Soil-Plant Heavy Metal Migration and Sustainability Risks in the Turkistan Region

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Received: 17 March 2026 | Revised: 21 April 2026 and 4 May 2026 | Accepted: 8 May 2026

 DOI: https://doi.org/10.48084/etasr.18802

ABSTRACT

The heavy metal content in the soil and in the plants of the Turkistan region in areas located near highways was studied in this paper. Physico-chemical parameters of the soil were determined. The transfer factor was calculated and a Pearson correlation analysis was performed to assess the intensity of metal absorption by plants. It has been established that the maximum concentration of heavy metals is observed in a strip 2-5 m from the roadway, exceeding the Maximum Permissible Concentrations (MPC) by 1.5–3.0 times. The accumulation of metals in the soil corresponds to the series: Pb>Zn>Cd. Despite the high content of lead in the soil, its mobility remains low (TF=0.16–0.32), whereas, on the contrary, cadmium exhibits maximum migration capacity (TF=2.9–4.4). A strong correlation was found between the level of soil pollution and the accumulation of metals in the fruits of grapes, melons, and strawberries. The results of the study confirm that motor transport is a powerful source of chemical pollution of agricultural areas. The risk of toxic substances contaminating the food chain could be further reduced by respecting a sanitary distance from the road, regularly monitoring the environment and, if necessary, using phytoremediation techniques.

Keywords-soil; heavy metals; migration; plants; pollution; sustainability

I. INTRODUCTION

Technogenic processes associated with the rapid industrial development (coal mining, metallurgy, chemical industry, energy sector) are the main sources of the existence of heavy metals in the environment [1]. Road vehicles are another source of heavy metal contamination in the soil and vegetation. The use of lead-based petrol accounts for 60-70% of atmospheric lead emissions [2]. The study of this impact is particularly relevant across different geographical regions and climatic conditions, where traffic intensity and anthropogenic pressure can vary significantly. Depending on traffic density, the area covering which lead pollution occurs has a strip width from 50 to 100 m up to 300 m. Most such materials are deposited in the soil within the range of 10-15 m and are concentrated to the depth up to 10 cm. The concentration of lead in the soil adjacent to a highway can be tens, and in some cases hundreds of times more than the background concentration. Other heavy metals that are contained in the vehicle exhaust gases are cadmium, cobalt, chromium, copper, zinc, iron, molybdenum [3].

Irrigation, spraying, the introduction of pesticides [4] are other anthropogenic sources of heavy metals soil contamination. When using mineral fertilizers, in the process of applying 6-15 kg of mineral fertilizer to the soil, lead is introduced at the rate of 7-225 mg/kg of dry mass of the soil [5]. The cadmium content in mineral fertilizers is 0.3-179 mg/kg. Although the cadmium content in phosphorus fertilizers is quite small, with its annual use, the content in agricultural products can reach 10 g/ha [6]. Irrigation with treated wastewater leads to the accumulation of elements such as Cu, Cd, and Ni in the soil, and prolonged application may result in their migration into deeper soil layers and even groundwater [7]. Moreover, the degree of accumulation and vertical distribution of these metals depends on the duration of irrigation, soil properties, and water management practices, highlighting the importance of considering temporal dynamics in such studies. The concentrations of cadmium and zinc in wastewater waste have been reported at 90 and 6000 mg/kg of soil dry weight, respectively, 1.5-3.0 times the generally accepted MPC norm [8]. Consequently, agricultural chemical inputs have the greatest impact on the state of the agroecosystem and serve as the channel for the contamination of the soil with heavy metals.

Heavy metals enter plants from the soil through the roots and from the atmosphere through the leaves [9]. The absorption of heavy metals through the vascular system is mediated by physical and chemical absorption, as well as due to the non-metabolic binding of metal ions through the active regions of the cell wall and the apoplast [10]. Cd, Zn, Cu and some other metals enter the plant tissues as a result of the adsorption exchange processes [11]. The ratio of heavy metals entering the plant through the passive metabolic import system and the active metabolic import system is influenced by the heavy metal concentrations in the soil. At background heavy metal concentrations, the main ingress is known to occur through the active metabolic pathway. And if the concentration of metals in the external environment exceeds the background several times, the absorption is non-metabolic, which is caused by the diffusion of cations in the free space of the roots [12]. It has been established that Cd, Br, Cs ions are very easily absorbed by the plant, and Ba, Ti, and Se are weakly absorbed. Pb enters the plant and is transported to underground roots more slowly than other heavy metals [13].

A comprehensive understanding of heavy metal contamination requires an integrated approach that includes comparative analysis across different regions, consideration of seasonal and long-term variability, and the use of standardized sampling and analytical methods for soil and plant assessment. The impact of heavy metals within the soil–plant system depends on their concentration, toxicity, migration pathways, and exposure duration. Therefore, studying the accumulation and distribution of heavy metals in soils and plants is essential for assessing the ecological state of agroecosystems. The present study aims to expand the geographical and temporal scope of contamination assessment and is based on detailed physicochemical analytical methods to improve the reliability of the obtained results. The research presents the results of physicochemical investigations of the soil–plant system with respect to heavy metal content in the Turkistan region.

II. MATERIALS AND METHODS

The samples were collected along major roadways in the Turkistan region of the Republic of Kazakhstan. Soils along the highways and vegetable plants and local plants were used as objects of research to find the transformation and migration properties of heavy metals in the "soil-plant" systems of the region.

Crushed plant samples weighing 0.1-0.2 g were placed in fluoroplastic cylinders with 1 cm^3 of concentrated nitric acid poured on top. The cylinder surface was covered with a laboratory film and the samples were placed in a thermoblock, heated to 115°C for 0.5-1.0 h, and were held until completely dissolved. The resulting transparent solution was transferred to a polypropylene test tube with a capacity of 250 cm^3. The sample under study was transferred from a fluoroplastic cylinder to a test tube, and the cylinder was rinsed three times with deionized water. The sample was closed with a laboratory membrane, mixed well, and then sent for Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The samples revealed the content of five heavy metals: hazard class I (Pb, Zn, Cd) and hazard class II (Cu, Cr).

Pearson's correlation coefficient (r) was calculated to assess the relationship between the concentrations of heavy metals in soil and plant samples. This method allowed us to determine the migration capacity of metals and the probability of their accumulation in plants. All results are given as the mean value (Mean) ± standard deviation (SD). Each experiment was performed three to five times ($n = 3–5$).

III. RESULTS AND DISCUSSION

The results confirm that road transport is a major anthropogenic source of heavy metal contamination. Transport is a source of pollutants such as zinc, lead, chromium, cuprum and cadmium in roadside soils. When studying samples taken from the surface layer of the soil and the 25-30 cm deep layer, the formation of ecological anomalies and their specific dependence on the sources of pollutants were revealed.

As shown in Table I, the highest concentration of heavy metals occurs in the soil along the road from 2 m to 5 m, whereas it decreases with increasing distance from the road. The results indicate that the soil contains a high amount of lead, while the zinc content is lower, and the cadmium content is minimal. Therefore, in terms of absolute concentration, the following decreasing order of Pb > Zn > Cd was established. This order of is consistent with the literature data, which mainly indicates that lead is present in high concentrations in areas with heavy traffic, caused by exhaust gases, tire wear products, and brake pads. The concentration of heavy metals in plants is given in Table II.

TABLE I. HEAVY METAL CONTENT IN ROADSIDE SOILS (mg/kg OF SOIL)

Road side (km)	Distance from highway (m)					
	2	5	10	150	200	300
	Pb					
5	23±0.47	19.50±0.2	13.5±0.14	9.5±0.1	4.52±0.13	1.3±0.04
10	22±0.47	19.0±0.2	13.5±0.14	9.4±0.1	4.21±0.13	1.2±0.048
15	23±0.47	19.50±0.2	13.2±0.14	9.65±0.1	4.34±0.13	1.2±0.04
	Zn					
5	19.2±0.12	14.7±0.28	9.5±0.08	9.5±0.07	4.32±0.09	1.0±0.09
10	19.3±0.12	14.7±0.28	9.34±0.08	9.4±0.07	4.3±0.09	1.01±0.09
15	19.0±0.12	14.1±0.28	9.51±0.08	9.65±0.07	4.1±0.09	1.2±0.09
	Cd					
5	0.48±0.004	0.31±0.008	0.14±0.009	0.09±0.008	0.05±0	0.01±0
10	0.47±0.004	0.32±0.008	0.16±0.009	0.1±0.008	0.05±0	0.01±0
15	0.47±0.004	0.3±0.008	0.16±0.009	0.08±0.008	0.05±0	0.01±0
	Cu					
5	0.01±0.001	0.01±0.001	0.01±0.001	0.01±0.001	0.01±0.001	0.01±0.001
10	0.02±0.001	0.02±0.001	0.02±0.001	0.02±0.001	0.02±0.001	0.02±0.001
15	0.01±0.001	0.01±0.001	0.01±0.001	0.01±0.001	0.01±0.001	0.01±0.001
	Cr					
5	1.20±0.12	1.20±0.12	1.20±0.12	1.20±0.12	1.20±0.12	1.20±0.12
10	1.23±0.12	1.23±0.12	1.23±0.12	1.23±0.12	1.23±0.12	1.23±0.12
15	1.22±0.12	1.22±0.12	1.22±0.12	1.22±0.12	1.22±0.12	1.22±0.12

TABLE II. CONCENTRATION OF HEAVY METALS IN PLANTS

Plants	Concentration of metals (mg/kg)					
	Pb	Cd	Zn	Cu	Cr	
Peach	0.25±0.001	0.02±0.002	5.87±0.01	1.87±0.01	1.05±0.02	
Strawberry	0.53±0.01	0.01±0.002	1.32±0.05	3.14±0.02	0.272 ±0.03	
Watermelon	0.5±0.002	0.03±0.002	5.11±0.07	1.19±0.001	0.141±0.01	
Melon	0.25±0.01	0.03±0.002	8.24±1.2	6.21±1.2	0.340±0.03	
Apples	0.4±0.002	0.06±0.001	2.34±0.01	1.50±0.09	0.437±0.01	
Grapes	1.82±0.001	0.05±0.001	1.33±0.02	2.13±0.08	0.521±0.01	

As can be seen, the roadside soil has a high content of heavy metals in the range from 2 m to 5 m. According to the content of heavy metals in the soil, they can be divided into 2 groups. Table III shows the Maximum Permissible Concentration (MPC) of each considered metal. It can be seen that the concentrations of Pb (36.1 mg/kg), Zn (29.2), and Cd (3.1) are above the respective MPCs and those of Cu and Cr are below.

TABLE III. MPC OF HEAVY METALS IN SOIL AND PLANTS

Metals	Hazard class	MPC (mg/kg)	
		In soil	In plants
Pb	1	32	0.5
Cu	2	3	0.045
Zn	1	23	0.45
Cr	2	6.0	0.2
Cd	1	0.5-2.0	0.03

The next step of the research was to study the transfer of heavy metals in the plants. The results are presented in Table IV and Figure 1.

TABLE IV. CORRELATION MATRIX OF HEAVY METAL TRANSFER FACTOR (TF) IN PLANTS.

Indicators	Pb (TF)	Zn (TF)	Cd (TF)
Pb (TF)	1.00	0.92	0.95
Zn (TF)	0.92	1.00	0.99
Cd (TF)	0.95	0.99	1.00

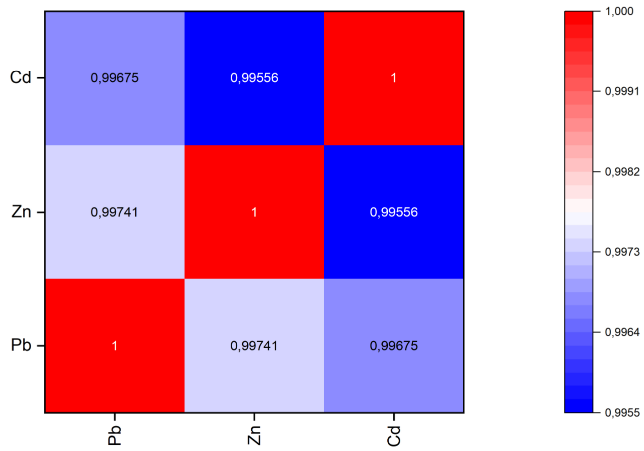

Fig. 1. Correlation matrix of the transfer factor.

The Pb and the Zn content of all studied plants were above the MPC values. The Cd concentration of the plants mentioned is below the norm. The maximum TF of Cd was 2.9 to 4.4, indicating a high bioavailability. The average bioavailability of Zn was 1.99 to 3.0, and the minimum bioavailability of Pb was 0.16 to 0.30, and thus in increasing order, the bioavailability of the metals was Cd>Zn>Pb. The results show that the statistical difference between cultures is significant for lead ($p<0.001$), and for zinc and cadmium ($p<0.05$), confirming the fact that the accumulation of heavy metals is species dependent.

Figure 2 shows the mapping of the hazard class of the areas in the region. The mapping criteria are given in Table V. According to the content of heavy metals in the composition of the extracted soils and depending on the criteria of Table V, the soil pollution is considered to belong to the weak category.

TABLE V. THE MAPPING CRITERIA

Amount in soil (mg / kg)	**Soil pollution category**		
Hazard class	1	2	3
$\geq K_{max}$	Very strong	Very strong	Strong
From MPC to K_{max}	Very strong	Strong	Average
From background concentration to MPC	Weak	Weak	Weak

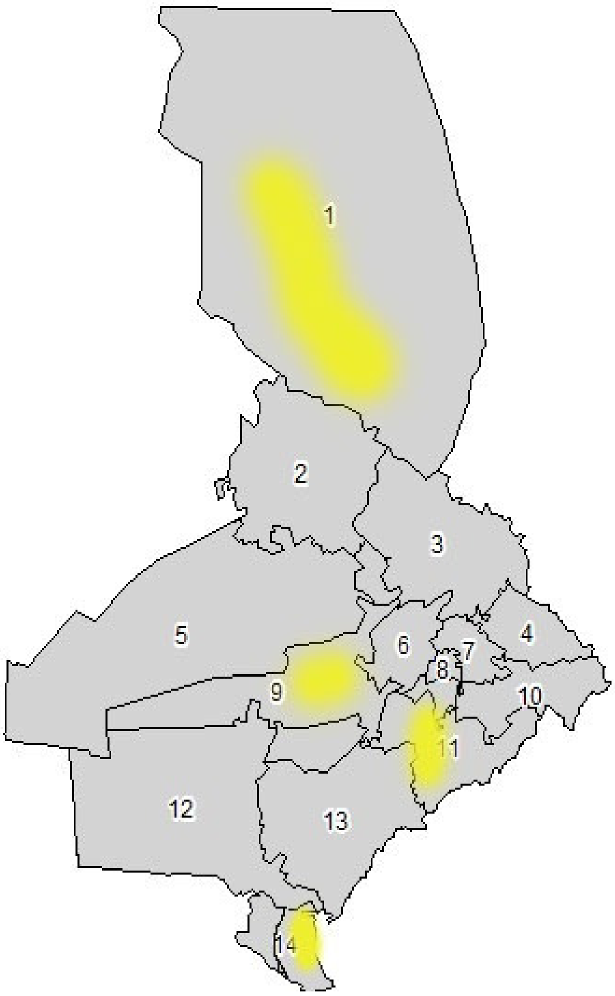

Fig. 2. Mapping of the level of soil pollution by heavy metals in the Turkistan region.

IV. CONCLUSION

The novelty of this study lies in the comprehensive assessment of heavy metal transfer in the soil–plant system of the Turkistan region, combining spatial analysis of roadside contamination with transfer factor evaluation and crop-specific accumulation patterns. This region has been insufficiently studied in terms of soil-to-plant metal migration, and the present work provides new quantitative data on the behavior of Pb, Zn, and Cd under local environmental conditions.

The migration of heavy metals from the soil to plants depends on the mobility of metal ions in the soil and their bioavailability to plants. Lead, which has a very low mobility, it is accumulated in the roots and leaves, which in turn limits its transfer into the fruits. However, in crops grown near roads, it can be accumulated on the surface layer of the plant surface due to atmospheric dust deposition.

Zinc is characterized by its high mobility and ability to transfer into the fruits of vegetables and cucurbits. In particular, tomatoes and cucumbers actively accumulate zinc in the fruits, and their high concentration in the soil can lead to exceeding safety standards. Although the concentration of cadmium is low in the soil, it can be easily transferred through the above-ground parts of the plants. Especially in the case of horticultural fruits, cadmium can be accumulated in the edible part of the fruit. Thus, according to our research results, motor vehicles remain a major source of heavy metal contamination in agro-vegetable natural areas. In particular, the accumulation of lead in the environment is a significant environmental and hygienic concern, which in turn requires constant monitoring of soil and plant products along the highway, as well as the development of methods to prevent the risk of heavy metals entering the food chain. Therefore, growing plants along highways poses a risk of accumulation of heavy metals such as cadmium and zinc in their fruits.

According to the results of this study, the heavy metal content in soils near highways in Turkistan was found to be 1.5–3 times higher than the permissible limit concentrations. It was observed that while the concentration was high in areas near the road, it decreased with increasing distance. The sequence of decreasing soil accumulation was determined as: Pb > Zn > Cd.

As a result of the evaluation of the transfer of heavy metals to plants, the transfer factor varied in the following range: Pb — 0.16–0.32; Zn — 1.99–3.0; Cd — 2.9–4.4. The highest values belong to Cd , proving its high mobility and its potential as a significant threat to food security. The conducted correlation analysis showed that there was a clear correlation between metal concentrations in soil and plants.

In summary, plants grown in proximity to high-traffic roads have an increased risk of heavy metal contamination, which, at high concentrations, may prove harmful to human health.

Recommendations regarding measures to be taken include:

- Constant monitoring of heavy metal concentration in plants.
- Keeping sanitary distance (200-300 m) from the road.
- Using bioremediation techniques to immobilize heavy metals and prevent their mobilization in agricultural areas.

Compared to previous studies that primarily focused on total metal concentrations, this research provides a more detailed understanding of metal mobility and bioavailability, as well as their direct transfer into agricultural products. These findings contribute to improved environmental risk assessment and offer practical implications for sustainable agricultural management in roadside areas.

DECLARATION OF COMPETING INTERESTS

The authors declare no competing interests.

ACKNOWLEDGMENT

This research was funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan, grant number AP22684097.

DATA AVAILABILITY

The accumulated data are available from the corresponding author upon reasonable request.

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