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Multi-index geochemical assessment of urban soil contamination under technogenic pressure

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Abstract. Soil contamination with heavy metals is becoming an increasingly serious problem worldwide. For this reason, a comprehensive quantitative assessment of the quality status of urban soils under technogenic pressure is important for understanding contamination patterns and potential ecological risks. The aim of this study was to conduct a spatiotemporal analysis of heavy metal contents and assess their impact on the urban soils of Cherkasy, as well as to identify sources of contamination for informed management decisions. Risk assessment was carried out using a multi-index geochemical approach, employing single-factor indices (geoaccumulation index I_{geo}, pollution index *PI*, ecological risk index *Er*) and composite indices (pollution load index *PLI*, Nemerow index, and potential ecological risk index RI). Statistical correlation analysis was used to identify probable sources of contamination. The analysis revealed significant spatial variations in metal concentrations. The coefficient of variation (CV) for Mn, Zn, Pb, Cu, and Cd was high ($51\% < CV \leq 100\%$) across different sites, indicating strong spatial heterogeneity. In contrast, Ni showed moderate variation ($21\% < CV \leq 50\%$), suggesting a natural-anthropogenic origin in the soil. A strong correlation between Pb and Cu indicated shared sources of pollution, likely from thermal power plants, paint and electrical manufacturing enterprises, and motor transport. High correlation coefficients between Ni and Mn suggest a mixed influence of geogenic (soil erosion) and anthropogenic sources (machinery and chemical industry enterprises, thermal power plants, and motor transport). A significant potential ecological risk for soil ecosystems was identified for Cd contamination in the study area. The multi-index approach to assessing heavy metal contamination across different

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urban locations showed that the most critical situations occurred in the southeastern and eastern industrial hubs. In residential-industrial areas, urban soils predominantly exhibited low to moderate contamination levels. Cadmium (Cd) was identified as the main potentially ecologically hazardous metal. The results of this study can serve as a basis for the development and implementation of targeted risk management strategies

Keywords: heavy metals; urban soils; correlations; spatial variability; ecological risk; anthropogenic impact

Introduction

Rapid urban growth and industrial development are closely linked to the accumulation of heavy metals in urban soils. These pollutants pose serious risks to urban ecosystems and are a growing concern at local, regional, and global scales. As cities expand and population density increases, along with intensified industrial and infrastructural activity, more potentially toxic elements are introduced into the environment and gradually build up in surface soils over time. Because these substances are persistent and do not break down naturally, they can enter food chains and ultimately threaten ecosystem balance and human health. For this reason, monitoring and assessing heavy metal contamination in urban soils has become an essential part of sustainable urban environmental management and the protection of public health.

L.S. Mustapha *et al.* (2025) noted that soil contamination by heavy metals constituted a serious contemporary environmental issue, driven by their resistance to biodegradation, toxicity, and their capacity for geoaccumulation and bioaccumulation. Q. Yang *et al.* (2018) observed that the content and variability of heavy metal concentrations in soils were largely determined by the parent material and the geological background of a given area. However, intensive anthropogenic activity significantly altered these patterns. Soil formed the foundation of terrestrial ecosystems and served as the primary sink for most environmental pollutants. As noted by L. He *et al.* (2023), heavy metals typically originated from various sources, including industrial activities, fossil fuel combustion, transportation, and waste disposal. They could enter soils from both local and distant emission sources and might therefore be deposited *in situ* or, when adsorbed onto dust particles, transported over considerable distances by air currents. Once released into the atmosphere, metals contaminated urban landscapes through dry or wet deposition. Following atmospheric deposition into soils, metals exhibited significantly greater mobility than those already present in the soil matrix, due to their higher reactivity. Although the concentration of atmospheric metals was relatively low, their hazard could exceed that of metals already present in soils. Y. Zhou *et al.* (2022) emphasised that urban landscapes in industrial zones and roadside areas were most heavily affected due to multiple sources of industrial emissions and intense traffic flows. The degree of contamination increased with proximity to the emission source. The accumulation of heavy metals led to soil degradation, disrupted the functioning of soil ecosystems, and posed a threat to human health. A significant presence of heavy metals in urban soils was considered an indicator of urban environmental quality, and the assessment of topsoil contamination in populated areas represented one of the key environmental challenges facing modern cities. It was therefore essential to identify potential sources of pollution, assess the risk of heavy metal contamination in soils, and propose effective remediation strategies.

The most promising approach for identifying areas of elevated environmental hazard is the comprehensive assessment of potential ecological risk. This approach makes it possible to determine acceptable levels of anthropogenic pressure in order to maintain the balance of the natural environment and ensure the regeneration of its key components, as well as to support informed decision-making aimed at minimising anthropogenic impacts. A key element in the comprehensive quantitative assessment of the ecological state of soil, as a fundamental component of technogenically impacted ecosystems contaminated by heavy metals, is the use of pollution indices (indicators). J.B. Kowalska *et al.* (2018) compared the similarities and differences among 18 indices proposed by various researchers for assessing the levels and risks of soil contamination by heavy metals. Each coefficient or index provides information on the individual levels of contamination by each analysed heavy metal; the overall extent of pollution; the sources of heavy metals; the potential ecological risk; areas with the highest potential risk of heavy metal accumulation; and the capacity of the surface soil horizon to accumulate heavy metals.

An important role in the determination of certain pollution indices is played by the establishment of an appropriate geochemical background, which should be based on soil- and site-specific criteria, as well as on the purpose and scale of the heavy metal impact assessment. The selection of an appropriate index is crucial for correctly interpreting contamination levels, identifying the origin of heavy metals, and evaluating potential ecological risks. In this context, both land-use types (agricultural, forest, and urban areas) and the purpose of calculating pollution indices should be taken into account. Moreover, a multi-index approach can be highly valuable for predicting the future resilience of ecosystems. S.L.C. Ferreira *et al.* (2022) noted that the application of a single index often fails to provide a comprehensive representation of soil contamination levels and the associated ecological risks, which may lead to biased assessment results and negatively affect the scientific validity of environmental quality management. Studies by Z. Yu *et al.* (2021) and M. Jin *et al.* (2025) emphasised that, in order to improve the reliability of soil contamination assessments, it is advisable to employ a set of indices, as multi-indicator approaches allow for a more comprehensive and objective characterisation of heavy metal pollution levels and the associated ecological risks. By quantitatively investigating and identifying the hazards arising from environmental contamination, it becomes possible to predict the likelihood and significance of potential disturbances to ecosystem integrity and public health, as well as to establish the priority and urgency of measures aimed at managing the negative impacts of technogenic factors.

The study by Y. Kuang *et al.* (2024) analysed the characteristics of heavy metal contamination in soils of the city of Chenzhou and assessed the associated risks to human health. To interpret the monitoring results, the following indices were employed: the enrichment factor, geoaccumulation index (I_{geo}), integrated pollution index, potential ecological risk index (*RI*), and health risk assessment models. The findings indicated that the accumulation of excessive amounts of heavy metals in soil matrices could lead to adverse consequences for both local ecosystems and human health. Statistical analysis further demonstrated that intensive industrial activity had a direct impact on the degree of soil contamination. The authors proposed incorporating ecological risk indicators into comprehensive monitoring programmes of urban ecosystems, as these indicators reflected environmental hazards to human health arising from the migration of hazardous metal compounds in urban soils. The analytical report by O.O. Reznikova *et al.* (2020) emphasised that the effective functioning of a national system for assessing risks and threats is a key element of strategic planning and ensuring national resilience, as demonstrated by the experience of many developed countries worldwide. The application of modern methods and technologies for assessing potential risks in Ukraine would enhance the reliability of environmental monitoring results and provide a robust evidence base for further analysis. Taking into account the specific features of the country's administrative-territorial structure and drawing on international experience, the authors argued that multi-level systems for risk and threat assessment are the most effective, whereby analysis is conducted at national, regional, and/or local levels.

Although considerable attention has been paid to heavy metal contamination of soils in Ukraine, there remains a lack of systematic reviews addressing the spatiotemporal distribution of heavy metals in soils and the associated ecological risks, particularly with consideration of different types of geochemical pollution indices at both regional and national scales. For these reasons, the present study is important for understanding the patterns of contamination and potential ecological risks, identifying sources of pollution, and supporting informed environmental management decisions. The aim of this study was to assess the level of heavy metal contamination in the urban soils of the city of Cherkasy in order to provide a scientific basis for urban environmental quality management measures. To achieve this aim, the following objectives were established: to investigate the spatio-temporal patterns of heavy metal distribution in the urban soils of Cherkasy; to evaluate the ecological condition of the city's soil cover using a multi-index approach based on the application of both single-factor and integrated indices, taking into account regional characteristics; to identify the probable sources of heavy metal inputs into urban soils through the application of statistical and correlation analyses.

Materials and Methods

Within the framework of this study, the city of Cherkasy was selected as a model object for assessing the potential ecological risks of heavy metal contamination in urban landscapes. The city is subject to significant aerotechnogenic pressure, which leads to the chemical degradation of urban soils. A considerable impact on the environmental state of the city is exerted by the thermal power sector, chemical and machine-building industries, as well as road transport (Mislyuk *et al.*, 2023). Meteorological conditions also play an important role. The city is located within a zone of environmental risk related to air quality deterioration (Fig. 1), owing to climatic conditions that are unfavourable for the dispersion of atmospheric pollutants. The potential genetic resilience of the natural environment is predominantly low, and the capacity of natural systems to withstand external technogenic pressures is insufficient (Yehorova *et al.*, 2025).

Each study site was geolocated using GPS coordinates, which made it possible to develop a geospatial database linked to the precise locations of the sampling sites (Fig. 2).

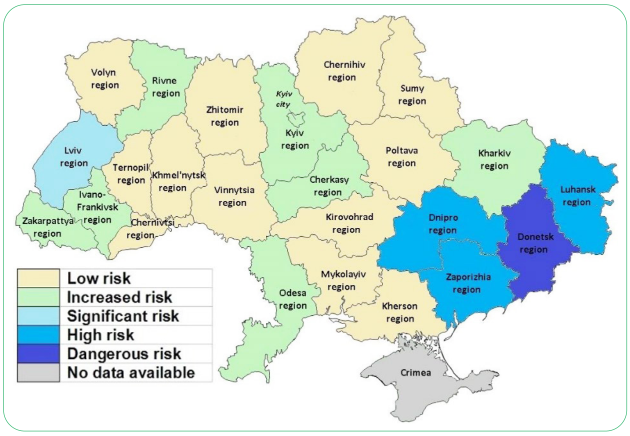

Figure 1. Ecological risk of air quality deterioration across the regions of Ukraine, taking into account the degree of chemical hazard

Source: O.V. Rybalova *et al.* (2022)

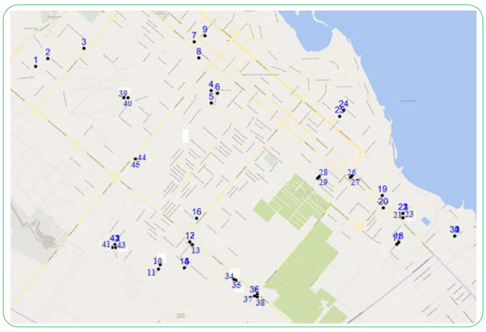

Figure 2. Location of the monitoring sites

Source: compiled by the author

To assess the degree of soil degradation caused by heavy metal contamination, a systematic approach was applied, incorporating bibliosemantic, comparative-analytical, and statistical methods. Statistical data analysis was performed using Microsoft Office Excel software. Correlation analysis was employed to identify potential sources of contamination. A set of geochemical indices and guidelines, in accordance with US EPA standards, was used to evaluate contamination levels and associated ecological risks. Potential ecological risks were assessed using both single-factor indices (I_{geoi}, pollution index *PI* and ecological risk index(*Er*)) and integrated indices (*PLI*, $PI_{Nemerow}$ and *RI*).

Single-factor indices. I_{geo_i} was calculated using the following formula:

$$I_{geo_i} = log_2\left(\frac{C_i}{GB_i}\right), \tag{1}$$

where C_i – the concentration of the metal in the soil; GB_i – its geochemical background value.

Considering the geographical context of the study area, background concentrations of heavy metals in soils of the Forest-Steppe zone of Ukraine were used, specifically for typical low-humus chernozems (genetic horizon HE). Based on the values of the index, contamination levels were classified into seven distinct classes (Table 1).

The *PI* was calculated using the following formula:

$$PI = \frac{C_i}{GB_i}. \tag{2}$$

Contamination was classified according to the scale presented in Table 2.

Table 1. Soil quality according to I_{geo} values

Class	Values of I_{geo}	Soil quality
0	$I \le 0$	unpolluted
1	0-1	unpolluted to moderately polluted
2	1-2	moderately polluted
3	2-3	moderately to highly polluted
4	3-4	highly polluted
5	4-5	highly to extremely high polluted
6	5-6	extremely high polluted

Source: J.B. Kowalska *et al.* (2018)

Table 2. Contamination classes of single *PI*

Class	Value of *PI*	Soil pollution
1	$PI < 1$	absent
2	$1 < PI < 2$	low
3	$2 < PI < 3$	moderate
4	$3 < PI < 5$	strong
5	$PI > 5$	very strong

Source: J.B. Kowalska *et al.* (2018)

The ecological risk index of the *i*-th metal (Er_i) was evaluated using the following equation:

$$Er_i = TR_i \cdot PI, \tag{3}$$

where *PI* – the calculated pollution index for the individual metal; TR_i – its toxic-response factor (Hakanson & Charlesworth, 1980).

Multi-factor indices. To assess the overall extent of contamination, the Pollution Load Index (*PLI*) was determined as the geometric mean of the pollution indices (*PI*) of individual heavy metals, using the following formula:

$$PLI = \sqrt[n]{PI_1 \cdot PI_2 \cdot PI_3 \cdot \ldots \cdot PI_n}, \tag{4}$$

where *n* – the number of analysed heavy metals; *PI* – the calculated values of the pollution index for each individual metal.

To assess soil contamination levels using the *PLI*, the scale proposed by S.G. Papadimou *et al.* (2023) was applied. *PLI* is classified into six classes: Class I: $PLI < 0$, no pollution; Class II: $0 < PLI < 1$, low degree of pollution; Class III: $1 < PLI < 2$, moderate degree of pollution; Class IV: $2 < PLI < 4$, high degree of pollution; Class V: $4 < PLI < 8$, very high degree of pollution; and Class VI: $8 < PLI < 16$, extremely high degree of pollution. $PI_{Nemerow}$, which evaluates the overall contamination level by multiple metals, taking into account both the average and maximum values of single-metal pollution indices, and was calculated using the following formula:

$$PI_{Nemerow} = \sqrt{\frac{\left(\frac{1}{n}\sum_{i-1}^{n} PI\right)^2 + PI_{max}^2}{n}}, \tag{5}$$

where *PI* – the calculated pollution index for each individual metal; PI_{max} is the maximum pollution index value among all heavy metals; *n* – is the number of heavy metals.

Soil quality was assessed according to the scale presented in Table 3.

Table 3. $PI_{Nemerow}$ soil pollution classes

$PI_{Nemerow}$	≤ 0.7	0.7-1	1-2	2-3	≥ 3
Quality of soil	Clean	Warning limit	Slight pollution	Moderate pollution	Heavy pollution

Source: J.B. Kowalska *et al.* (2018)

The potential ecological risk to the soil environment and ecosystems was determined as the sum of the individual risks from each studied metal (*Er*), using the following formula:

$$RI = \sum_{i-1}^{n} Er_i, \quad (6)$$

where Er_i – is the ecological risk index of the *i*-th metal.

Risk assessment was conducted according to the scale presented in Table 4.

This approach enabled the identification of contamination levels and the assessment of the overall ecological threat associated with metal accumulation in soils, thereby providing a basis for comparing environmental conditions across the investigated urban ecosystems.

Table 4. Classification of the potential ecological risk index and integrated potential ecological risk index

Er_i	Pollution Degree	*RI*	Hazards Level
<40	Slight	<150	Slight
40-80	Moderate	150~300	Moderate
80-160	Strong	300~600	Strong
160-320	Very strong	≥600	Very strong
≥320	Extremely strong		

Source: H. Cheng *et al.* (2019)

Results and Discussion

The city of Cherkasy is located in the Forest-Steppe zone. Based on geomorphological and orohydrographic characteristics, the city's landscapes are predominantly formed by loess and loess-like loams, as well as sand-derived loams. The soil cover is heterogeneous, characterised by a light mechanical composition and the presence of anthropogenic inclusions (e.g., construction debris) and allochthonous materials. Soils are contaminated with xenobiotics, including heavy metals (Yehorova *et al.*, 2025). A significant impact on urban soils is exerted by aerotechnogenic pollution, which ranks as the leading source of technogenic contaminants in urban landscapes in terms of environmental influence. The primary pollutants in the city are enterprises from the energy and chemical industries (Regional Report, 2025). In 2024, the largest emissions were recorded from the Cherkasy Thermal Power Plant (PraT "Cherkaske Khimvolokno" VP "Cherkaska TPP"), totalling over 29,637 tons, which is 647.845 tons more than in 2023, due to increased coal consumption. Concentrations and the overall level of technogenic load, the city of Cherkasy ranks among the most environmentally burdened settlements in the region. Based on the Comprehensive Air Pollution Index (API), calculated from monthly average concentrations of sulfur dioxide, ammonia, formaldehyde, nitrogen dioxide, and carbon monoxide, the air pollution level in Cherkasy is classified as elevated (5-7) and high (7-14) (Fig. 3).

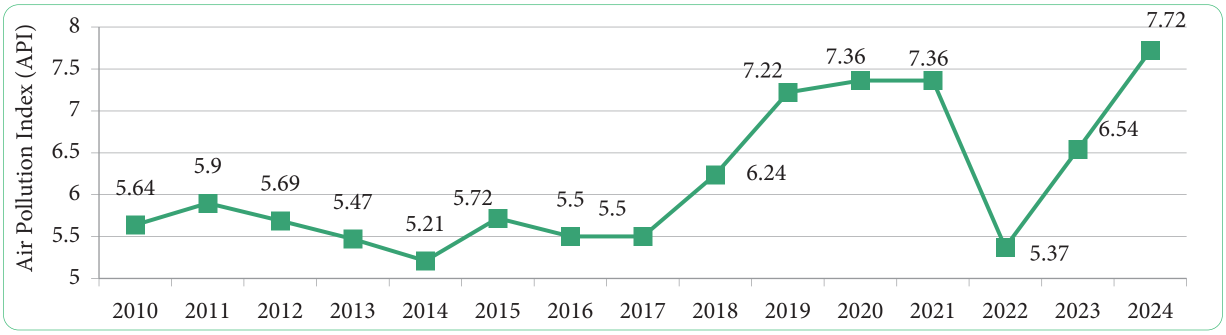

Figure 3. Dynamics of the comprehensive air *PI* in Cherkasy from 2010 to 2024
Source: compiled by the authors

Meteorological conditions play a significant role in shaping air quality. The city is located in climatic conditions unfavourable for the dispersion of pollutants, within a zone of high atmospheric pollution potential. The inherent genetic stability of the natural environment is mostly low, and the self-purifying capacity of nature is insufficient to counteract external technogenic loads. Despite the decline in industrial activity, air pollution levels for individual pollutants remain high. One of the main reasons for this is the atmosphere's limited self-cleaning capacity. Long-term observations indicate that processes promoting the accumulation of harmful pollutants, rather than their dispersion, predominate in the city (atmospheric meteorological potential $K_m > 1$) (Yehorova *et al.*, 2025). Heavy metals present in emissions from industrial facilities and mobile sources (Fig. 4) contaminate urban landscapes through dry or wet deposition.

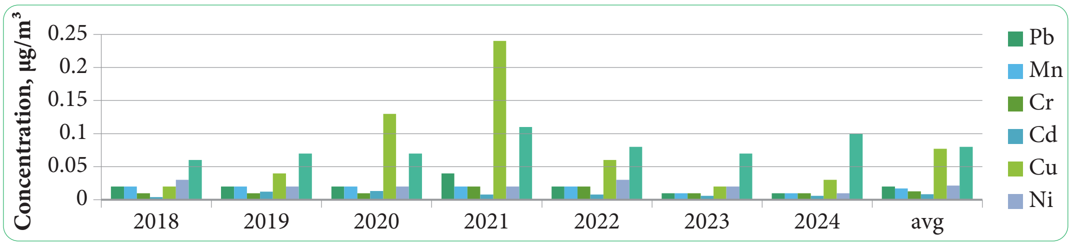

Figure 4. Heavy metal concentrations in the atmospheric air of Cherkasy, μg/m³
Source: compiled by the authors

As a result of intensive technogenesis within urban areas, stable geochemical anomalies are formed in urban soils (Yehorova *et al.*, 2025), accompanied by the disruption of natural soil self-purification mechanisms, alterations in the physicochemical properties of the environment, and an increase in the mobility of pollutants. Such transformations of urbanised geosystems intensify ecotoxicological pressure and contribute to the accumulation of heavy metals in the near-surface atmospheric layer, soils, and biota. Once released into the environment, these elements can persist for extended periods in various ecosystem components, moving through surface runoff, infiltration into groundwater, or wind-driven dust transport. This mobility of pollutants facilitates their wide dispersion beyond emission sources and increases environmental and public health risks, even at considerable distances (He *et al.*, 2023). Soil samples were analysed for heavy metal content by specialists of the Central Laboratory of the Ukrainian Hydrometeorological Center using the method of atomic emission spectrometry. Descriptive statistics of heavy metal concentrations at the reference points are presented in Table 5.

Correlation relationships between different metal pollutants were found to be quite pronounced in some cases (Fig. 5).

Table 5. Results of soil monitoring in Cherkasy in 2016 and 2021

Sampling Site No.	Pb, mg/kg		Zn, mg/kg		Cu, mg/kg		Ni, mg/kg		Mn, mg/kg		Cd, mg/kg	
	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021
1	20	8	51	37	11	5	13	11	179	237	0.50	0.50
2	70	11	259	85	54	32	42	16	419	311	1.75	0.75
3	13	7	47	32	13	6	19	9	302	250	0.75	0.75
4	15	8	50	40	9	8	19	12	207	170	0.50	0.50
5	94	7	319	45	37	4	28	11	324	241	1.25	0.75
6	21	12	58	48	14	10	19	13	330	303	1.00	0.25
7	22	13	43	43	10	11	16	15	274	267	1.00	0.25
8	66	18	244	43	26	12	18	10	307	179	1.00	1.00
9	38	11	95	47	20	10	23	12	386	175	1.00	0.50
10	45	16	62	158	17	21	20	20	246	430	1.25	1.00
11	40	12	88	49	21	11	20	17	319	311	0.50	0.50
12	23	23	87	207	18	76	14	14	218	457	1.00	0.75
13	40	8	191	31	20	7	20	16	341	399	0.50	0.25
14	29	30	70	215	17	42	19	37	414	2,406	0.75	0.75
15	49	41	71	260	17	73	11	50	313	2,402	1.00	1.00
16	213	25	296	199	104	53	16	42	207	2,389	1.25	1.25
17	38	510	318	311	87	132	20	25	279	580	1.00	1.00
18	126	22	251	129	25	10	20	15	319	465	2.00	0.25
19	65	11	274	145	50	11	18	16	330	325	1.00	0.75
20	30	23	214	129	31	14	15	20	408	892	0.50	1.25
21	40	9	184	96	23	11	19	20	358	250	0.25	0.25
22	49	8	169	100	28	10	23	24	369	245	0.50	0.50
23	28	11	48	158	9	14	13	20	190	232	0.00	0.00
24	40	9	244	29	18	5	17	12	195	175	0.50	0.50
25	32	30	69	49	25	15	23	11	274	241	0.50	0.25
26	77	7	251	39	24	4	16	6	173	87	0.00	0.00
27	155	7	206	41	28	5	23	7	319	91	0.25	0.00
28	40	27	176	207	34	14	25	19	330	364	0.25	0.25

Table 5. Continued

Sampling Site No.	Pb, mg/kg		Zn, mg/kg		Cu, mg/kg		Ni, mg/kg		Mn, mg/kg		Cd, mg/kg	
	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021
29	111	9	273	88	23	22	23	15	475	338	0.75	0.75
30	21	19	91	50	16	28	23	16	285	281	0.00	0.75
31	38	11	311	29	20	11	23	20	307	259	0.75	0.25
32	23	8	65	39	13	10	14	20	123	267	0.25	0.50
33	41	14	99	44	19	23	23	21	285	311	0.00	0.50
34	45	14	236	47	25	13	28	16	1,181	241	0.75	0.25
35	31	8	191	39	18	13	15	18	274	303	0.25	0.50
36	56	12	199	45	20	15	24	15	498	320	0.25	0.50
37	83	9	221	39	31	14	23	15	307	232	0.50	0.25
38	56	15	214	43	19	19	16	15	319	272	0.00	0.25
39	67	9	229	40	26	8	18	13	1,408	201	0.50	0.25
40	68	6	206	29	45	4	11	10	257	188	0.00	0.00
41	44	5	73	43	21	7	21	7	263	245	0.00	0.00
42	27	26	68	49	17	17	15	12	285	285	0.25	0.25
43	40	9	86	39	21	8	18	16	363	254	0.25	0.50
44	29	9	69	207	23	24	22	20	212	355	0.50	0.50
45	33	8	68	174	18	27	11	17	291	289	0.25	0.25
mini	13	5	43	29	9	4	11	6	123	87	0	0
max	213	510	319	311	104	132	42	50	1,408	2,406	2	1.25
medium	52	25	159	89	26	20	19	17	344	434	0.6	0,5
SD	38.2	74.4	91.0	73.4	18.1	23.4	5.5	8.4	222.6	546.6	0.5	0.3
CV, %	70	300	60	80	70	120	30	50	60	130	80	70
Background site	11		52		20		26		735		0.13	

Source: compiled by the authors

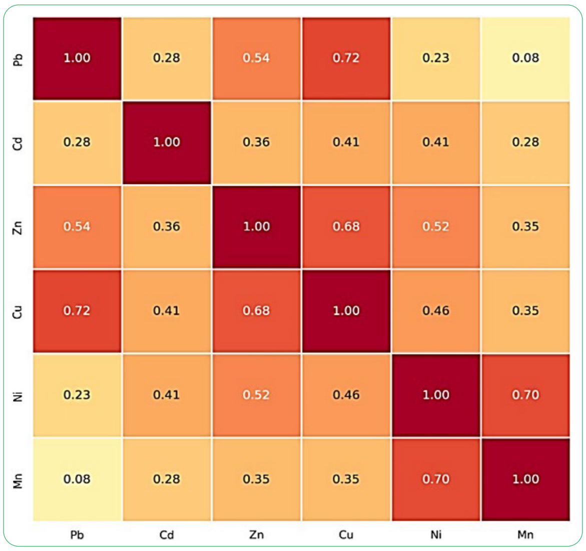

Figure 5. Correlation matrix of heavy metals in the soils of Cherkasy

Source: compiled by the authors

Strong correlations (correlation coefficient $r > 0.7$) were observed between Pb and Cu ($r = 0.72$) and between Ni and Mn ($r = 0.70$), indicating that the sources of these elements may be similar. Moderate correlations ($0.50 < r < 0.69$) were found for Cu and Zn ($r = 0.68$), Pb and Zn ($r = 0.54$), and Ni and Zn ($r = 0.52$). Mn exhibited weak correlations ($r < 0.4$) with all metals except Ni, suggesting that the patterns of Mn input and accumulation may differ from those of the other metals. Using soil monitoring data on heavy metal concentrations, the I_{geo} was calculated to evaluate the extent of anthropogenic influence on heavy metal levels, taking into account possible natural fluctuations in background concentrations (Table 6). Geoaccumulation indices varied significantly across time and space (Fig. 6-7). In 2016, based on Pb content, only 3% of the studied soils were classified as uncontaminated ($I_{geo} \leq 0$), 25% ranged from uncontaminated to moderately contaminated ($0 < I_{geo} \leq 1$), 48% were moderately contaminated ($1 < I_{geo} \leq 2$), 22% ranged from moderately to strongly contaminated ($2 < I_{geo} \leq 3$), and 2% were strongly contaminated ($3 < I_{geo} \leq 4$).

Table 6. Calculated values of the I_{geo} for Soil Contamination in the City of Cherkasy

Sampling Site No.	I_{geo}											
	Pb		Zn		Cu		Ni		Mn		Cd	
	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021
1	0.3	-1.0	-0.6	-1.1	-1.4	-2.6	-1.6	-1.8	-2.6	-2.2	1.4	1.4
2	2.1	-0.6	1.7	0.1	0.8	0.1	0.1	-1.3	-1.4	-1.8	3.2	1.9
3	-0.3	-1.2	-0.7	-1.3	-1.2	-2.3	-1.0	-2.1	-1.9	-2.1	1.9	1.9
4	-0.1	-1.0	-0.6	-1.0	-1.7	-1.9	-1.0	-1.7	-2.4	-2.7	1.4	1.4
5	2.5	-1.2	2.0	-0.8	0.3	-2.9	-0.5	-1.8	-1.8	-2.2	2.7	1.9
6	0.3	-0.5	-0.4	-0.7	-1.1	-1.6	-1.0	-1.6	-1.7	-1.9	2.4	0.4
7	0.4	-0.3	-0.9	-0.9	-1.6	-1.4	-1.3	-1.4	-2.0	-2.0	2.4	0.4
8	2.0	0.1	1.6	-0.9	-0.2	-1.3	-1.1	-2.0	-1.8	-2.6	2.4	2.4
9	1.2	-0.6	0.3	-0.7	-0.6	-1.6	-0.8	-1.7	-1.5	-2.7	2.4	1.4
10	1.4	0.0	-0.3	1.0	-0.8	-0.5	-1.0	-1.0	-2.2	-1.4	2.7	2.4
11	1.3	-0.5	0.2	-0.7	-0.5	-1.4	-1.0	-1.2	-1.8	-1.8	1.4	1.4
12	0.5	0.5	0.2	1.4	-0.7	1.3	-1.5	-1.5	-2.3	-1.3	2.4	1.9
13	1.3	-1.0	1.3	-1.3	-0.6	-2.1	-1.0	-1.3	-1.7	-1.5	1.4	0.4
14	0.8	0.9	-0.2	1.5	-0.8	0.5	-1.0	-0.1	-1.4	1.1	1.9	1.9
15	1.6	1.3	-0.1	1.7	-0.8	1.3	-1.8	0.4	-1.8	1.1	2.4	2.4
16	3.7	0.6	1.9	1.4	1.8	0.8	-1.3	0.1	-2.4	1.1	2.7	2.7
17	1.2	4.9	2.0	2.0	1.5	2.1	-1.0	-0.6	-2.0	-0.9	2.4	2.4
18	2.9	0.4	1.7	0.7	-0.3	-1.6	-1.0	-1.4	-1.8	-1.2	3.4	0.4
19	2.0	-0.6	1.8	0.9	0.7	-1.4	-1.1	-1.3	-1.7	-1.8	2.4	1.9
20	0.9	0.5	1.5	0.7	0.0	-1.1	-1.4	-1.0	-1.4	-0.3	1.4	2.7
21	1.3	-0.9	1.2	0.3	-0.4	-1.4	-1.0	-1.0	-1.6	-2.1	0.4	0.4
22	1.6	-1.0	1.1	0.4	-0.1	-1.6	-0.8	-0.7	-1.6	-2.2	1.4	1.4
23	0.8	-0.6	-0.7	1.0	-1.7	-1.1	-1.6	-1.0	-2.5	-2.2	0.0	0.0
24	1.3	-0.9	1.6	-1.4	-0.7	-2.6	-1.2	-1.7	-2.5	-2.7	1.4	1.4
25	1.0	0.9	-0.2	-0.7	-0.3	-1.0	-0.8	-1.8	-2.0	-2.2	1.4	0.4
26	2.2	-1.2	1.7	-1.0	-0.3	-2.9	-1.3	-2.7	-2.7	-3.7	0.0	0.0
27	3.2	-1.2	1.4	-0.9	-0.1	-2.6	-0.8	-2.5	-1.8	-3.6	0.4	0.0
28	1.3	0.7	1.2	1.4	0.2	-1.1	-0.6	-1.0	-1.7	-1.6	0.4	0.4
29	2.8	-0.9	1.8	0.2	-0.4	-0.4	-0.8	-1.4	-1.2	-1.7	1.9	1.9
30	0.3	0.2	0.2	-0.6	-0.9	-0.1	-0.8	-1.3	-2.0	-2.0	0.0	1.9
31	1.2	-0.6	2.0	-1.4	-0.6	-1.4	-0.8	-1.0	-1.8	-2.1	1.9	0.4
32	0.5	-1.0	-0.3	-1.0	-1.2	-1.6	-1.5	-1.0	-3.2	-2.0	0.4	1.4
33	1.3	-0.2	0.3	-0.8	-0.7	-0.4	-0.8	-0.9	-2.0	-1.8	0.0	1.4
34	1.4	-0.2	1.6	-0.7	-0.3	-1.2	-0.5	-1.3	0.1	-2.2	1.9	0.4
35	0.9	-1.0	1.3	-1.0	-0.7	-1.2	-1.4	-1.1	-2.0	-1.9	0.4	1.4
36	1.8	-0.5	1.4	-0.8	-0.6	-1.0	-0.7	-1.4	-1.1	-1.8	0.4	1.4
37	2.3	-0.9	1.5	-1.0	0.0	-1.1	-0.8	-1.4	-1.8	-2.2	1.4	0.4
38	1.8	-0.1	1.5	-0.9	-0.7	-0.7	-1.3	-1.4	-1.8	-2.0	0.0	0.4
39	2.0	-0.9	1.6	-1.0	-0.2	-1.9	-1.1	-1.6	0.4	-2.5	1.4	0.4
40	2.0	-1.5	1.4	-1.4	0.6	-2.9	-1.8	-2.0	-2.1	-2.6	0.0	0.0
41	1.4	-1.7	-0.1	-0.9	-0.5	-2.1	-0.9	-2.5	-2.1	-2.2	0.0	0.0
42	0.7	0.7	-0.2	-0.7	-0.8	-0.8	-1.4	-1.7	-2.0	-2.0	0.4	0.4
43	1.3	-0.9	0.1	-1.0	-0.5	-1.9	-1.1	-1.3	-1.6	-2.1	0.4	1.4
44	0.8	-0.9	-0.2	1.4	-0.4	-0.3	-0.8	-1.0	-2.4	-1.6	1.4	1.4
45	1.0	-1.0	-0.2	1.2	-0.7	-0.2	-1.8	-1.2	-1.9	-1.9	0.4	0.4
min	-0.3	-1.7	-0.9	-1.4	-1.7	-2.9	-1.8	-2.7	-3.2	-3.7	0.0	0.0
max	3.7	4.9	2.0	2.0	1.8	2.1	0.1	0.4	0.4	1.1	3.4	2.7
mean	1.4	-0.3	0.7	-0.2	-0.4	-1.1	-1.1	-1.3	-1.8	-1.8	1.4	1.1

Source: compiled by the authors

Figure 6. Geoaccumulation indices (I_{geo}) of heavy metals in the soils of Cherkasy city in 2016
Source: compiled by the authors

By 2021, 69% of the soils were uncontaminated, 24% were uncontaminated to moderately contaminated, 3% were moderately contaminated, and 3% were strongly contaminated.

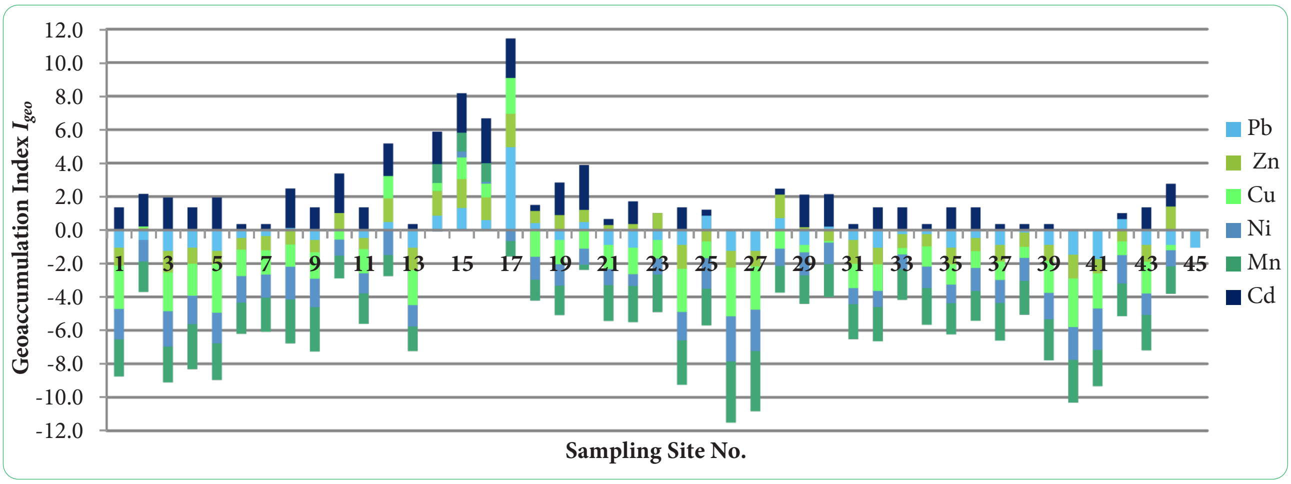

Figure 7. Geoaccumulation indices (I_{geo}) of heavy metals in the soils of Cherkasy city in 2021
Source: compiled by the authors

In 2016, the I_{geo} values for Zn indicated soil contamination levels as follows: 33% of sampling points were uncontaminated, 13% were uncontaminated to moderately contaminated, 47% were moderately contaminated, and 7% were moderately to strongly contaminated. By 2021, the soil condition had improved significantly: 62% of the studied soils were uncontaminated, 16% were uncontaminated to moderately contaminated, 18% were moderately contaminated, and 2% were moderately to strongly contaminated. In 2016, the I_{geo} values for Cu indicated that 84% of the studied soils were uncontaminated, 11% were uncontaminated to moderately contaminated, and 5% were moderately contaminated. By 2021, 86% of soils were uncontaminated, 7% were uncontaminated to moderately contaminated, 5% were moderately contaminated, and 2% were moderately to strongly contaminated. For Ni, the I_{geo} values in 2016 and 2021 showed that 98% and 96% of soils, respectively, were uncontaminated, while 2% and 4% were uncontaminated to moderately contaminated. Regarding Mn, in 2016 and 2021, 96% and 93% of soils were uncontaminated, and 4% and 7% were uncontaminated to moderately contaminated, respectively. For Cd, the I_{geo} values in 2016 and 2021 indicated that only 16% and 12% of soils were uncontaminated, 20% and 32% were uncontaminated to moderately contaminated, 36% and 45% were moderately contaminated, and 24% and 11% were moderately to strongly contaminated. In 2016, 4% of soils were strongly contaminated with Cd. Overall, the I_{geo} indicates that Pb and Cd exhibit significantly higher levels of contamination, whereas the other metals generally show only minor pollution. The results of the assessment of soil contamination hazards associated with heavy metals, conducted using both single-metal *PI* and integrated multi-element pollution indices (*PLI* and $PI_{Nemerow}$), are presented in Table 7.

Table 7. Individual metal *PI* and integrated pollution indices accounting for the multi-element nature of contamination (*PLI* and $PI_{Nemerow}$)

Sampling Site No.	*PI*												*PLI*		$PI_{Nemerow}$	
	Pb		Zn		Cu		Ni		Mn		Cd					
	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021
1	1.8	0.7	1.0	0.7	0.6	0.3	0.5	0.4	0.2	0.3	3.8	3.8	0.9	0.6	2	2
2	6.4	1.0	5.0	1.6	2.7	1.6	1.6	0.6	0.6	0.4	13.5	5.8	3.2	1.3	6	2
3	1.2	0.6	0.9	0.6	0.7	0.3	0.7	0.3	0.4	0.3	5.8	5.8	1.0	0.7	2	2
4	1.4	0.7	1.0	0.8	0.5	0.4	0.7	0.5	0.3	0.2	3.8	3.8	0.9	0.7	2	2
5	8.5	0.6	6.1	0.9	1.9	0.2	1.1	0.4	0.4	0.3	9.6	5.8	2.8	0.7	4	2
6	1.9	1.1	1.1	0.9	0.7	0.5	0.7	0.5	0.4	0.4	7.7	1.9	1.2	0.8	3	1
7	2.0	1.2	0.8	0.8	0.5	0.6	0.6	0.6	0.4	0.4	7.7	1.9	1.1	0.8	3	1
8	6.0	1.6	4.7	0.8	1.3	0.6	0.7	0.4	0.4	0.2	7.7	7.7	2.1	0.9	3	3
9	3.5	1.0	1.8	0.9	1.0	0.5	0.9	0.5	0.5	0.2	7.7	3.8	1.7	0.8	3	2
10	4.1	1.5	1.2	3.0	0.9	1.1	0.8	0.8	0.3	0.6	9.6	7.7	1.5	1.6	4	3
11	3.6	1.1	1.7	0.9	1.1	0.6	0.8	0.7	0.4	0.4	3.8	3.8	1.4	0.9	2	2
12	2.1	2.1	1.7	4.0	0.9	3.8	0.5	0.5	0.3	0.6	7.7	5.8	1.3	2.0	3	3
13	3.6	0.7	3.7	0.6	1.0	0.4	0.8	0.6	0.5	0.5	3.8	1.9	1.6	0.7	2	1
14	2.6	2.7	1.3	4.1	0.9	2.1	0.7	1.4	0.6	3.3	5.8	5.8	1.4	2.9	2	3
15	4.5	3.7	1.4	5.0	0.9	3.7	0.4	1.9	0.4	3.3	7.7	7.7	1.4	3.9	3	4
16	19.4	2.3	5.7	3.8	5.2	2.7	0.6	1.6	0.3	3.3	9.6	9.6	3.1	3.2	8	4
17	3.5	46.4	6.1	6.0	4.4	6.6	0.8	1.0	0.4	0.8	7.7	7.7	2.4	4.7	4	19
18	11.5	2.0	4.8	2.5	1.3	0.5	0.8	0.6	0.4	0.6	15.4	1.9	2.7	1.1	7	1
19	5.9	1.0	5.3	2.8	2.5	0.6	0.7	0.6	0.4	0.4	7.7	5.8	2.4	1.2	3	2
20	2.7	2.1	4.1	2.5	1.6	0.7	0.6	0.8	0.6	1.2	3.8	9.6	1.7	1.8	2	4
21	3.6	0.8	3.5	1.8	1.2	0.6	0.7	0.8	0.5	0.3	1.9	1.9	1.5	0.9	2	1
22	4.5	0.7	3.3	1.9	1.4	0.5	0.9	0.9	0.5	0.3	3.8	3.8	1.8	1.0	2	2
23	2.5	1.0	0.9	3.0	0.5	0.7	0.5	0.8	0.3	0.3	0.0	0.0	0.7	0.9	1	1
24	3.6	0.8	4.7	0.6	0.9	0.3	0.7	0.5	0.3	0.2	3.8	3.8	1.5	0.6	2	2
25	2.9	2.7	1.3	0.9	1.3	0.8	0.9	0.4	0.4	0.3	3.8	1.9	1.4	0.9	2	1
26	7.0	0.6	4.8	0.8	1.2	0.2	0.6	0.2	0.2	0.1	0.0	0.0	1.4	0.3	3	0
27	14.1	0.6	4.0	0.8	1.4	0.3	0.9	0.3	0.4	0.1	1.9	0.0	2.0	0.3	6	0
28	3.6	2.5	3.4	4.0	1.7	0.7	1.0	0.7	0.4	0.5	1.9	1.9	1.6	1.3	2	2
29	10.1	0.8	5.3	1.7	1.2	1.1	0.9	0.6	0.6	0.5	5.8	5.8	2.4	1.2	4	2
30	1.9	1.7	1.8	1.0	0.8	1.4	0.9	0.6	0.4	0.4	0.0	5.8	1.0	1.2	1	2
31	3.5	1.0	6.0	0.6	1.0	0.6	0.9	0.8	0.4	0.4	5.8	1.9	1.9	0.7	3	1
32	2.1	0.7	1.3	0.8	0.7	0.5	0.5	0.8	0.2	0.4	1.9	3.8	0.8	0.8	1	2
33	3.7	1.3	1.9	0.8	1.0	1.2	0.9	0.8	0.4	0.4	0.0	3.8	1.2	1.1	2	2
34	4.1	1.3	4.5	0.9	1.3	0.7	1.1	0.6	1.6	0.3	5.8	1.9	2.5	0.8	3	1
35	2.8	0.7	3.7	0.8	0.9	0.7	0.6	0.7	0.4	0.4	1.9	3.8	1.3	0.9	2	2
36	5.1	1.1	3.8	0.9	1.0	0.8	0.9	0.6	0.7	0.4	1.9	3.8	1.7	0.9	2	2
37	7.5	0.8	4.3	0.8	1.6	0.7	0.9	0.6	0.4	0.3	3.8	1.9	2.0	0.7	3	1
38	5.1	1.4	4.1	0.8	1.0	1.0	0.6	0.6	0.4	0.4	0.0	1.9	1.4	0.9	2	1
39	6.1	0.8	4.4	0.8	1.3	0.4	0.7	0.5	1.9	0.3	3.8	1.9	2.4	0.6	3	1
40	6.2	0.5	4.0	0.6	2.3	0.2	0.4	0.4	0.3	0.3	0.0	0.0	1.5	0.4	3	0
41	4.0	0.5	1.4	0.8	1.1	0.4	0.8	0.3	0.4	0.3	0.0	0.0	1.1	0.4	2	0
42	2.5	2.4	1.3	0.9	0.9	0.9	0.6	0.5	0.4	0.4	1.9	1.9	1.0	0.9	1	1
43	3.6	0.8	1.7	0.8	1.1	0.4	0.7	0.6	0.5	0.3	1.9	3.8	1.3	0.8	2	2
44	2.6	0.8	1.3	4.0	1.2	1.2	0.8	0.8	0.3	0.5	3.8	3.8	1.2	1.3	2	2
45	3.0	0.7	1.3	3.3	0.9	1.4	0.4	0.7	0.4	0.4	1.9	1.9	1.0	1.1	1	1
min	1.2	0.5	0.8	0.6	0.5	0.2	0.4	0.2	0.2	0.1	0	0	0.7	0.3	1	0
max	19.4	46.4	6.1	6.0	5.2	6.6	1.6	1.9	1.9	3.3	15.4	9.6	3.2	4.7	9	6
mean	4.7	2.3	3.0	1.7	1.3	1.0	0.7	0.7	0.5	0.6	4.6	3.8	1.6	1.2	2	1

Source: compiled by the authors

Soil pollution indices also varied significantly over time and space for different metals and sampling sites (Fig. 8-9). Based on the average *PI* values, the metals were ranked as follows: Pb (4.7) > Cd (4.6) > Zn (3.0) > Cu (1.3) > Ni (0.7) > Mn (0.5) in 2016, and Cd (3.8) > Pb (2.3) > Zn (1.7) > Cu (1.0) > Ni (0.7) > Mn (0.6) in 2021.

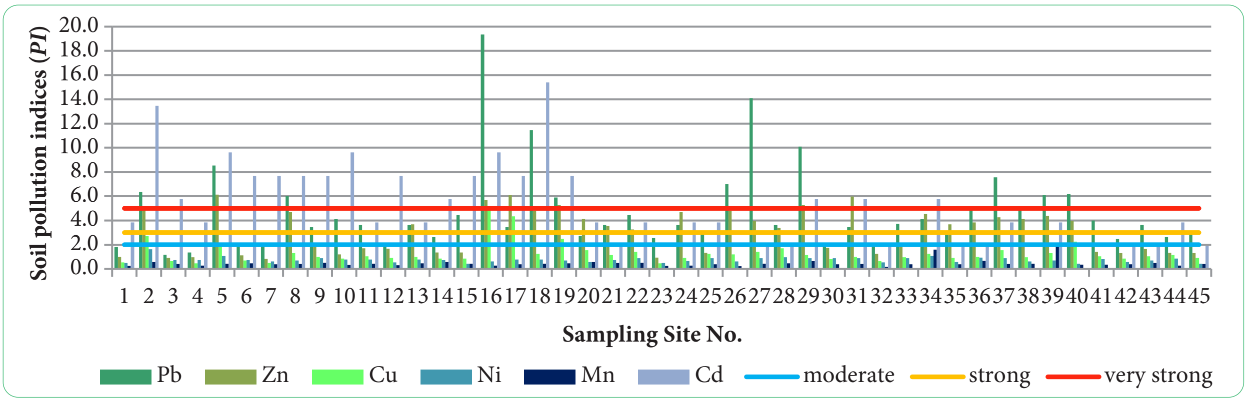

Figure 8. Soil *PI* for heavy metals in 2016

Source: compiled by the authors

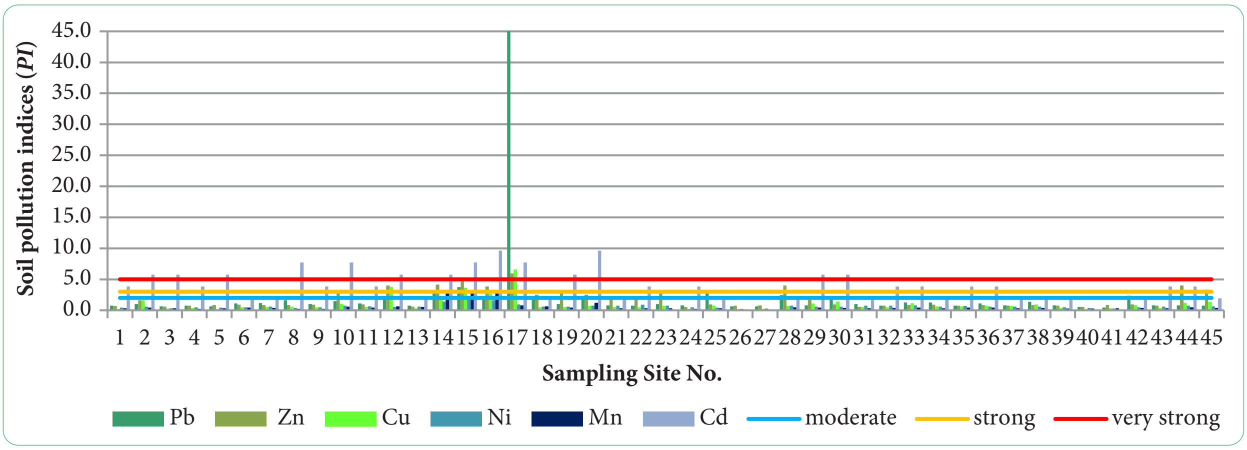

Figure 9. Soil *PI* for heavy metals in 2021

Source: compiled by the authors

Particularly high *PI* values ($PI > 5$) were observed in 2016 for Cd (40% of sites) and Pb (31%). By 2021, the number of sites with very high pollution levels decreased, with Cd exceeding $PI > 5$ at 33% of sites. For Pb, a very high *PI* was observed only at site 17 ($PI = 45$). According to the *PLI* for all heavy metals (Fig. 10), a high level of contamination ($PLI = 4.7$) was observed at site 17 in 2021. Moderately contaminated soils accounted for 22% of samples (sites 2, 3, 16-19, 29, 34, 39) in 2016 and 9% (sites 14, 15, 16) in 2021. At the remaining locations, soils were classified as uncontaminated ($PLI \leq 1$). $PI_{Nemerow}$ were slightly higher than the *PLI*. Soils exhibited a high level of contamination at 33% and 13% of the sites, and a medium level at 60% and 18% of the sites in 2016 and 2021, respectively (Fig. 11).

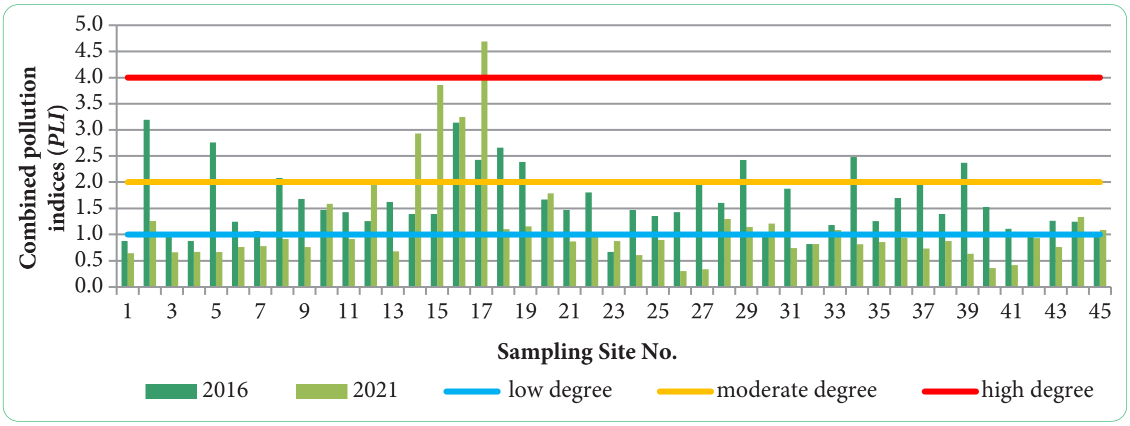

Figure 10. *PLI* of heavy metals in soils

Source: compiled by the authors

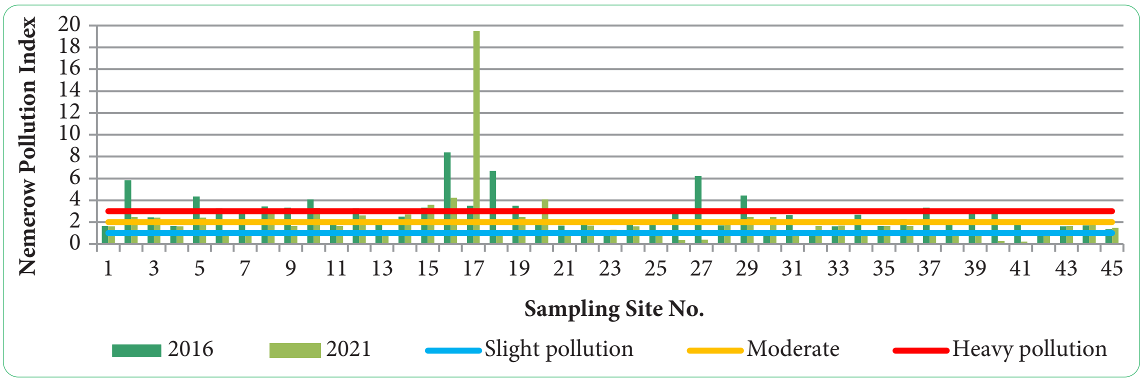

Figure 11. Levels of combined soil contamination by heavy metals according to the $PI_{Nemerow}$
Source: compiled by the authors

The results of the assessment of ecological risks associated with soil contamination by individual heavy metals, as well as the integrated potential ecological risk, are presented in Table 8 and Figures 12-14.

Table 8. Ecological risk indices for soil contamination in the city of Cherkasy: individual heavy metal risk (*Er*) and integrated potential ecological risk (*RI*)

Sampling Site No.	*Er*												*RI*	
	Pb		Zn		Cu		Ni		Mn		Cd			
	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021
1	9.1	3.6	1.0	0.7	2.8	1.3	2.5	2.1	0.2	0.3	115.4	115.4	131	123
2	31.8	5.0	5.0	1.6	13.5	8.0	8.1	3.1	0.6	0.4	403.8	173.1	463	191
3	5.9	3.2	0.9	0.6	3.3	1.5	3.7	1.7	0.4	0.3	173.1	173.1	187	180
4	6.8	3.6	1.0	0.8	2.3	2.0	3.7	2.3	0.3	0.2	115.4	115.4	129	124
5	42.7	3.2	6.1	0.9	9.3	1.0	5.4	2.1	0.4	0.3	288.5	173.1	352	181
6	9.5	5.5	1.1	0.9	3.5	2.5	3.7	2.5	0.4	0.4	230.8	57.7	249	69
7	10.0	5.9	0.8	0.8	2.5	2.8	3.1	2.9	0.4	0.4	230.8	57.7	248	70
8	30.0	8.2	4.7	0.8	6.5	3.0	3.5	1.9	0.4	0.2	230.8	230.8	276	245
9	17.3	5.0	1.8	0.9	5.0	2.5	4.4	2.3	0.5	0.2	230.8	115.4	260	126
10	20.5	7.3	1.2	3.0	4.3	5.3	3.8	3.8	0.3	0.6	288.5	230.8	319	251
11	18.2	5.5	1.7	0.9	5.3	2.8	3.8	3.3	0.4	0.4	115.4	115.4	145	128
12	10.5	10.5	1.7	4.0	4.5	19.0	2.7	2.7	0.3	0.6	230.8	173.1	250	210
13	18.2	3.6	3.7	0.6	5.0	1.8	3.8	3.1	0.5	0.5	115.4	57.7	147	67
14	13.2	13.6	1.3	4.1	4.3	10.5	3.7	7.1	0.6	3.3	173.1	173.1	196	212
15	22.3	18.6	1.4	5.0	4.3	18.3	2.1	9.6	0.4	3.3	230.8	230.8	261	286
16	96.8	11.4	5.7	3.8	26.0	13.3	3.1	8.1	0.3	3.3	288.5	288.5	420	328
17	17.3	231.8	6.1	6.0	21.8	33.0	3.8	4.8	0.4	0.8	230.8	230.8	280	507
18	57.3	10.0	4.8	2.5	6.3	2.5	3.8	2.9	0.4	0.6	461.5	57.7	534	76
19	29.5	5.0	5.3	2.8	12.5	2.8	3.5	3.1	0.4	0.4	230.8	173.1	282	187
20	13.6	10.5	4.1	2.5	7.8	3.5	2.9	3.8	0.6	1.2	115.4	288.5	144	310
21	18.2	4.1	3.5	1.8	5.8	2.8	3.7	3.8	0.5	0.3	57.7	57.7	89	71
22	22.3	3.6	3.3	1.9	7.0	2.5	4.4	4.6	0.5	0.3	115.4	115.4	153	128
23	12.7	5.0	0.9	3.0	2.3	3.5	2.5	3.8	0.3	0.3	0.0	0.0	19	16
24	18.2	4.1	4.7	0.6	4.5	1.3	3.3	2.3	0.3	0.2	115.4	115.4	146	124
25	14.5	13.6	1.3	0.9	6.3	3.8	4.4	2.1	0.4	0.3	115.4	57.7	142	78
26	35.0	3.2	4.8	0.8	6.0	1.0	3.1	1.2	0.2	0.1	0.0	0.0	49	6
27	70.5	3.2	4.0	0.8	7.0	1.3	4.4	1.3	0.4	0.1	57.7	0.0	144	7
28	18.2	12.3	3.4	4.0	8.5	3.5	4.8	3.7	0.4	0.5	57.7	57.7	93	82
29	50.5	4.1	5.3	1.7	5.8	5.5	4.4	2.9	0.6	0.5	173.1	173.1	240	188
30	9.5	8.6	1.8	1.0	4.0	7.0	4.4	3.1	0.4	0.4	0.0	173.1	20	193
31	17.3	5.0	6.0	0.6	5.0	2.8	4.4	3.8	0.4	0.4	173.1	57.7	206	70
32	10.5	3.6	1.3	0.8	3.3	2.5	2.7	3.8	0.2	0.4	57.7	115.4	76	126
33	18.6	6.4	1.9	0.8	4.8	5.8	4.4	4.0	0.4	0.4	0.0	115.4	30	133
34	20.5	6.4	4.5	0.9	6.3	3.3	5.4	3.1	1.6	0.3	173.1	57.7	211	72
35	14.1	3.6	3.7	0.8	4.5	3.3	2.9	3.5	0.4	0.4	57.7	115.4	83	127

Table 8. Continued

Sampling Site No.	Er												RI	
	Pb		Zn		Cu		Ni		Mn		Cd			
	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021	2016	2021
36	25.5	5.5	3.8	0.9	5.0	3.8	4.6	2.9	0.7	0.4	57.7	115.4	97	129
37	37.7	4.1	4.3	0.8	7.8	3.5	4.4	2.9	0.4	0.3	115.4	57.7	170	69
38	25.5	6.8	4.1	0.8	4.8	4.8	3.1	2.9	0.4	0.4	0.0	57.7	38	73
39	30.5	4.1	4.4	0.8	6.5	2.0	3.5	2.5	1.9	0.3	115.4	57.7	162	67
40	30.9	2.7	4.0	0.6	11.3	1.0	2.1	1.9	0.3	0.3	0.0	0.0	49	6
41	20.0	2.3	1.4	0.8	5.3	1.8	4.0	1.3	0.4	0.3	0.0	0.0	31	7
42	12.3	11.8	1.3	0.9	4.3	4.3	2.9	2.3	0.4	0.4	57.7	57.7	79	77
43	18.2	4.1	1.7	0.8	5.3	2.0	3.5	3.1	0.5	0.3	57.7	115.4	87	126
44	13.2	4.1	1.3	4.0	5.8	6.0	4.2	3.8	0.3	0.5	115.4	115.4	140	134
45	15.0	3.6	1.3	3.3	4.5	6.8	2.1	3.3	0.4	0.4	57.7	57.7	81	75
min	5.9	2.3	0.8	0.6	2.3	1.0	2.1	1.2	0.2	0.1	0.0	0.0	19	6
max	96.8	231.8	6.1	6.0	26.0	33.0	8.1	9.6	1.9	3.3	461.5	288.5	534	507
mean	23.5	11.3	3.0	1.7	6.5	4.9	3.7	3.3	0.5	0.6	138.5	112.8	176	135

Source: compiled by the authors

The potential ecological risk factor (*Er_i*) for Pb, Zn, Cu, Ni, Mn, and Cd in 2016 ranged from 5.9-96.8 (mean 23.5), 0.8-6.1 (mean 3.0), 2.3-26.0 (mean 6.5), 2.1-8.1 (mean 3.7), 0.2-1.9 (mean 0.5), and 0.0-461.5 (mean 138.5), respectively. In 2021, Er_i varied as follows: Pb – 2.3-231.8 (mean 11.3), Zn – 0.6-6.0 (mean 1.7), Cu – 1.0-33.0 (mean 4.9), Ni – 1.2-9.6 (mean 3.3), Mn – 0.1-3.3 (mean 0.6), and Cd – 0-288 (mean 113), respectively. The main environmentally hazardous metal present in the soils of the studied area was Cd. The ecological risk level of soil contamination by this toxicant in 2016 was assessed as moderate (20%), considerable (24%), high (41%), very high (2%), while 13% of the soils were uncontaminated by this toxic metal. In 2021, 31% of the soil samples fell into the moderate ecological risk category, 27% – considerable, 31% – high, and 11% were uncontaminated.

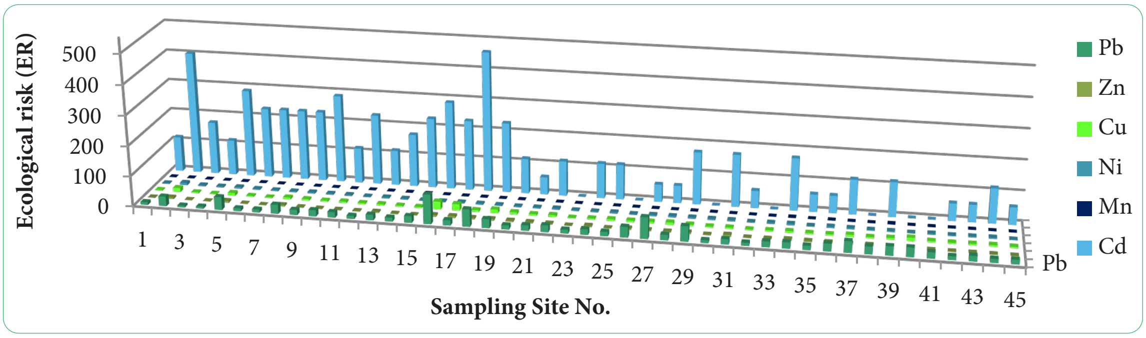

Figure 12. *Er* levels in 2016

Source: compiled by the authors

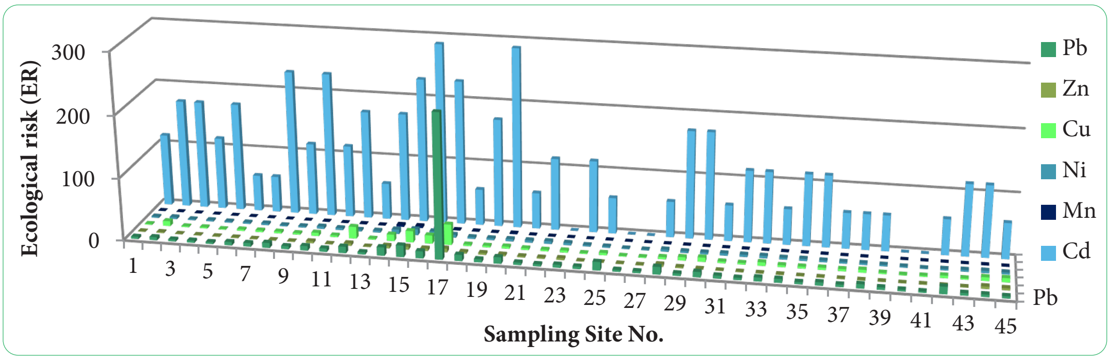

Figure 13. *Er* levels in 2021

Source: compiled by the authors

The ecological risk level of Pb contamination in 2016 was low for 89% of the soils, moderate for 9%, and considerable for 2%. In 2021, only one soil sample (site 17) exhibited a high ecological risk, while all other locations were low. For the other heavy metals, the ecological risk of soil contamination remained low. Based on the cumulative ecological risk (Fig. 14), in 2016, 53% of soil samples were classified as having a low contamination level, 36% as moderate, and 11% as high. In 2021, these proportions were 69%, 24%, and 7%, respectively.

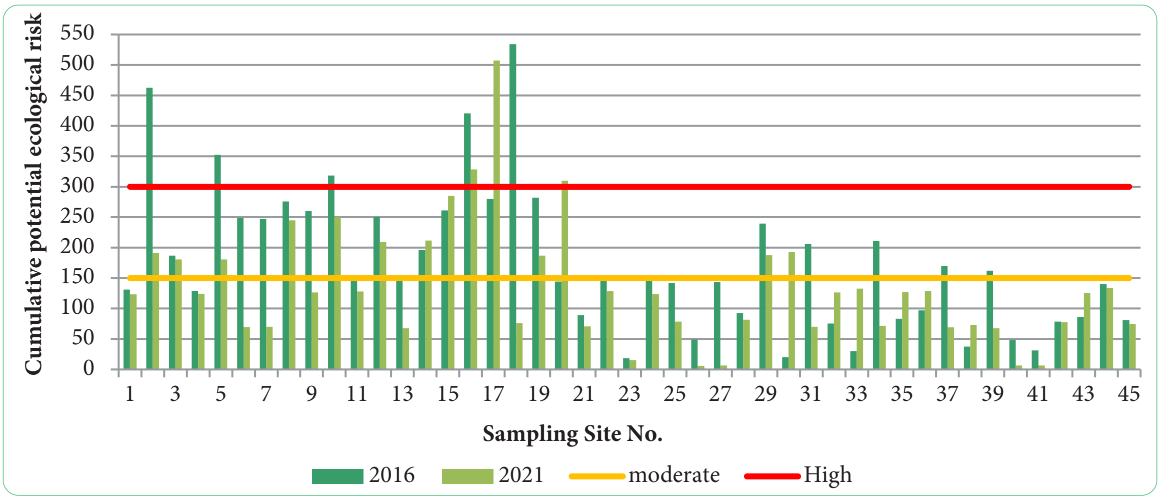

Figure 14. Cumulative potential ecological risk of heavy metal contamination in soils
Source: compiled by the authors

The most critical situations in 2016 were observed at sites 2, 5, 10, 16, and 18, whereas in 2021 the highest risk was recorded at sites 16 and 17. None of the samples exhibited an extremely high level of risk; however, in 2016, sites 2, 5, 10, 16, and 18 showed values exceeding 300, indicating a significant cumulative heavy metal load and a high potential ecological risk. In 2021, the number of such sites decreased (Fig. 13).

The study summarised and statistically processed the results of soil quality monitoring in Cherkasy for Pb, Zn, Cu, Ni, Mn, and Cd using both single-factor and multi-factor soil quality indices. Variations in heavy metal concentrations in the soil primarily depend on the parent material and geological background, but human economic activity also has a significant influence (Yang *et al.*, 2018). The study demonstrated notable spatial differences in the concentrations of the metals analysed. It was found that Mn had the highest content, while Cd had the lowest. The average concentrations decreased in the order Mn > Zn > Pb > Cu > Ni > Cd. High Mn concentrations in the city's soils are attributed to its geological background, as confirmed by pollution indices remaining below 1 across almost all sampling sites. Statistical analysis of the Cherkasy urban soil monitoring data revealed significant spatial and temporal variability in the concentrations of all heavy metals (Table 5), indicating localized enrichment patterns and heterogeneity. The uneven distribution of heavy metals is likely influenced by differences in soil texture (sandy vs. clayey) and industrial emissions, which create artificial and often uneven element concentrations. The coefficient of variation (CV) for Mn, Zn, Pb, Cu, and Cd across different sampling sites in 2016 indicated high variability (50% < CV ≤ 100%), suggesting strong spatial heterogeneity. In 2021, these values significantly exceeded 100% (Pb – 300%, Mn – 130%, Cu – 120%), indicating an even higher degree of spatial variability in heavy metal distribution. This considerable variability in heavy metal concentrations may be associated with localised anthropogenic impacts or similar migration patterns (Rahman *et al.*, 2022; Wu *et al.*, 2025).

Extremely high values of the coefficient of variation for Pb were caused by a very high concentration of this metal at local site 17 (c = 510 mg/kg), against a background of sites with low Pb content. Such elevated lead levels may be attributed to paint fragments, battery residues, and technogenic microparticles. The high degree of variation in Mn and Cu was associated with elevated concentrations of these metals at sites 14-16 (for Mn) and site 17 (for Cu), which may have been caused by local contamination from waste generated by machine-building industries or by changes in the soil's mechanical composition at these sites. In contrast, the coefficient of variation (CV) for Ni across different sampling sites showed moderate variability (21% < CV ≤ 50%), indicating that the sources of Ni may be both natural (geogenic influences) and anthropogenic (emissions from industrial enterprises and vehicles, as well as subsequent atmospheric transport). The strong correlation between Pb and Cu identified in the correlation analysis suggests common pollution sources, likely related to human activities. Potential industrial sources of these metals in the environment include materials used in battery production, electricity generation, and paints (Swain, 2024). In the study area, the shared sources of Pb and Cu contamination in the landscapes are the thermal power plant (TPP), enterprises producing paint and electrical engineering products, and motor transport (exhaust gases, brake pad wear). High correlation values between Ni and Mn also suggest common sources, but these are likely predominantly natural (e.g., weathering of rocks, wind erosion) and partially anthropogenic, considering the moderate coefficient of variation for Ni and the weak correlations of Mn with all other metals. Manganese is typically present in soils at relatively high natural concentrations. Therefore, limited human activity in the study area may not significantly affect its concentration. Consequently, its presence in the investigated soils may not be directly related to anthropogenic activities (Taghavi *et al.*, 2022). Potential anthropogenic sources of Ni and Mn contamination in Cherkasy include mechanical engineering and chemical industries, thermal power generation (combustion of fossil fuels), and motor transport.

The complex interaction between natural and anthropogenic factors that regulate the distribution and accumulation patterns of heavy metals has also been noted in previous studies (Wu *et al.*, 2025). Differentiating natural versus anthropogenic contributions and identifying human-derived inputs of chemical elements into soils was facilitated by the I_{geo}, which is used to assess the intensity of technogenic contamination. The predominantly natural origin of Mn, Ni, and Cu is confirmed by the strongly negative values of this index. More than 93% of the investigated soils were found to be uncontaminated by these elements. I_{geo} values for Pb and Cd indicate a significant impact of anthropogenic pollution, with only some locations showing lightly or moderately contaminated soils where Pb content was low. The obtained I_{geo} values for Zn suggest a mixed natural-anthropogenic origin for the input and accumulation of this metal. Like the I_{geo} values, *PI* showed high variability, ranging from uncontaminated to very heavily contaminated soils, depending on the specific metals analysed. *PI* values above 1 for all metals except Ni and Mn indicate elevated concentrations due to anthropogenic influence. $PI_{Nemerow}$ were higher than the *PLI* values, which can be explained by the calculation algorithm of $PI_{Nemerow}$ as it accounts for both the average and the maximum values of single-metal *PI*.

A detailed analysis of potential ecological risk, which predominates in assessing the extent of heavy metal contamination in soils and the associated ecological consequences for soil ecosystems, shows that Cd posed mainly moderate, considerable, or high ecological risk and was the main contributor to the overall risk. Only in one location was a high ecological risk observed for Pb in 2021, while all other heavy metals posed a negligible ecological risk. Z. Wang *et al.* (2015) presented the results of a study on soil contamination by metals conducted using geochemical indices and multivariate statistical methods, which enabled the identification of possible sources and pathways of pollutants, as well as the assessment of their potential impact on soil quality and human health. The multi-index analysis of soil quality across different urban sites revealed that the most critical situation was observed in the southeastern and eastern industrial zones. In residential-industrial areas, urban soils generally exhibited low to moderate levels of contamination.

Similar findings have been reported in numerous other studies examining the impact of anthropogenic activities on urban ecosystems. For example, Y. Kuang *et al.* (2024) demonstrated that intensive human activity directly affects soil contamination levels-samples from industrial zones exhibited elevated potential ecological risk, posing a threat to public health. Statistical analyses confirmed that intensive industrial operations significantly influence the degree of soil pollution. A principal component analysis of urban soil contamination, presented by B. Ghosh *et al.* (2023), revealed clear patterns of metal covariation, indicating likely sources such as industrial emissions, vehicular traffic, and natural factors. Comparing soil monitoring data from 2016 and 2021 showed certain trends. Most metals exhibited a positive dynamic, with decreasing concentrations: Pb decreased on average by 28%, Cd by 21%, and Zn by 15%. Concentrations of other elements remained largely unchanged, with Cu fluctuating within ±5% and Ni showing a slight decline of 8%. Some elements experienced localised increases, with Mn content rising by 12%.

The spatiotemporal and multi-index geochemical assessment of urban soils in Cherkasy provides critical insights into the dynamics of technogenic pressure and associated ecological hazards. Contextualising these findings within both national baselines and international literature allows for a comprehensive understanding of anthropogenic intervention and environmental risk patterns. The high spatial heterogeneity observed for manganese (Mn), zinc (Zn), lead (Pb), copper (Cu), and cadmium (Cd), indicated by coefficients of variation (CV) ranging from 51% to 100%, confirms that these elements are strongly influenced by localised point sources rather than uniform natural distribution. This high variability in urban zones aligns with the global observations compiled by Q. Yang *et al.* (2018), who noted that industrialisation and intense agricultural practices create highly fragmented soil pollution profiles across diverse geographical regions. In Cherkasy, the concentration of the highest pollution levels within the southeastern and eastern industrial hubs reflects patterns identified by Y. Zhou *et al.* (2022), who demonstrated that areas surrounding long-standing industrial complexes with extensive production histories act as primary sinks for heavy metal accumulation. Conversely, the moderate variation of nickel (Ni), with a coefficient of variation between 21% and 50%, suggests a more balanced interplay between geogenic baselines and diffuse anthropogenic inputs, matching the urban soil characteristics documented by Y. Kuang *et al.* (2024), where intermediate variability typically signified a dual natural-anthropogenic origin. Geochemical Relationships and Source Apportionment Statistical correlation analysis revealed a robust relationship between lead

(Pb) and copper (Cu), pointing toward a shared suite of anthropogenic vectors. In urban environments, this geochemical pairing is frequently driven by the combustion of fossil fuels, vehicular emissions, and discharges from paint and electrical manufacturing. This signature corresponds closely with the long-term urban soil dynamics described by S.G. Papadimou *et al.* (2023), where vehicular traffic and municipal infrastructure served as persistent sources of concurrent Pb and Cu accumulation over extended monitoring periods. In contrast, the strong correlation between nickel (Ni) and manganese (Mn) highlights a mixed geogenic-anthropogenic pathway. While natural soil erosion contributes significantly to the baseline presence of these metals, their concentrations are augmented by machinery manufacturing, chemical processing, and thermal power generation. This dual-origin behaviour is well-documented in the methodological frameworks reviewed by J.B. Kowalska *et al.* (2018), which emphasise that moderate-to-strong correlations among elements like Ni and Mn often reflect underlying lithogenic properties that are partially masked by widespread, low-intensity industrial fallout. Ecological Risk Assessment and Methodological Efficacy The identification of cadmium (Cd) as the primary contributor to potential ecological risk within Cherkasy is a critical outcome of the multi-index approach. Under the foundational framework established by L. Hakanson & S. Charlesworth (1980), elements are evaluated not merely by absolute concentration, but by their biological toxicity weighting factors. Because Cd possesses an exceptionally high toxic-response coefficient, even minor elevations above the natural Ukrainian regional baselines established by A.I. Fateiev & Ya.V. Pashchenko (2003) trigger severe risk classifications. The utilisation of both single-factor indices I_{geo}, contamination, *PI*, *Er* and composite indices *PLI*, $PI_{Nemerow}$, and RI proved essential for preventing the underestimation of localised threats. As discussed by Ferreira *et al.* (2022), single-factor indices can occasionally overemphasise isolated anomalies, whereas composite models provide a holistic overview of the total pollution burden. In Cherkasy, while $PI_{Nemerow}$ and potential *RI* accurately highlighted the severity of the industrial hubs. This gradient confirms that urban zoning and proximity to heavy infrastructure remain the definitive factors shaping the urban soil profile, mirroring the urban soil indicators evaluated by T.F. Iakovyshyna (2022) across other Ukrainian ecosystems and reinforcing the need for targeted, zone-specific risk management strategies.

Conclusions

The study revealed significant spatial and temporal transformations of urban soils due to the long-term accumulation of heavy metals, resulting in an altered geochemical soil province associated with anthropogenic sources. Spatial analysis of zones with high and low metal concentrations demonstrated clear heterogeneity influenced by both natural and anthropogenic factors. Using various geochemical indices and statistical-correlation analysis, patterns of grouping and associations between the analysed metals were identified, providing insight into potential pollution sources and their interrelationships. The study demonstrated that, based on the average heavy metal content in the city, the following geochemical sequence of urban soil contamination was formed: Mn > Zn > Pb > Cu > Ni > Cd, reflecting a natural-technogenic element association. Most metals showed a decreasing trend in concentrations over the period 2016-2021. For Pb, an average decrease of 28% was observed, with the most pronounced reduction in residential areas. Cadmium concentrations decreased by 21%, and zinc by 15%, while concentrations of other elements remained relatively stable. Strong correlations ($r > 0.7$) were observed between Pb and Cu, as well as between Ni and Mn, indicating similar sources of these elements in urban soils. The applied geochemical indices provided information on the contamination levels of each analysed heavy metal, allowed assessment of the overall scale of pollution and potential ecological risk, enabled identification of probable heavy metal sources, highlighted sites with the highest potential accumulation risk, and characterised the capacity of the surface soil horizon to accumulate heavy metals. The conducted study of urban soils in Cherkasy indicated the formation of localised areas of moderate and high ecological load, posing long-term risks to the ecosystem and human health. A significant potential ecological risk associated with cadmium contamination was identified. Over the period 2016-2021, the proportion of moderately contaminated soils increased 1.4-fold, reaching 31% of the analysed samples, while heavily contaminated soils increased 1.1-fold to 27%. The proportion of uncontaminated soils decreased 1.2-fold. Regarding integrated ecological risk, the proportion of soils with high and moderate contamination decreased 1.6- and 1.5-fold, respectively, while the proportion of soils with low contamination increased 1.3-fold. None of the samples exhibited an extremely high risk level; however, in 2016, sites 2, 5, 10, 16, and 18 exceeded a value of 300, indicating a significant cumulative heavy metal load and a high potential ecological risk. The next stages of the research include assessing the impact of heavy metals on human health; developing cartographic models of the geoecological state of urban soils and identifying areas of significant transformation of urban soils using modern GIS technologies; and addressing the problem of high pollutant concentrations to support sustainable urban development.

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Conflict of Interest

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Анотація. Забруднення ґрунтів важкими металами стає дедалі серйознішою проблемою в усьому світі. З цих причин комплексна кількісна оцінка якісного стану урбоземів, які знаходяться під техногенним навантаженням, є важливою для розуміння закономірностей забруднення та потенційних екологічних ризиків. Метою проведення дослідження був просторово-часовий аналіз вмісту і оцінка впливу важких металів на стан урбоземів м. Черкаси, ідентифікація джерел забруднення для прийняття обґрунтованих управлінських рішень. Оцінювання ризиків проводили за допомогою багатоіндексного геохімічного аналізу з використанням однофакторних (індекс геоакумуляції I_{geo}, індекс забруднення *PI*, індекс екологічного ризику *Er*) і комплексних індексів (індекс забруднення *PLI*, індекс забруднення Немерова та потенційний екологічний ризик *RI*). Для виявлення імовірних джерел забруднення використовували статистично-кореляційний аналіз. Проведений аналіз продемонстрував значні просторові відмінності в концентраціях досліджених металів. Коефіцієнт варіації для Mn, Zn, Pb, Cu та Cd мав високу (51 % < CV ≤ 100 %) мінливість на різних ділянках, що свідчить про сильну просторову гетерогенність. Натомість значення коефіцієнтів варіації Ni були помірними (21 % < CV ≤ 50), що вказує на його природно-антропогенне походження у ґрунті. Сильний зв'язок для Pb і Cu, виявлений за допомогою кореляційного аналізу, свідчить про спільні джерела забруднення, ймовірно, теплоелектроцентраль, підприємства з виробництва лакофарбової та електротехнічної продукції, автотранспорт. Високі значення коефіцієнта кореляції між Ni і Mn вказують на змішаний вплив геогенних (ерозія ґрунтів) і антропогенних джерел (підприємства машинобудівної та хімічної промисловості, теплоелектроцентраль та автотранспорт). Значний потенційний екологічний ризик для ґрунтових екосистем у разі забруднення ґрунтів на дослідженій території виявлений для Cd. Багатоіндексний підхід до оцінки впливу забруднення важкими металами досліджених ґрунтів на різних локаціях міста показав, що найбільш небезпечна ситуація склалася в південно-східному і східному промислових вузлах. В селітебно-промислових районах урбоземи мали переважно незначний та помірний рівень забруднення. Основним потенційно екологічно небезпечним важким металом виявився Cd. Результати цього дослідження можуть бути основою для розробки та впровадження цілеспрямованих методів управління ризиками

Ключові слова: важкі метали; міські ґрунти; кореляційні залежності; просторова мінливість; екологічний ризик; антропогенний вплив