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Assessment of the levels of heavy metal pollution in roadside soils of Termiz – Taskent, Uzbekistan

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ABSTRACT

This study investigates the contamination of roadside soils by heavy metals (Pb, Zn, Ni, and Mo) along the Tashkent-Termiz International M-39 highway, utilizing indices such as the enrichment factor (EF), geo-accumulation index (Igeo), and pollution load index (PLI). Soil samples collected at 21 distances (5–1000 m) indicate that metal concentrations decrease with distance from the road, with rapid reductions observed within the 5–100 m range. Pb levels decline from 24 mg kg^{-1} at 5 m to 1.4 mg kg^{-1} at 1000 m, while Zn reduces from 26.3 mg kg^{-1} to 2.1 mg kg^{-1}. Ni and Mo follow similar trends, but Mo exhibits lower mobility. Pb, Zn, and Ni stand out as indicators of anthropogenic pollution, with high correlation values between their DTPA-extractable and total concentrations (R^2: Pb = 0.953, Zn = 0.930, Ni = 0.932). The Igeo values reveal moderate to high contamination near the road, particularly for Pb and Zn. The EF values for Mo (2.06) suggest moderate enrichment due to anthropogenic sources, such as traffic emissions, while Pb (0.76), Zn (0.89), and Ni (0.93) show minimal enrichment. PLI values of 4.24, 4.03, 3.63, and 4.87 for Pb, Zn, Ni, and Mo, respectively, classify the area as "highly polluted" for most metals. These findings highlight the significant anthropogenic contribution to heavy metal accumulation, driven by vehicular emissions, tire wear, and industrial activities. The contamination poses risks to soil health, biodiversity, and human safety through bioaccumulation in the food chain. Sustainable environmental management and pollution mitigation strategies are urgently required to address these concerns and safeguard agricultural productivity and ecosystem functions.

Keywords: contamination, heavy metal, pollution, road, soil, Uzbekistan.

INTRODUCTION

Heavy metals have become a significant concern for governments and societies worldwide due to the serious risks they pose to food safety, environmental health, and the sustainability of agricultural soils. In developing countries, heavy metal contamination in agricultural soils is increasingly exacerbated by rapid urbanization, population growth, and the impacts of industrialization (Li et al., 2022; Wu et al., 2011). These activities have enhanced the mobility and bioavailability of trace metals, significantly influencing their concentrations in the atmosphere, hydrosphere, and soils, thereby posing threats to both the natural environment and human health (Mohiuddin et al., 2014; Kholikulov et al., 2023). Studies have reported that traffic-related emissions significantly contribute to the accumulation of heavy metals (particularly Pb, Cd, Zn, etc.) in roadside soils (Wiseman et al., 2013). These traffic-related pollutants originate from various sources, including exhaust emissions, brake pad wear, oil combustion/leakage, tire abrasion, and road surface wear (Winther and Slentø, 2010). The level of heavy metal contamination in roadside soils depends on various factors, including traffic density, site age, site configuration, topography, climatic conditions, and soil properties (Guan et al., 2018). Living organisms near roadways (plants, animals, and humans) are exposed to these pollutants through suspended airborne particulates or direct contact (Guo et al., 2023).

The accumulation of heavy metals in roadside soils typically occurs through processes such as atmospheric deposition and surface runoff (Viard et al., 2004; Kholikulov et al., 2021). Research on this soil contamination has predominantly focused on metals like Cu, Zn, Cd, and Pb, although some studies have also examined Cr, Ni, and As (Akbar et al., 2006; Zhang et al., 2012). Additionally, studies conducted in highly populated metropolises and large cities with heavy traffic have emphasized that traffic volume, the proximity of roadside soils to the road, and the spatial distance of roadside soils are the most critical factors influencing the distribution of heavy metals along roadside soils (An et al., 2022; Fakayode and Olu-Owolabi, 2003; Nabulo et al., 2006; Viard et al., 2004). In general, there is a positive correlation between the daily traffic volume of a highway and the heavy metal concentrations in soils near the road (Trujillo-González et al., 2016). Studies have reported that heavy metal concentrations in roadside soils decrease with increasing distance from the road (Li et al., 2001). However, some research suggests that the distribution of these metals does not always show a clear relationship with road distance (Lee et al., 2006). This inconsistency is often attributed to factors such as the type and sources of heavy metals, agricultural activities, and the presence and species of vegetation near the roadside (Li et al., 2004).

The maximum effective distance of roadside heavy metal dispersion can vary significantly depending on the type of metal. For most metals, this distance typically remains below 20 meters but can extend up to 100 meters in certain cases (Swaileh et al., 2004). Lead (Pb) has been reported to impact roadside soils up to 320 meters from the road, highlighting the importance of studying the spatial distribution of traffic-related heavy metals in areas free from other pollution sources (Morton-Bermea et al., 2002). Heavy metals can enter the human body through soil or dust ingestion, inhalation, or dermal contact, posing significant health risks (Jaradat and Momani, 1999). Common heavy metals such as Cd, Pb, Zn, and Cu, which are found in high concentrations in roadside soils due to traffic activities, pose significant toxicity risks by entering the human body through the food chain. In agricultural areas, the uptake of these metals from soil by plants plays a critical role in human exposure (Fakayode and Olu-Owolabi, 2003; Rai et al., 2019). High concentrations of heavy metals in the environment are associated with adverse health effects, including damage to the nervous, cardiovascular, renal, hematopoietic, and reproductive systems. Additionally, such contamination has been linked to cognitive impairments, attention deficits, behavioral disorders, and an increased risk of cardiovascular diseases in adults (Fu and Xi, 2020; Lu et al., 2014). While some trace metals, such as Cu and Zn, are considered harmless in small amounts, others, including Pb, As, Hg, and Cd, are highly toxic even at extremely low concentrations. These toxic metals can act as initiators, triggers, or cofactors for various diseases, particularly contributing to an increased risk of cancer (Balali-Mood et al., 2021). Due to the toxic, persistent, and non-biodegradable nature of these metals, regular monitoring of heavy metal levels, particularly in roadside agricultural production areas, is of critical importance.

This study aims to determine the extent of heavy metal pollution caused by highways, analyze the effectiveness of mitigation practices, and evaluate their impacts on soil and plant health in an agricultural context. To achieve this, indices such as the EF, Igeo, CF, and PLI were employed. Through these indices, the sources, distribution, and levels of heavy metal contamination were comprehensively analyzed. The EF determined the degree of enrichment of metals from anthropogenic sources, while the Igeo classified the contamination status of soils. Additionally, the CF and PLI indices were utilized to reveal the overall pollution load and the levels of heavy metal contamination in soils.

MATERIALS AND METHODS

Study area

The study area is located within the “Jomboy Plantation Estate Service” LLC cluster in the “Ulugbek” massif of the district. It is characterized by scattered irrigated meadow serozem soils. The location is along the “Tashkent-Termiz” international M-39 highway, which intersects the border of Jomboy district (39° 43’ 9” N, 67° 6’ 57” E) (Fig 1.) This highway experiences heavy traffic, with an average daily vehicle count of approximately 28800. This area receives high solar radion and low average annual precipitation of only 250–300 mm (most concentrated in spring, winter and autumn months). The average long-term temperature is +13.5 °C, and the maximum temperature corresponds to July, +43.3 °C. The elevation of the Ulugbek region is 724 m.

The study area is characterized by a rich and diverse natural vegetation, including species such as chamomile (*Matrigaria*), tulip (*Papaver pavoninum*), carac (*Cousinia resinosa* C.), wormwood (*Artemisia*), licorice (*Glycyrrhiza*), mint (*Mentha*), alongside various other plant species. The cultivation of wheat, corn, and other agricultural crops further adds to the region’s diversity. The presence of gardens and vineyards also contributes to the area’s rich agricultural landscape. The soil samples collected from the study area exhibited pH values ranging from 7.4 to 7.6, were rich in organic matter (2–3%), and contained lime levels varying between 7% and 12% (Singh, 2024).

Sample collection and instrumental analysis

Soil samples were randomly collected from the Tashkent-Termiz International M-39 highway at 5, 10, 20, 30, 40, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900 and 1000 m away from the road for each sampling point, and a total of 21 (each sample approximately 1000 g) surface soil (0~10 cm) was collected (She et al., 2022). Additionally, a reference soil sample (FON soil) was collected from an agricultural area located 20 km away from the highway at a depth of 0–10 cm. Soil samples collected from different locations were air-dried under laboratory conditions and subsequently sieved through a 2 mm nylon mesh.

The diethylenetriaminepentaacetic acid (DTPA) extraction of the metals was made by shaking 5.0 g of soil with 25 ml of a solution of 5 mM DTPA and 10 mM $CaCl_2$ in a end-over-end shaker for 1 h (Lindsay and Norvell, 1978). Then, the suspension was filtered on Whatman No. 1 filter paper. The analysis of heavy metals (Pb, Zn, Ni, and Mo) in soil samples was conducted using the wet digestion method. According to this method, 0.5 g of the sample was digested with a 3:1 mixture of HCl and HNO_3 in a microwave digestion system (CEM Mars 6). The digested samples were subsequently filtered into 50 ml volumetric flasks, and the final volume was adjusted to the mark for further analysis (Sastre et al., 2002). The soil extracts were analyzed for Pb, Zn, Ni and Mo concentrations using an inductively coupled plasma optical emission spectrometer (ICP-OES) (Varian Vista Pro) (Bataglia et al., 1983).

Contamination evaluation

There are numerous studies dedicated to assessing the pollution levels of heavy metals in soil and plants (Neeraj et al., 2023). To examine the heavy metal retention in the layered soil samples and conduct a preliminary environmental risk assessment, the following indices were calculated: Normalized EF, Cf, Cd, and PLI.

The enrichment factor (EF)

The enrichment factor (EF) for each metal in the soil samples was calculated by dividing the

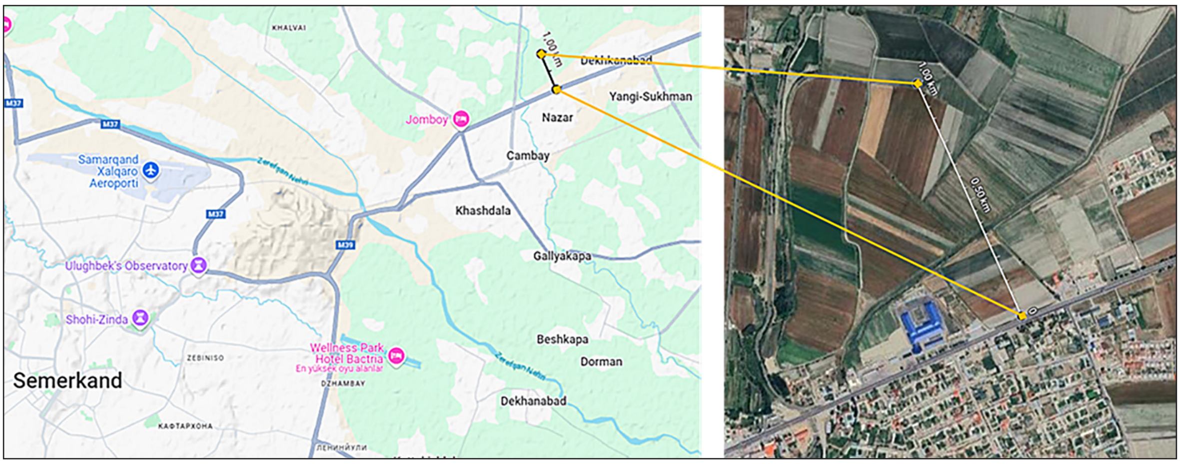

Figure 1. Study area

ratio of the metal to the normalizer (reference) element (Pb, Zn, Ni, Mo) in the sample, by the same ratio in the selected reference region (Buat-Menard and Chesselet, 1979).

The formula for calculating the EF is as follows:

$$EF = \frac{(Metal)\ sample}{(Metal)\ reference} \quad (1)$$

where: (Metal) sample – is the ratio of the metal concentration to the reference element (Pb, Zn, Ni, Mo) concentration in the sample, (Metal) reference – is the ratio of the metal concentration to the reference element (Pb, Zn, Ni, Mo) concentration in the selected reference region.

EF < 1 indicates a deficiency or minimal enrichment of the metal in the soil, suggesting a natural abundance. EF = 1 represents the baseline concentration, with no enrichment. EF values between 1–3 indicate minor enrichment, likely from natural weathering processes. EF values between 3–5 suggest moderate enrichment, potentially from a combination of natural and anthropogenic sources. EF values between 5 – 10 indicate severe enrichment, implying a significant anthropogenic influence on the metal accumulation. EF > 10 represents very high enrichment, which is typically associated with high levels of pollution from human activities.

The geo-accumulation index (Igeo)

The geo-accumulation index (Igeo) is a parameter used to determine the pollution level of a place or region. This index is an important tool for determining the degree of heavy metal pollution in a region, assessing environmental risks, and comparing pollution levels between different regions or time periods. The Igeo provides a way to quantify the degree of heavy metal contamination in the environment. It is calculated based on the comparison of the measured metal concentrations in the soil or sediment samples to the geochemical background or reference values.

$$Igeo = log2\left[\frac{Cn}{1.5 \times Bn}\right] \quad (2)$$

where: Cn – is the heavy metal concentration determined in the soil, Bn – is the geochemical background concentration of the trace element (middle crust) (Ackah, 2019; Y. Wang et al., 2017).

High I-geo values indicate the potential presence of risks to ecological systems and human health. The higher the I-geo value, the greater the degree of heavy metal pollution and the potential for adverse environmental impacts (Table 1). This index is widely used to evaluate the level of heavy metal pollution and to identify areas that may require further investigation or remediation measures. Comparing I-geo values between different locations or over time can also provide insights into the trends and sources of heavy metal contamination.

The pollution load index (PLI)

The PLI is a composite index estimates the total value of all trace elements at a specific location by using the parametric mean of pollution factors. This index is very simple and suitable for many types of pollution assessment (Jiang et al., 2020). The CF was calculated by computing the metal concentration using the background value equation (Sabo et al., 2013).

$$CF = \frac{C_{metal}}{C_{background}} \quad (3)$$

The PLI is a valuable tool for assessing the level of elemental pollution in soils. The method proposed by Xian et al. (2015) involves comparing the measured element concentrations in the soil to a predetermined standard or reference

Table 1. The geo-accumulation index (I-geo) classifies, values, and levels of contamination in soil

I-geo class	I-geo value	Level of contamination
0	I-geo ≤ 0	Uncontaminated
1	0 < I-geo < 1	Uncontaminated/moderately contaminated
2	1 < I-geo < 2	Moderately contaminated
3	2 < I-geo < 3	Moderately/strongly contaminated
4	3 < I-geo < 4	Strongly contaminated
5	4 < I-geo < 5	Strongly/extremely contaminated

concentration. This comparison allows for a quantitative evaluation of the soil's pollution load.

$$PLI = \sqrt[n]{CF1 \times CF2 \times CF3 \times \ldots \times CFn} \quad (4)$$

where: n – is the number of elements, PLI – is a simple and convenient method for the evaluation of level of heavy metal contamination, namely, this one assesses the pollution load for individualised sites by expression the concentrations of all individual elements under our consideration.

CF is calculated as a ratio indicating how much a metal in the soil is contaminated compared to the natural background concentration. The metal number (n) expresses the total type of metal analyzed. By evaluating the CF and n values together, a more comprehensive idea of the total soil pollution in a region can be obtained. PLI is an index that determines the total pollution load in the soil using these values. According to the PLI categorization presented in the study of Xu et al. (2017), different PLI values represent low, medium or high pollution levels (Table 2). Soil pollution is affected not only by metal concentrations, but also by other factors such as soil properties and climatic conditions. Indexes such as PLI and CF are used in many areas such as the evaluation of agricultural lands and the examination of soils around waste storage areas.

RESULTS AND DISCUSSION

Distance dependent variation of heavy metals

The change in Pb, Zn, Ni and Mo concentrations depending on the distance from the highway was examined in this study. The table 1 shows the concentrations of Pb, Zn, Ni, and Mo in soil samples at different distances from the highway.

The data demonstrate that the concentrations of all metals decrease with increasing distance from the road. Notably, heavy metal concentrations decline rapidly within the 5–100 m range, followed by a slower rate of decrease (Table 3, Fig. 2). This trend suggests that most metals originate from road-related pollutants, and their distribution is influenced by transport and deposition processes that depend on distance. The literature indicates that such decreasing trends are associated with particle size and the chemical properties of the metals (Thorpe and Harrison, 2008; Zhu et al., 2008). According to the data in Table 1, Pb concentrations consistently decrease with distance from the road. Pb levels drop from 24 mg kg^{-1} at 5 m to 20.7 mg kg^{-1} at 40 m, 14.3 mg kg^{-1} at 100 m, and 1.4 mg kg^{-1} at 1000 m (Table 3, Fig. 2). This rapid decline indicates that Pb is largely derived from vehicle traffic. The primary sources of Pb include exhaust emissions, brake pad wear, and legacy deposits on road surfaces (Wuana and Okieimen, 2011). However, Pb's low mobility in soil suggests that this reduction is limited by physical transport processes such as wind and precipitation. Pb accumulation in roadside soils has been reported by various studies to be high at close distances to the road and generally decreases beyond 30–50 meters (Akbar et al., 2006).

Zn concentrations also exhibit a clear reduction with increasing distance from the road. For instance, Zn levels decrease from 26.3 mg kg^{-1} at 5 m to 16 mg kg^{-1} at 100 m and 2.1 mg kg^{-1} at 1000 m (Table 3, Fig. 2). Zn is primarily derived from tire wear and motor oil contamination (Thorpe and Harrison, 2008). Due to its high mobility, Zn can be transported to greater distances by wind and surface runoff. The rapid decline observed within the 5–100 m range indicates intensive accumulation near the road, while dilution occurs at farther distances due to environmental dispersion (Al-Chalabi and Hawker, 2000).

Table 2. The pollution load index (PLI) classifies, values, and levels of contamination in soil

PLI class	PLI value	Level of pollution
1	0 < PLI ≤ 1	Unpolluted
2	1 < PLI ≤ 2	Moderately polluted to unpolluted
3	2 < PLI ≤ 3	Moderately polluted
4	3 < PLI ≤ 4	Moderately to highly polluted
5	4 < PLI ≤ 5	Highly polluted
6	5 ≤ PLI	Very highly polluted

Ni concentrations decrease more gradually compared to other metals. Ni levels decline from 18.2 mg kg^{-1} at 5 m to 9 mg kg^{-1} at 100 m and 1.4 mg kg^{-1} at 1000 m (Table 3, Fig. 2). This pattern can be attributed to Ni's dual origin from exhaust emissions and industrial activities (Kabata-Pendias, 2000). Among the analyzed metals, Mo exhibits the lowest concentrations. Near the road (5 m), Mo is measured at 11.9 mg kg^{-1}, decreasing to 3.2 mg kg^{-1} at 100 m and 0.6 mg kg^{-1} at 1000 m. Mo's low mobility and limited anthropogenic sources explain this declining trend. Mo is primarily derived from vehicle emissions and fossil fuel combustion (Alloway, 2012). This distance-dependent reduction is also influenced by Mo's low solubility and its strong binding affinity to clay minerals.

The background values (FON) in Table 3 represent the natural concentrations of metals in uncontaminated soils. For example, the FON value for Pb is 1.6 mg kg^{-1}, whereas the highest roadside concentration reaches 24 mg kg^{-1}. The FON value for Zn is 2.1 mg kg^{-1}, compared to a roadside concentration of 26.3 mg kg^{-1} (Table 3). These discrepancies clearly illustrate the impact of road emissions on soil contamination. The literature suggests that soils near urban roads may exhibit heavy metal accumulation levels 5–10 times higher than those in rural areas (Adimalla, 2020; Zhu et al., 2008).

The pH level of the soil is generally expected to decrease the concentrations of DTPA-extractable Pb, Zn, and Ni, while potentially increasing the concentration of Mo. However, it was determined that the pH levels of the soils in the study area, which range between 7.4 and 7.6 (Table 3), have no statistically significant effect on the DTPA-extractable concentrations of Pb, Zn, Ni, and Mo (R^2: Pb = 0.01541^{ns}, Zn = 0.02046^{ns}, Ni = 0.00223^{ns}, Mo = 0.00269^{ns}).

She et al. (2022) reported that the concentrations of Zn, Cu, Pb, and Cd in soil samples collected at distances of 2, 5, 10, 15, 30, and 50 meters from major national and international highways (G318, G219, G562, G216) in the southern Tibet region of China decreased with increasing distance from the road. The researchers generally reported that soil Cu and Zn contents peaked at distances of 10–20 meters from national

Table 3. Distance-dependent heavy metal concentrations of roadside soils

т/р	Distance from road, (m)	pH	DTPA extractable concentration of heavy metals, (mg kg^{-1})				Total concentration of heavy metals, (mg kg^{-1})			
			Pb	Zn	Ni	Mo	Pb	Zn	Ni	Mo
1	5	7.47	24.0	26.3	18.2	11.9	62.3	77.4	79.6	78.2
2	10	7.53	24.5	26.5	19.5	12.3	60.2	76	75.6	76
3	20	7.42	25.2	28.0	18.5	11.9	61.0	75.4	75	75.2
4	30	7.50	23.1	26.6	16.5	10.6	61	75	68.3	75
5	40	7.59	20.7	25.5	12.4	8.9	60.2	70	60	60
6	50	7.54	18.3	25.2	10.8	4.9	56.3	66.3	59.3	66.6
7	75	7.47	16.2	20.7	9.7	3.6	52.6	61.2	58.5	61.2
8	100	7.60	14.3	16.0	9.0	3.2	48	54	48.5	54.2
9	150	7.40	11.0	12.6	7.6	3.0	42.6	52.3	42	52.6
10	200	7.48	8.6	10.2	6.5	2.8	37.2	52	37	52
11	250	7.47	7.6	8.6	6.2	2.8	35	50.5	35.3	50
12	300	7.41	6.2	7.5	6.5	2.8	28	52.1	28.2	52
13	350	7.46	4.2	6.0	3.6	2.6	24.2	46	24.3	36.6
14	400	7.40	3.3	4.5	3.0	1.9	15.2	47	15.6	27
15	450	7.53	3.2	4.5	2.8	1.8	15.2	44.3	15.2	14.2
16	500	7.49	3.2	3.2	2.7	1.8	15	43.2	15	8
17	600	7.50	2.6	2.7	2.7	1.6	13.2	35.6	13.3	8
18	700	7.59	2.0	2.7	1.7	0.9	13	35	13	8
19	800	7.56	1.6	2.4	1.5	0.8	12.5	36.1	12.8	7.2
20	900	7.41	1.3	2.3	1.4	0.9	13	37	13	7
21	1000	7.47	1.4	2.1	1.4	0.6	13	32	13.2	6
22	*FON*	*7.55*	*1.6*	*2.1*	*1.5*	*0.6*	*14*	*42*	*14*	*6*

highways, while the peak values for most non-national highways were observed at a distance of 50 meters. Additionally, soil Pb concentrations were found to peak at distances of 2–30 meters from both national and non-national highways.

The observed decrease in heavy metal concentrations with increasing distance from the road confirms that this pollution largely originates from road-related sources. However, it should be noted that some of these metals can persist in the environment for extended periods and may affect distant areas through transport processes. For instance, metals such as Pb and Mo tend to accumulate near the road, whereas Zn and Ni exhibit greater potential for dispersion over wider areas.

Similar to the DTPA-extractable concentrations of Pb, Zn, Ni, and Mo, the total concentrations of these heavy metals in soils were also observed to decrease with increasing distance from the roadside (Kumar et al., 2024). These findings strongly indicate that anthropogenic activities such as road traffic, exhaust emissions, tire wear, and road salting contribute significantly to heavy metal accumulation. For instance, the concentration of lead (Pb) was measured at 62.3 mg kg^{-1} near the roadside, decreasing to 13 mg kg^{-1} at a distance of 1000 meters (Table 3). Zinc (Zn), nickel (Ni), and molybdenum (Mo) displayed elevated concentrations close to the roadside, progressively diminishing and nearing their natural background levels with increasing distance.

Pb, Zn, and Ni stand out as indicators of anthropogenic pollution, with high correlation values between their DTPA-extractable and total concentrations (R^2: Pb = 0.953, Zn = 0.930, Ni = 0.932) (Fig. 2). The concentrations of these metals are heavily concentrated near roadways and decline rapidly with increasing distance. Pb and Zn primarily originate from brake pad wear, tire abrasion, and fuel additives, while Ni is predominantly associated with exhaust emissions. Mo, on the other hand, exhibits a weaker correlation between its DTPA-extractable and total concentrations (R^2 = 0.602), indicating that its distribution is influenced by both natural soil components and limited anthropogenic inputs (Fig. 2).

The accumulation of heavy metals adversely impacts soil quality and poses risks to human health through agricultural products. This necessitates regular pollution monitoring, the control of vehicle emissions, and the remediation of contaminated soils using techniques such as bioremediation.

Indices for the pollution assessment

The geo-accumulation index

The I-geo index was used to analyze soil pollution in this study, focusing on Mo, Ni, Pb, and Zn contamination at various distances from the road. The study examined the Pb (I-geo) values at distances ranging from 5 meters to 1000 meters from the road (Table 2). The highest I-geo value of 0.10 was measured at 5 meters, indicating moderate accumulation of Pb near the road. However, as the distance increased, the I-geo value decreased to 0.27 at 1000 meters, showing a reduction in Pb pollution with increasing distance from the road (Table 4). This finding aligns with

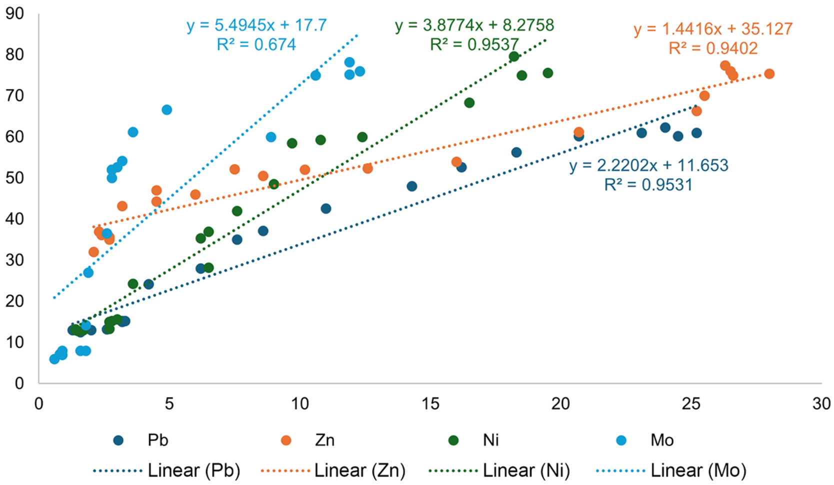

Figure 2. The relationship between DTPA-extractable Pb, Zn, Ni, and Mo and the total Pb, Zn, Ni, and Mo concentrations

previous studies indicating that Pb contamination typically diminishes with distance from traffic sources due to reduced particulate deposition and vehicle emissions (Yan et al., 2013).

Similarly, the Zn (I-geo) decreased from 0.10 at 5 meters to 0.17 at 1000 meters, signifying a decline in Zn pollution as distance from the road increased (Table 4). This pattern can be attributed to the contribution of tire wear and vehicle corrosion to Zn pollution, which predominantly affects soils closer to roads (Thorpe and Harrison, 2008).

For Ni, the I-geo values decreased from 0.10 at 5 meters to 0.27 at 1000 meters (Table 4). This indicates that Ni pollution is more concentrated near the road and diminishes with distance. The observed trend highlights the role of vehicle emissions as a primary source of Ni in roadside soils (Fakayode and Olu-Owolabi, 2003).

In contrast, the Mo (I-geo) increased from 0.11 at 5 meters to 0.79 at 1000 meters, suggesting moderate Mo accumulation near the road, which becomes more pronounced at greater distances (Table 4). This finding might indicate geogenic contributions or specific anthropogenic inputs, such as industrial activities influencing Mo distribution in soils (Reimann et al., 2015).

In general, the I-geo values for all heavy metals were highest near the road and decreased with increasing distance. These results reveal that the most concentrated area for heavy metal pollution from the highway is within 50–100 meters of the road. Similar patterns have been reported in other regions, where traffic density and proximity to highways significantly impact heavy metal accumulation in roadside soils (Guan et al., 2018).

Enrichment factor (EF)

The EF for each metal was assessed using Equation 1, and the EF ranges for the examined elements are presented in Table 5. The mean EF values were as follows: Mo (2.06) > Ni (0.93) > Zn (0.89) > Pb (0.76) (Table 5). The highest EF value for Mo classified the soil as moderately polluted, with an EF value of 2.06 indicating the anthropogenic origin of this metal. Molybdenum's presence can be attributed to its use as an additive in diesel fuels and engine oils, which is consistent with findings

Table 4. Distance-dependent I_{GEO} index of roadside soils

т/р	Distance (m)	I_{GEO} index			
		Pb	Zn	Ni	Mo
1	5	0.100891	0.096340	0.101613	0.108274
2	10	0.100397	0.096344	0.100712	0.107895
3	20	0.099989	0.095683	0.102899	0.108498
4	30	0.101455	0.097298	0.106765	0.114575
5	40	0.104149	0.098635	0.111891	0.115925
6	50	0.107229	0.099942	0.114700	0.130834
7	75	0.110890	0.104806	0.120585	0.142384
8	100	0.115397	0.109604	0.125356	0.146841
9	150	0.123583	0.114014	0.132442	0.149244
10	200	0.130742	0.118712	0.137797	0.152804
11	250	0.139892	0.121616	0.145668	0.151494
12	300	0.150506	0.127462	0.148846	0.164089
13	350	0.184794	0.132370	0.191332	0.180231
14	400	0.197492	0.141760	0.203004	0.239874
15	450	0.200000	0.142492	0.208015	0.306463
16	500	0.207660	0.160079	0.218276	0.306463
17	600	0.222519	0.167300	0.219856	0.323299
18	700	0.246373	0.166060	0.259158	0.473702
19	800	0.263605	0.169851	0.270238	0.526187
20	900	0.286206	0.178041	0.276020	0.541126
21	1000	0.269700	0.170133	0.269700	0.791744
22	*FON*	*0.164927*	*0.128978*	*0.169756*	*0.251521*

Table 5. Distance-dependent EF values of roadside soils

Distance (m)	EF			
	Pb	Zn	Ni	Mo
5	1.71	1.88	2.19	5.59
10	1.75	1.89	2.34	5.77
20	1.80	2.00	2.22	5.59
30	1.65	1.90	1.98	4.97
40	1.48	1.82	1.49	4.17
50	1.31	1.80	1.30	2.30
75	1.16	1.48	1.16	1.69
100	1.02	1.14	1.08	1.50
150	0.79	0.90	0.91	1.41
200	0.61	0.73	0.78	1.31
250	0.54	0.62	0.74	1.31
300	0.44	0.54	0.78	1.31
350	0.30	0.43	0.43	1.22
400	0.24	0.32	0.36	0.89
450	0.23	0.32	0.34	0.84
500	0.23	0.23	0.32	0.84
600	0.19	0.19	0.32	0.75
700	0.14	0.19	0.20	0.42
800	0.11	0.17	0.18	0.37
900	0.09	0.16	0.17	0.42
1000	0.10	0.15	0.17	0.28
Average	*0.76*	*0.89*	*0.93*	*2.04*

in other studies that highlight traffic as a significant source of heavy metal pollution in soils (Reimann et al., 2015). Additionally, the low EF values, such as 0.93 for Ni, 0.89 for Zn, and 0.76 for Pb, indicate minimal contamination in the soils (Table 5). This aligns with previous research suggesting that the contamination levels of these metals decrease with increasing distance from the road, reflecting their limited dispersion range due to particle size and deposition characteristics (Wang et al., 2017; Zhang et al., 2015). Pb, for instance, tends to accumulate closer to roads due to its heavy particle size and limited mobility in soil, as noted by Viard et al. (2004) and Fakayode and Olu-Owolabi (2003).

In general, the findings reveal that the dispersion and accumulation of metals are influenced by multiple factors, including traffic intensity, metal sources, soil characteristics, and environmental conditions. While the EF values for Ni, Zn, and Pb indicate minimal enrichment, the moderate enrichment of Mo underscores its distinct anthropogenic origins and environmental behavior, requiring specific mitigation strategies to reduce its impact on soil and surrounding ecosystems.

The pollution load index

The pollution load index (PLI) is a widely used metric for assessing soil contamination by heavy metals. It provides a straightforward method for quantifying the extent of environmental degradation caused by the accumulation of these metals (Kowalska et al., 2018). In this study, the PLI values for Pb, Zn, Ni, and Mo were determined to be 4.24, 4.03, 3.63, and 4.87, respectively. These values indicate "highly polluted" levels for Pb, Zn, and Mo, while Ni falls into the "moderate to highly polluted" category (Fig. 3).

Al-Dabbas and Abdullah (2020) carried out a study on heavy metal (Ni, Cd, Zn and Pb) contamination levels of soils of Ishaqi region (0–15 cm) of Iraq using I-geo and PLI. The researchers reported that the Cd contamination status in different soil layers showed that the study area was significantly contaminated, in terms of Cd and Ni contamination, Zn and Pb maps showed that a significant part of the study area was moderately to severely contaminated. The elevated PLI values reflect a significant anthropogenic contribution to the accumulation of

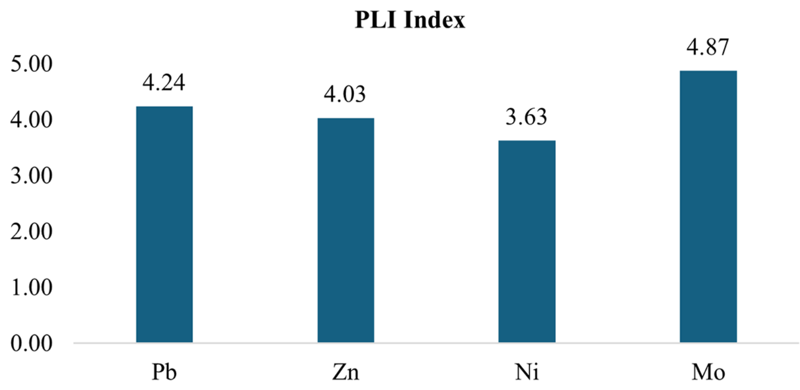

Figure 3. PLI index values

heavy metals in the study area. Anthropogenic impacts, typically defined as pollution arising from human activities, suggest deficiencies or inadequacies in the region's environmental management policies. The accumulation of heavy metals in soil at high concentrations can disrupt soil microbial activity, thereby reducing biodiversity. The presence of toxic elements such as lead (Pb) and nickel (Ni) is particularly concerning as it can hinder plant growth, negatively affect crop quality, and reduce agricultural productivity (Yerli et al., 2020).

The elevated PLI levels recorded in the region may have long-term impacts on agricultural and ecosystem functions. Heavy metals can strongly bind to soil particles, but they may also be taken up by plants under certain environmental conditions, eventually entering the food chain. This process can lead to the bioaccumulation of heavy metals within the soil-plant-animal-human continuum, causing significant health issues. For instance, elevated levels of elements such as lead (Pb) can exert toxic effects on humans and animals, particularly under chronic exposure conditions, posing substantial risks (Seven et al., 2018). In conclusion, the PLI values measured in this study indicate that the pollution levels in the examined area have reached alarming proportions. Long-term solutions require not only the mitigation of existing pollution sources but also the development of sustainable environmental management strategies. This approach is essential for preserving ecosystem services, ensuring sustainable agricultural production, and safeguarding human health.

CONCLUSIONS

This study has revealed the extent of heavy metal contamination along the Tashkent-Termiz International M-39 highway, demonstrating particularly high levels of pollution in roadside soils. It was observed that the concentrations of Pb, Zn, Ni, and Mo significantly decrease with increasing distance from the road, exhibiting a rapid decline within 5–100 meters, followed by a slower rate of reduction.

The significant decrease in total heavy metal concentrations in roadside soils with increasing distance from the road clearly reflects the impact of anthropogenic activities such as vehicle emissions, tire wear, and road salting. The strong correlations between DTPA-extractable and total concentrations of Pb, Zn, and Ni highlight these metals as key indicators of pollution, while the weaker correlation for Mo suggests a combined influence of natural and anthropogenic sources. Moreover, PLI values indicated "highly polluted" levels for Pb (4.24), Zn (4.03), Ni (3.63), and Mo (4.87). The findings suggest that anthropogenic sources, including vehicle emissions, tire wear, and industrial activities, play a significant role in this pollution. This contamination can disrupt soil microbial activities, reduce biodiversity, lower agricultural productivity, and pose toxic risks to human health. Furthermore, the low mobility of metals such as Pb and Mo in soil highlights their potential for long-term environmental risks.

To mitigate heavy metal pollution, several recommendations are proposed. Pollution control strategies should focus on reducing vehicle emissions and promoting the use of environmentally friendly materials in components such as tires and brake pads. Sustainable environmental management approaches, such as policies to minimize soil contamination and alternative road planning to reduce traffic density, are essential. Innovative bioremediation techniques, such as phytoremediation, should be implemented to remediate heavy metals accumulated in soils. Additionally, regular monitoring programs should be established to assess heavy metal concentrations and evaluate their long-term impacts on soil health. Public health awareness measures, including educating local communities about pollution risks and improving agricultural practices to limit heavy metal entry into the food chain, are also crucial. These findings underscore the urgent need for preventive actions and effective management strategies to address heavy metal contamination and mitigate associated environmental risks.

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