keywords: sludge, heavy metals, phytoremediation, plant growth

¹Rahma Mejri, Isparta University of Applied Sciences, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Isparta, TÜRKİYE;

¹İbrahim Erdal (corresponding author: ibrahimerdal@isparta.edu.tr), Isparta University of Applied Sciences, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Isparta, TÜRKİYE. Notes: The authors declare that they have no conflicts of interest. Authorship Form signed online.

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INTRODUCTION

Rapid population growth and industrialization have led to a substantial increase in wastewater generation worldwide. Wastewater treatment plants play a crucial role in reducing the environmental impacts associated with municipal and industrial effluents. However, the treatment process generates large amounts of sewage sludge, a semi-solid by-product rich in organic matter and essential nutrients. Owing to its high concentrations of N, P and other plant nutrients, sewage sludge has been widely considered a valuable soil amendment capable of improving soil fertility, enhancing water-holding capacity, and promoting crop productivity (Singh and Agrawal, 2008; Bouriou *et al.*, 2015).

Despite these agronomic benefits, the application of sewage sludge to agricultural soils may pose environmental risks because sludge can contain potentially toxic elements, organic pollutants, and pathogenic microorganisms (Harrison *et al.*, 2006; Cherfouh *et al.*, 2025). Continuous or excessive sludge applications may increase heavy metal accumulation in soils and consequently enhance metal transfer to crops, thereby affecting food quality and environmental sustainability (Celary and Sobik-Szołtysek, 2014; Warman and Termeer, 2005). Furthermore, the characteristics of sewage sludge vary considerably depending on its origin and treatment processes, emphasizing the need to evaluate different sludge sources before their agricultural use (Kumari *et al.*, 2023). Phytoremediation has emerged as an environmentally friendly and cost-effective approach for reducing the concentration and mobility of contaminants in soils (Nedjimi, 2021). This strategy relies on the ability of certain plant species to extract, accumulate, stabilize or transform pollutants, thereby contributing to the restoration of contaminated environments (Qiu *et al.*, 2014; Santos *et al.*, 2022). Hyperaccumulator plants are capable of tolerating and accumulating heavy metals at concentrations far exceeding those observed in ordinary plants without exhibiting severe phytotoxic effects (Van der Ent *et al.*, 2013). In addition to reducing environmental risks, these plants may facilitate the productive use of contaminated soils and contribute to sustainable land management (Al Chami *et al.*, 2015).

Canola has attracted attention because of its relatively high biomass production and its ability to accumulate certain heavy metals (Zein *et al.*, 2009; Çakmakci and Ucar, 2014; Nawaz *et al.*, 2022). However, information regarding the residual effects of phytoremediation on the performance and metal accumulation of subsequent crops remains limited. Most previous studies have focused primarily on the response of the phytoremediating species itself, whereas the consequences for the following crop have received less attention.

Therefore, the present study aimed to evaluate the effects of industrial and urban sewage sludges applied at different rates on heavy metal dynamics in a sequential canola–maize cultivation system. In the first stage, canola was grown to investigate its phytoremediation potential in sludge-amended soils. Subsequently, maize was cultivated in both remediated and non-remediated soils to assess the residual fertilizing effects of sewage sludge and to determine how prior canola cultivation influenced heavy metal concentrations and uptake in the succeeding

crop. The findings provide further insight into the role of crop succession in balancing the agronomic benefits of sewage sludge with the potential risks associated with heavy metal transfer.

MATERIAL AND METHODS

Experimental soil

The soil used for the experiment had a clay-loam texture, slightly alkaline reaction, and low salinity. Calcium carbonate content was high, whereas organic matter content was low to moderate. Available nutrient concentrations were generally within sufficient ranges, and total heavy metal concentrations were below the permissible limits reported by Şimşek *et al.*, (2021)

Sewage sludges used for the experiment

Industrial sewage sludge (ISS) and urban sewage sludge (USS) were used as experimental materials. ISS was collected from the Isparta Süleyman Demirel Organized Industrial Zone Wastewater Treatment Plant, whereas USS was obtained from the Isparta Municipal Wastewater Treatment Plant. Both sludges were naturally dried and stabilized. Before use, the materials were crushed and passed through a 2-mm sieve.

Setting up the experiment

The experiment was conducted under greenhouse conditions using a completely randomized factorial design with three replications and consisted of two successive stages. In the first stage, canola was cultivated to evaluate its phytoremediation potential in sludge-amended soils. Industrial and urban sewage sludges were applied at rates of 0, 20, and 40 t ha⁻¹ to pots containing 4 kg of soil. No additional fertilizer was supplied during this stage in order to avoid interference with the phytoremediation process. Ten seeds were sown per pot and, after emergence, seedlings were thinned to three plants per pot. Plants were grown for two months under regular irrigation according to water requirements and harvested at the end of the growth period.

In the second stage, maize was grown under two different soil conditions. In the remediated soil treatment, maize was cultivated in soils previously cropped with canola, whereas in the non-remediated treatment maize was grown in newly established sludge-amended soils without prior canola cultivation. The same sludge application rates used in the first stage were applied. Basal fertilization equivalent to 300, 200, and 100 mg kg⁻¹ of N, P, and K, respectively, was supplied using urea, monoammonium phosphate, and potassium nitrate. Five maize seeds were initially sown per pot and later thinned to two plants. Plants were grown for two months under regular irrigation and harvested at the end of the experiment

Plant analysis

After harvest, shoot samples were washed with tap water followed by deionized water, dried at 70 °C for 72 h, and weighed to determine dry matter production. Dried samples were ground and dry-ashed at 500–550 °C for at least 6 h. The ash residues were dissolved in concentrated HCl and filtered. Following

appropriate dilution, K, Ca, Mg, Fe, Mn, Zn, Cu, Cd, Co, Cr, Ni, and Pb concentrations were determined using inductively coupled plasma optical emission spectrometry (ICP-OES; ICAP 6300, Thermo Electron). Phosphorus concentration was determined spectrophotometrically at 430 nm using the vanadomolybdophosphoric acid method, whereas total nitrogen was measured by the Kjeldahl method according to Jones and Case (1990).

Soil analysis

Soil organic matter was determined according to the method of Walkley and Black (1934). Total N concentration was measured by the Kjeldahl method. Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil-to-water suspension. Calcium carbonate content was measured using the calcimetric method, and cation exchange capacity (CEC) was determined using the BaCl₂ method (Hendershot *et al.*, 1993). Available P was extracted according to Olsen (1954) whereas exchangeable K, Ca, and Mg were determined using ammonium acetate extraction (Jones, 2001).

Table 1. Some physico-chemical properties of the experiment soil

Properties	Values
Soil texture	Clay-loam
Soil reaction (pH: 1/2.5 soil/water w/w)	7.5
Electrical conductivity (EC, ds m ⁻¹)	0.14
Total N (%)	0.044
Organic matter (OM, %)	1.5
CaCO ₃ (%)	28
Cation exchange capacity (CEC, mmol kg ⁻¹)	230
Field capacity (w/w, %)	28
Pot capacity (w/w, %)	36
Plant available nutrients (mg kg ⁻¹)	
P	10.5
K	161
Ca	5227
Mg	189
Fe	3.5
Mn	15.6
Zn	1.2
Cu	3.7
Heavy metal concentrations (mg kg ⁻¹)	
Available Cd	0.017
Available Ni	0.92
Available Cr	Below detection limit
Available Co	0.06
Total Cd	0.04
Total Ni	59
Total Cr	27
Total Co	6

Available micronutrients (Fe, Mn, Zn, Cu) and heavy metals (Cd, Ni, Cr, Co) were extracted with DTPA-CaCl₂-TEA solution (Lindsay and Norvell, 1978) and measured by ICP-OES. Total heavy metal concentrations were determined following aqua regia digestion (HCl+HNO₃, 3:1, v:v) and quantified by ICP-OES. Some physico-chemical properties of the soil used in the experiment are presented in Table 1.

Sludge analysis

The pH and EC values of the sludge samples were measured in a 1:5 sludge-to-water suspension (Belhaj *et al.*, 2016). Organic matter content was determined by loss on ignition at 550 °C, and total N concentration was measured by the Kjeldahl method. Phosphorus concentration was determined using the vanadomolybdophosphoric yellow color method. Nutrient elements and heavy metals were analyzed after wet digestion with a concentrated HNO₃:HClO₄ mixture (4:1, v/v), followed by ICP-OES measurements as mentioned in the methodology cited by Kuboyama *et al.*, (2005).

Some of the properties of the sewage sludges used in the experiment are outlined in Table 2.

Table 2. Some characteristics of the sludges used in the experiment

Parameters	ISS	USS
Organic matter (%)	64	52
pH	7.6	6.8
EC (dS m ⁻¹)	9.7	3.9
Macronutrients (%)		
N	4.1	5.5
P	1.63	1.14
K	0.38	0.17
Ca	1.93	2.50
Mg	0.41	1.0
Micronutrients (mg kg ⁻¹)		
Fe	4103	5940
Cu	48	78
Mn	51	100
Zn	1037	872
Heavy metals (mg kg ⁻¹)		
Cd	7.9	1.8
Co	1.2	3.0
Cr	625	30
Ni	112	17

ISS: Industrial sewage sludge, USS: Urban sewage sludge

Statistical analysis

Statistical analyses were performed using Minitab version 17 (Minitab Inc., State College, PA, USA). The experiment was conducted as a completely randomized factorial design with three replications and consisted of two successive

experimental stages. In the first stage (canola), the effects of sewage sludge source and application dosage and their interaction were evaluated using factorial analysis of variance (two-way ANOVA). In the second stage (maize), data obtained from remediated and non-remediated soils were analyzed to evaluate the effects of sewage sludge source, sludge dosage and the corresponding interaction effects. In the maize experiment, the results for remediated and non-remediated soil were evaluated separately. For this reason, two separate two-way ANOVA tests were applied. Means were separated using Tukey's honestly significant difference (HSD) test at the 5% probability level.

RESULTS AND DISCUSSION

Effects of sewage sludge treatments on dry weight of canola

The individual effects of dosages and the material dose interaction significantly ($p < 0.05$) affected the dry weight of canola (Fig. 1). For both materials, the lowest dry weight value was obtained from the control plants with 12.8 g pot^{-1} , the highest weight value (28.7 g pot^{-1}) was obtained from 40 tons of ISS application per hectare. According to means of dosages, plant dry weight increased from 12.8 g to 23.3 g and 24.8 g with increasing doses. However, the effects of 20 and 40 ton sewage sludge dosages on dry weight were found to be statistically similar. While no significant difference was observed between the materials, 21.6 g plant dry weights were obtained with ISS application and 19.0 g plant dry weights were obtained with USS application.

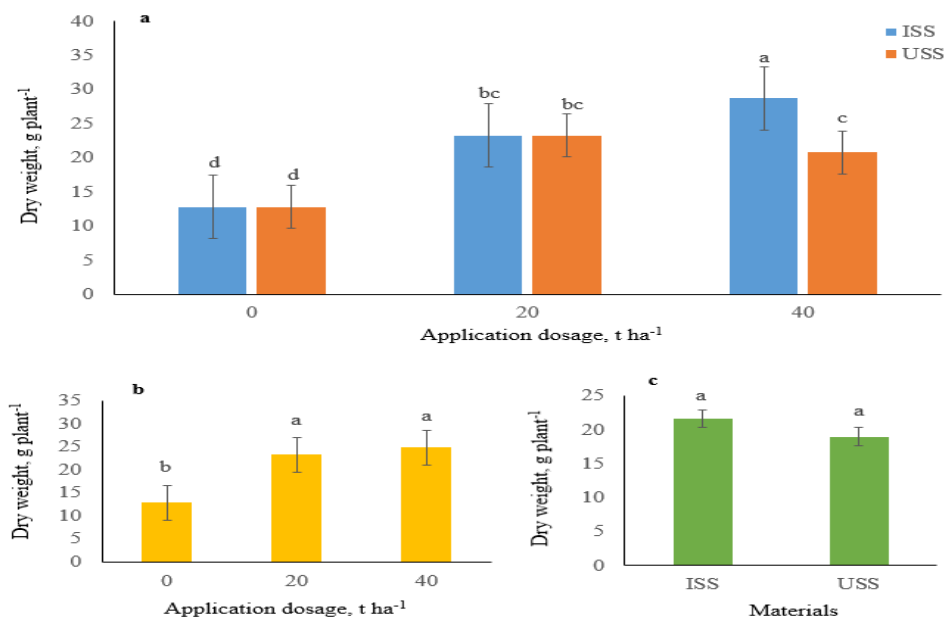


Figure 1. Effects of the sewage sludge treatments on dry weight of canola (a: interactions, b: means of dosages, c: means of materials)

Notes: There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS: Industrial sewage sludge, USS: Urban sewage sludge

Sewage sludge applications increased the plant dry weight about two fold when compared to control. At the same time dry weight results indicated that due to there are no significant differences between 20 and 40 t ha⁻¹ dosages, choosing the lower dosage will be more meaningful. Thus, the risk of possible toxic effects due to high dosages will be further reduced. Similar to us, previous researches implied the positive impact of sludges on plant growth (Choi *et al.*, 2002; Nahar and Hossen 2021). Chu *et al.*, (2017) suggested that a reasonable rate of sewage sludge addition could enhance the plant height and root diameter of *Mangifera persiciforma* plant. The positive response observed in the present study may be associated with the organic matter and nutrients supplied by the sludge (Mejri and Erdal, 2026).

Effects of sewage sludge treatments on heavy metal concentrations and uptakes of canola

Results of the treatments on heavy metal concentrations and uptakes are given in Fig. 2 and Fig.3, respectively. Increasing sewage sludge application rates significantly enhanced both heavy metal concentrations and metal uptake by canola plants, generally (Fig. 2a, Fig. 3a). In particular, Cr and Ni concentrations in leaves increased markedly with increasing sludge doses, and this increase was accompanied by a substantial rise in their uptake (Fig 2b, Fig.3b). Similar observations have been reported by Singh and Agrawal (2008), who showed that sewage sludge treatments can increase the availability of elements and consequently enhance their uptake by crops. The strong increase in Cr uptake observed at 40 t ha⁻¹, especially under ISS treatments, is consistent with the greater Cr concentration of ISS and may therefore reflect a greater contribution of the sludge to the soil metal pool, although metal availability and translocation processes were not directly measured. Walter *et al.*, (2006) also emphasized that the chemical composition of sewage sludge can influence the transfer of metals from soil to plants. Results demonstrated that ISS promoted higher Cr and Ni concentrations and uptake than USS (Fig. 2c, Fig. 3c). This finding is consistent with previous reports indicating that industrial sewage sludge may contain larger amounts of potentially available metals than urban sludge (Smith, 2009). Similarly, Singh and Agrawal (2010) reported that sludge origin affects metal accumulation patterns in plants and that metal uptake may increase with the amount of sludge applied. Nickel exhibited the highest uptake values among all metals. This pattern reflects the combined contribution of tissue concentration and biomass production to total uptake (Jamali *et al.*, 2009; Kabata-Pendias, 2011). Cd and Co concentrations exhibited relatively small changes with increasing sludge doses, and their uptake remained considerably lower than that of Cr and Ni. Nevertheless, Cd uptake increased with application rate, particularly in ISS-amended treatments. This situation may partly reflect the higher Cd concentration of ISS than USS (Smith, 2009), together with differences in plant biomass. Interestingly, Co concentrations were not significantly influenced by sludge type and dosages. This may be consistent with relatively limited changes in Co availability under the experimental conditions. Kabata-Pendias (2011) noted that Co availability can be affected by soil redox conditions and pH. The higher concentrations and uptake

values observed under ISS compared with USS indicate that sludge origin was associated with differences in metal accumulation by canola.

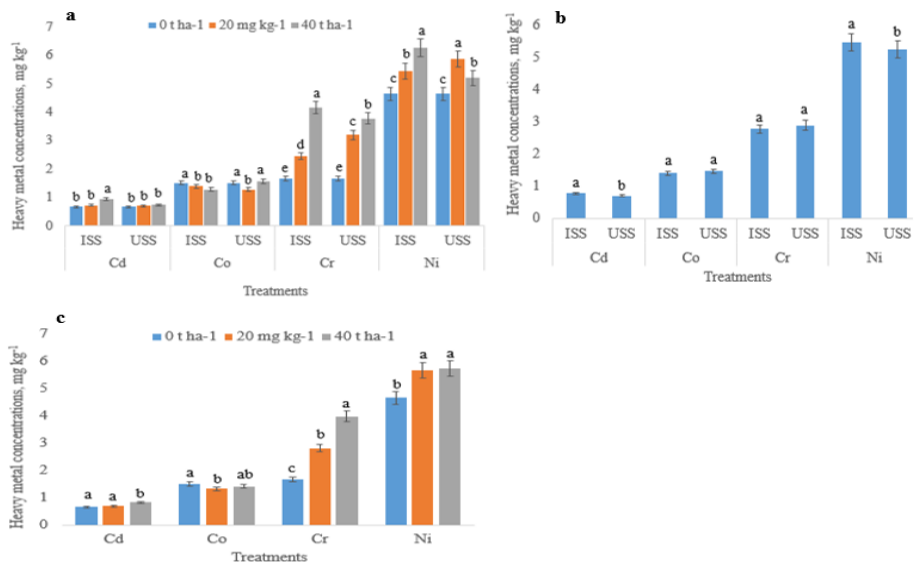


Figure 2. Effects of the sewage sludge treatments on Cd, Co, Cr and Ni concentrations of canola (a: interactions, b: means of materials, c: means of dosages)

Notes: There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS: Industrial sewage sludge, USS: Urban sewage sludge

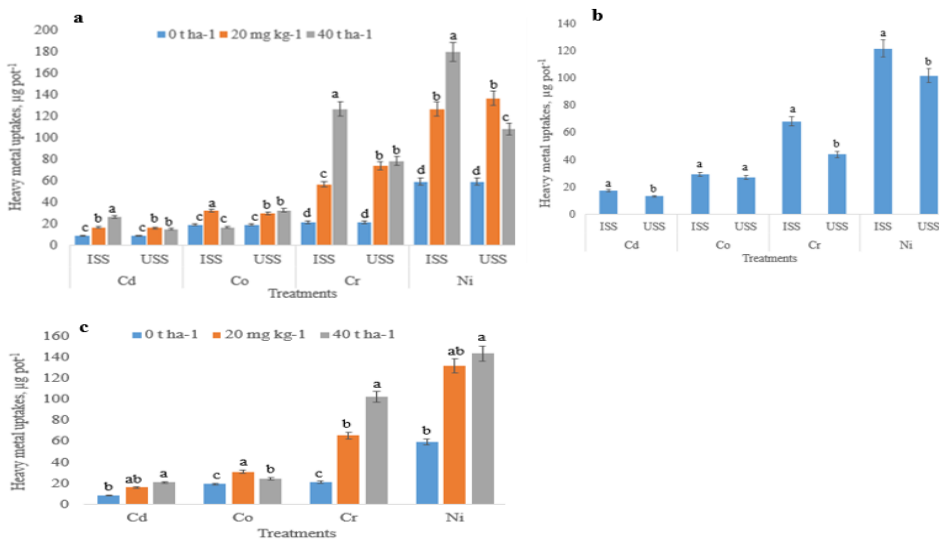


Figure 3. Effects of the sewage sludge treatments on Cd, Co, Cr and Ni uptakes of canola (a: interactions, b: means of materials, c: means of dosages)

Notes: There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS: Industrial sewage sludge, USS: Urban sewage sludge

Maize growth in remediated and non-remediated soils

The interaction between sludge source and application rate had a limited effect on maize dry weight (Fig. 4a). The highest dry weights were recorded under the 0 t ha⁻¹ of both ISS and USS treatment in remediated soil, whereas the highest dry weights were recorded under the 40 t ha⁻¹ of both sludges in non-remediated soil. The main effect of application rates revealed that dry weight tended to decrease with sludge treatments in remediated soil. However, sludge applications maintained or increased biomass production, in the non-remediated soil (Fig. 4b). These findings suggest that maize growth was maintained under the tested sludge treatments, including after the preceding canola cultivation. Growing canola to remove heavy metals did not result in a detectable negative effect on maize growth under the current trial conditions. Singh and Agrawal (2008) emphasized that sewage sludge can contribute to plant growth because of its organic matter and nutrient contents.

No significant differences were observed between ISS and USS treatments in both soil conditions, suggesting that both sludge types exhibited similar agronomic performance (Fig. 4c). This similar response may reflect the overall nutrient and organic matter contributions of the two sludges (Kominko *et al.*, 2018).

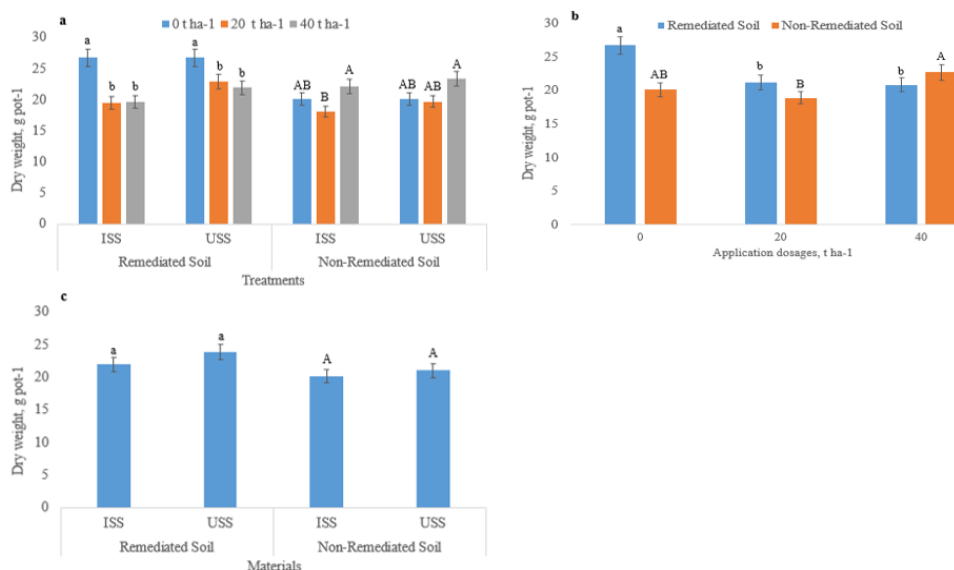


Figure 4. Effects of the sewage sludge treatments on dry weight of maize (a: interaction effects, b: means of dosages, c: means of materials)

Notes: Each soil was evaluated individually, lowercase letters represent results from remediated soil, while uppercase letters represent results from non-remediated soil. There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS: Industrial sewage sludge, USS: Urban sewage sludge

Heavy metal concentration and uptakes of maize grown in remediated and non-remediated soils

Cadmium concentrations and uptake values in maize significantly varied with sludge types and dosage interaction in remediated and non-remediated soils generally (Fig. 5a, Fig. 6a). In both conditions, increased sludge dosages increased plant Cd concentrations and uptakes (Fig. 5b, Fig. 6b). While Cd concentration in the plant growing on remediated soil did not vary with sludge types, higher Cd uptakes were determined with USS applications. ISS was dominant material for Cd concentration and uptake in non-remediated condition (Fig. 5c and Fig. 6c). These results suggest that the preceding canola cultivation was associated with lower Cd accumulation in maize. A possible explanation is that canola removed part of the Cd from the soil–plant system, as reported for Brassica species in previous studies (Marchiol *et al.*, 2004; Angelova *et al.*, 2017).

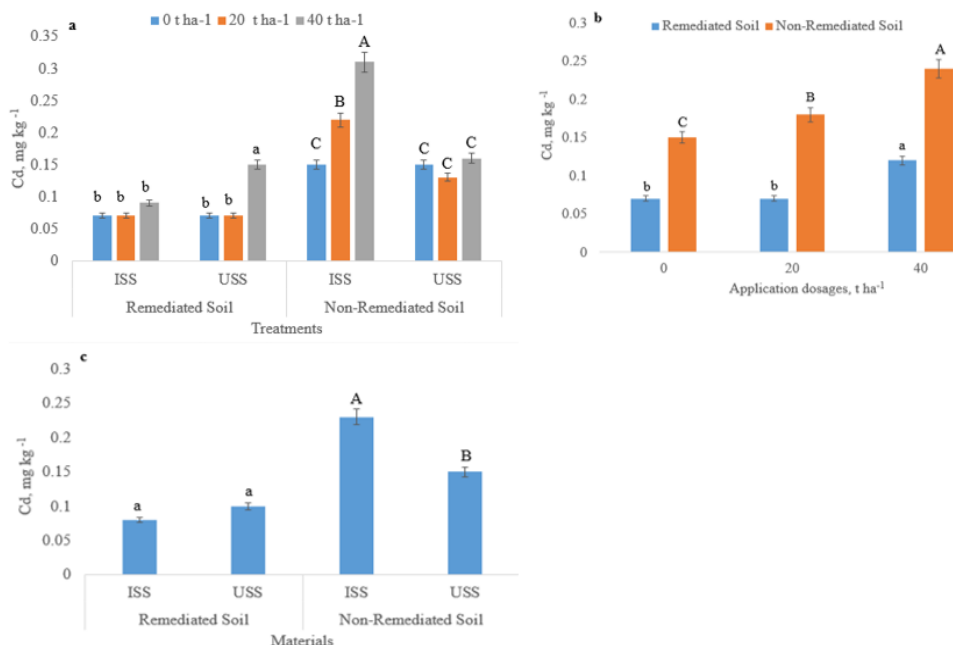


Figure 5. Effects of the sewage sludge treatments on Cd concentrations of maize (a: interaction effects, b: means of dosages, c: means of materials)

Notes: Each soil was evaluated individually. Lowercase letters represent results from remediated soil, while uppercase letters represent results from non-remediated soil. There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS: Industrial sewage sludge, USS: Urban sewage sludge

In terms of Co concentrations, sludge types showed different behavior pattern depending on soil conditions (Fig. 7a). Under remediated soil conditions, both sludge dosages did not affect plant Co concentration.

On the other hand, under non-remediated soil, increasing sludge rates significantly increased Co concentration in maize (Fig. 7b). Both sludges showed similar effects under same soil conditions on Co concentrations and no significant differences were observed between the soil types (Fig. 7c).

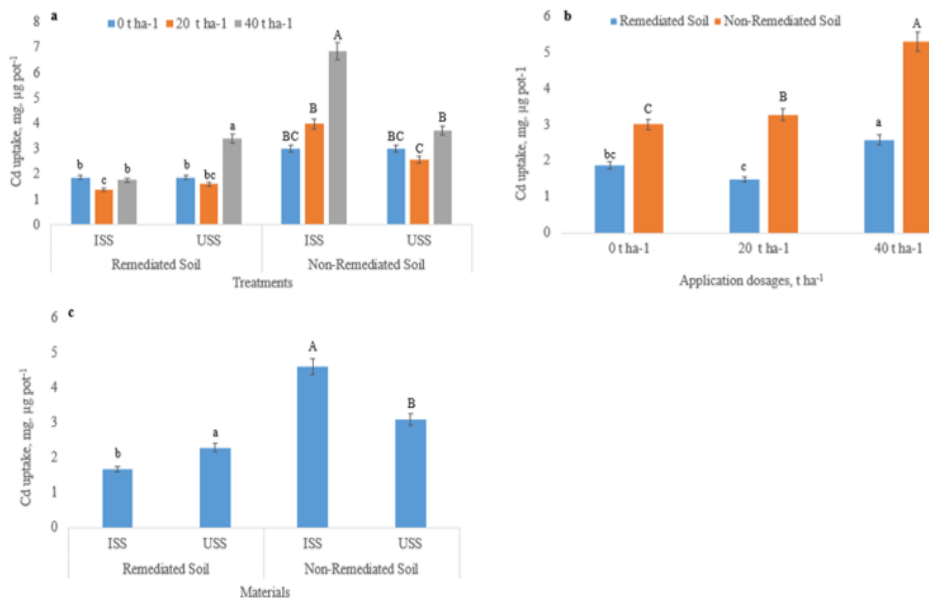


Figure 6. Effects of the sewage sludge treatments on Cd uptake of maize (a: interaction effects, b: means of dosages, c: means of materials)

Notes: Each soil was evaluated individually. Lowercase letters represent results from remediated soil, while uppercase letters represent results from non-remediated soil. There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS: Industrial sewage sludge, USS: Urban sewage sludge

Materials and dosage interactions significantly affected Co uptake by plant (Fig. 8a). While Co uptake decreased with application dosages for both sludges, regular increases were recorded under non-remediated soil condition (Fig. 8b). In both soil conditions, no significant differences were observed between sludge types (Fig. 8c). Cobalt is generally regarded as a relatively immobile element in soils, and its uptake can be strongly affected by soil chemical properties rather than total metal concentrations (Kabata-Pendias, 2011). The limited differences observed between ISS and USS treatments suggest that sludge origin may have played a secondary role compared with soil condition and application rate under the present experimental conditions (Walter *et al.*, 2006). The higher Co uptake observed in remediated soils may be associated with changes occurring during the preceding canola cultivation. Although Brassica species are recognized for their capacity to remove heavy metals, the effectiveness of phytoextraction varies among elements (Marchiol *et al.*, 2004).

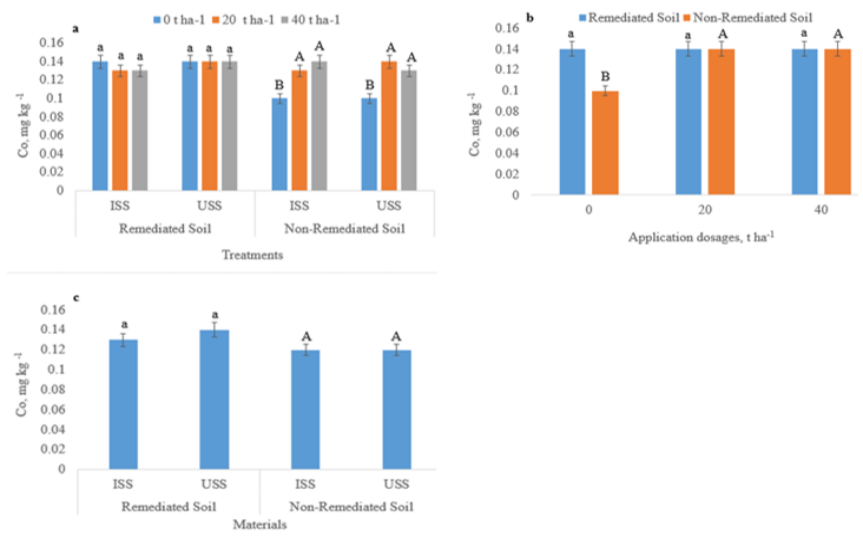


Figure 7. Effects of the sewage sludge treatments on Co concentrations of maize (a: interaction effects, b: means of dosages, c: means of materials)

Notes: Each soil was evaluated individually. Lowercase letters represent results from remediated soil, while uppercase letters represent results from non-remediated soil. There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS: Industrial sewage sludge, USS: Urban sewage sludge

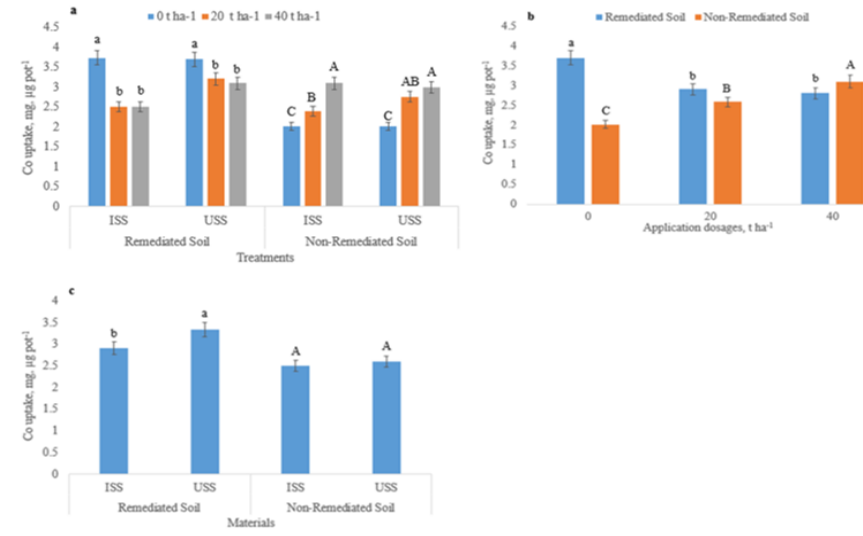


Figure 8. Effects of the sewage sludge treatments on Co uptake of maize (a: interaction effects, b: means of dosages, c: means of materials)

Notes: Each soil was evaluated individually. Lowercase letters represent results from remediated soil, while uppercase letters represent results from non-remediated soil. There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS: Industrial sewage sludge, USS: Urban sewage sludge

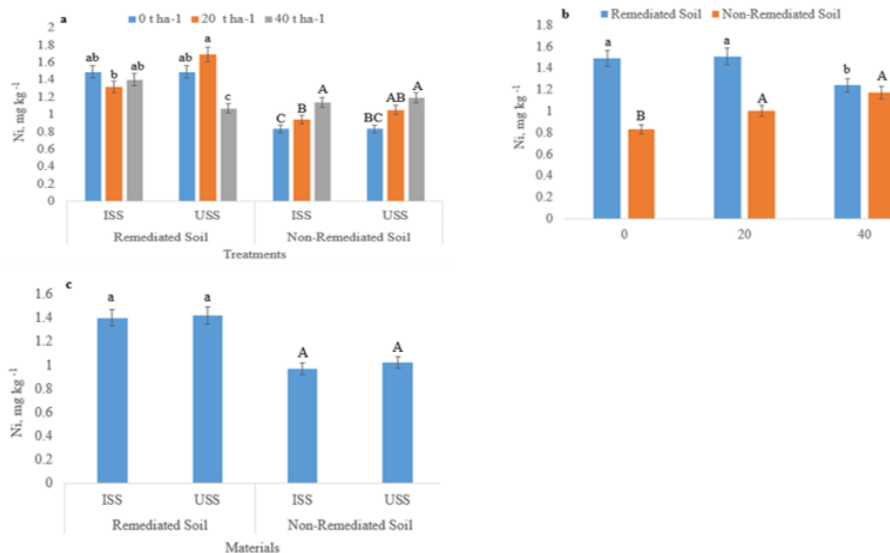


Figure 9. Effects of the sewage sludge treatments on Ni concentrations of maize (a: interaction effects, b: means of dosages, c: means of materials)

Notes: Each soil was evaluated individually. Lowercase letters represent results from remediated soil, while uppercase letters represent results from non-remediated soil. There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS: Industrial sewage sludge, USS: Urban sewage sludge

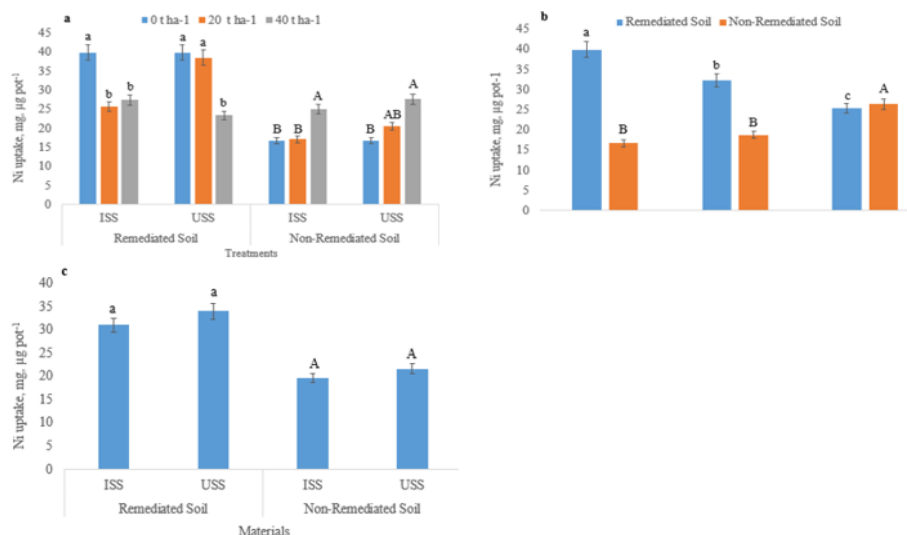


Figure 10. Effects of the sewage sludge treatments on Ni uptake of maize (a: interaction effects, b: means of dosages, c: means of materials)

Notes: Each soil was evaluated individually. Lowercase letters represent results from remediated soil, while uppercase letters represent results from non-remediated soil. There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS: Industrial sewage sludge, USS: Urban sewage sludge

Ni concentrations and uptakes significantly varied with dose-material interactions (Fig. 9a, Fig. 10a). In remediated soils, the highest Ni concentration was obtained with the 20 t ha⁻¹ ISS application. Increasing the dose to 40 t ha⁻¹ led to a significant decrease in Ni concentration. In non-remediated soils, sewage sludge treatments generally increased Ni concentrations and uptakes but decreased in remediated soils compared to the control group (Fig. 9b, Fig. 10b). Sludges showed a similar effects on Ni concentrations and uptakes under same soil conditions (Fig. 9c, Fig. 10c). The reduction in Ni concentration at the highest application rate may be consistent with a dilution effect associated with increased biomass (Erdal *et al.*, 2014; Mejri and Erdal, 2026). The most remarkable finding is the higher Ni concentration and uptake of maize grown in remediated soils. Although phytoremediation is generally expected to reduce the amount of metal available to subsequent crops (Ali *et al.*, 2013), the higher Ni values observed after canola cultivation suggest that the preceding crop may have influenced Ni availability or plant uptake. Root activity and rhizosphere processes are possible explanations reported in the literature (McGrath *et al.*, 2001; Sheoran *et al.*, 2016).

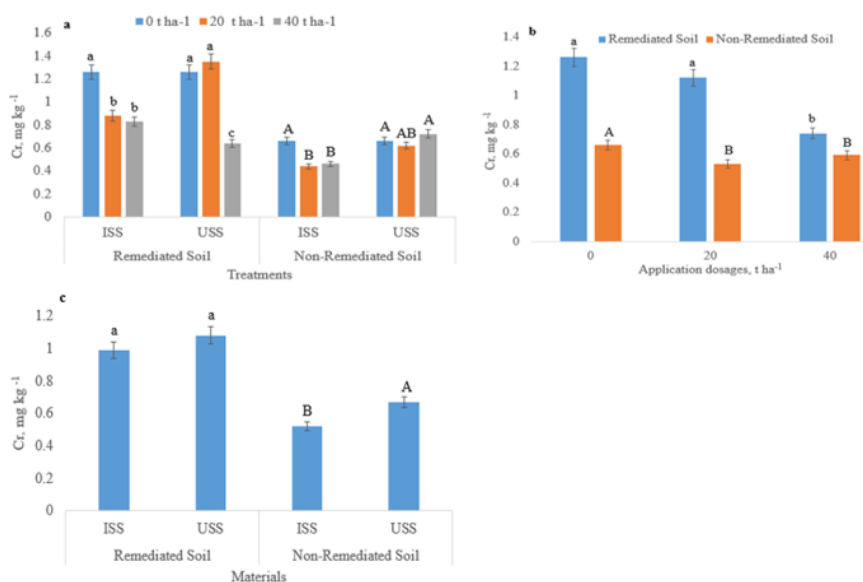


Figure 11. Effects of the sewage sludge treatments on Cr concentrations of maize (a: interaction effects, b: means of dosages, c: means of materials)

Notes: Each soil was evaluated individually. Lowercase letters represent results from remediated soil, while uppercase letters represent results from non-remediated soil. There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS: Industrial sewage sludge, USS: Urban sewage sludge

Under dose-material interaction, increasing doses of ISS and USS either had no effect or a negative effect on plant Cr concentration in both soil conditions. A similar trend was observed for plant Cr uptake (Fig. 11a, Fig. 12a). This situation

was also reflected in the means of dosages (Fig. 11b, Fig 12b). USS was found to be more effective on Cr concentration and uptake in both soil conditions (Fig.11c, Fig. 12c). Similar to Ni, the decrease in tissue Cr concentration at the higher dosages may be consistent with a growth dilution effect (Jarrell and Beverly, 1981). The higher Cr uptake observed in remediated soil suggests that the preceding canola cultivation was associated with greater Cr accumulation by maize. One possible explanation is that root activity and rhizosphere processes during canola growth may have altered Cr availability. Chromium is often strongly retained in soils, and its behavior depends on factors such as oxidation state, pH, organic matter, and mineral interactions. Therefore, the possibility that organic compounds released during canola growth influenced Cr availability (McGrath *et al.*, 2001; Sheoran *et al.*, 2016).

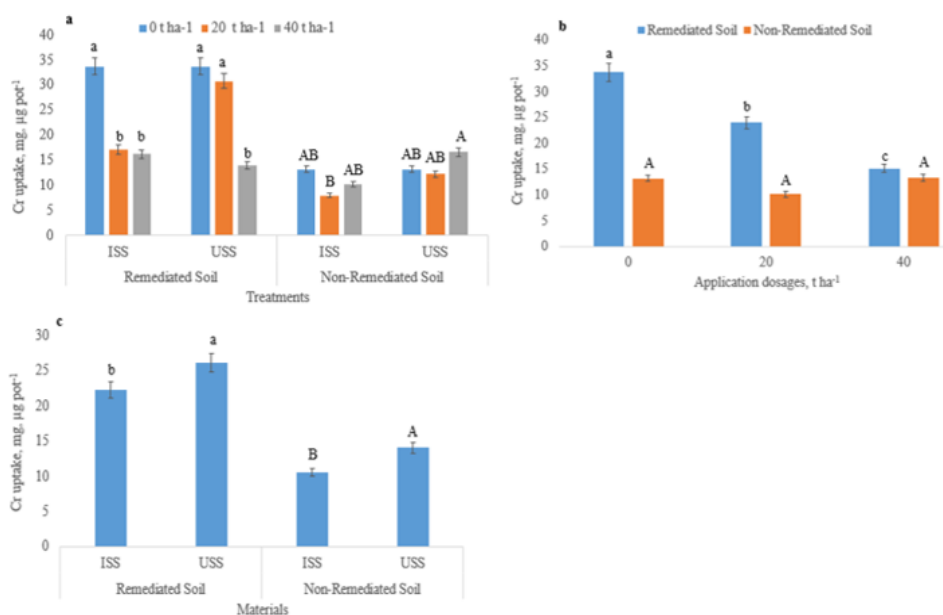


Figure 12. Effects of the sewage sludge treatments on Cr uptake of maize (a: interaction effects, b: means of dosages, c: means of materials)

Notes: Each soil was evaluated individually. Lowercase letters represent results from remediated soil, while uppercase letters represent results from non-remediated soil. There is no significant difference between the numbers sharing the same letters according to Tukey's test at $p < 0.05$. ISS:

CONCLUSIONS

The present study demonstrated that both industrial and urban sewage sludges improved crop growth and provided a residual fertilizing effect that was maintained even after the cultivation of canola. Sewage sludge applications significantly increased canola biomass, although they also enhanced heavy metal accumulation, particularly for Ni and Cr. Despite the preceding canola cultivation,

maize biomass production in remediated soils remained comparable to that in non-remediated soils, indicating that phytoremediation did not compromise the agronomic value of sludge-amended soils.

The response of heavy metals differed according to the element. Previous canola cultivation was associated with lower Cd concentration and uptake in maize, suggesting that canola may have contributed to reduced Cd transfer to the subsequent crop. In contrast, maize grown in remediated soils exhibited greater Ni and Cr concentrations and uptake than plants grown in non-remediated soils. These differences may reflect changes in metal availability or soil–plant interactions following canola cultivation, but the specific mechanisms were not directly measured. Cobalt showed a less pronounced response and appeared to be influenced mainly by soil conditions rather than sludge origin.

Overall, the results indicate that the effectiveness of phytoremediation is element-specific and that the cultivation of canola before maize may reduce the transfer of some metals while increasing the availability of others. Therefore, crop succession strategies involving phytoremediation plants should be carefully evaluated according to the behavior of individual heavy metals.

Because the experiment was conducted under greenhouse conditions and over a relatively short period, the results should be interpreted with caution. Further long-term field studies are required to evaluate the persistence of rhizosphere-mediated effects and to determine suitable crop sequences that maximize the agronomic benefits of sewage sludge while minimizing the risk of heavy metal transfer to subsequent crops.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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