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ASSESSING THE DEPOSITION OF HEAVY METALS IN EDAPHOTOPES AND SYNANTROPHY VEGETATION UNDER THE CONDITIONS OF TECHNOLOGICAL POLLUTION OF THE CITY

Oksana Yehorova
Corresponding author
PhD, Associate Professor*
E-mail: ok.yehorova@chdtu.edu.ua

Liudmyla Zhytska
PhD, Associate Professor*

Volodymyr Bakharev
Doctor of Technical Sciences, Professor, Director
Institute of Education and Science in Mechanical Engineering, Transport and Natural Sciences
Kremenchuk Mykhailo Ostrohradskyi National University
Universytetska str., 20, Kremenchuk, Ukraine, 39600

Olga Mislyuk
PhD, Associate Professor*

Elena Khomenko
PhD, Associate Professor*

*Department of Ecology
Cherkasy State Technological University
Shevchenko blvd., 460, Cherkasy, Ukraine, 18006

The object of this study is a regional center with a developed industry and a significant traffic load. The study provides an assessment of the impact of the urbanization process on the conditions of development of urban edaphotopes and their role in the functioning of urban ecosystems. It was determined that the geochemistry of the soils of urban ecosystems is significantly different from natural landscapes, which is due to the symbiosis of natural and anthropogenic factors. The content of mobile forms of heavy metals in the soil of 14 localities of different functional zones within the city was investigated. A comparative assessment of the spatial heterogeneity of the content of heavy metals in the vegetative organs (root, shoot) of the diagnostic species Polygonum aviculare L. was performed. Based on the sources of emission of heavy metals and the formed geochemical anomalies, a direct dependence was established on their accumulation by the vegetative organs of Polygonum aviculare L. According to the calculated biological absorption coefficient (BAC), high bioavailability for the accumulation of man-made toxicants Cu, Zn, Pb, Cd by the phytomass of Polygonum aviculare L. was proven. It was determined that the content of heavy metals in different parts of the test object is due to their physiological ability to accumulate these toxicants in the root and above ground mass. Active translocation of toxicants from the soil to the roots is characteristic of localities with intense influence of man-made factors, for which the value of the bioavailability coefficient varies within 0.6>BAC<0.85. Correlation coefficients between the content of heavy metals in the atmosphere, soil, and vegetative organs of the plant were determined. The research allows us to evaluate the prospects for using Polygonum aviculare L. as a cumulative indicator of metal pollution in urban technogenic ecosystems and their high phytoremediation value under conditions of environmental pollution with heavy metals

Keywords: heavy metals, deposition, Polygonum aviculare L., urban edaphotopes, synanthropic plants, phyto indication

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1. Introduction

Intensive industrialization of cities and development of motor transport infrastructure lead to environmental pollution with various chemical substances. The soil cover of the city occupies a special place in ensuring the ecological safety of the territory and its condition directly affects all components of the environment since it is within the soil that all biogeochemical processes of various elements of ecosystems are combined. The soil is capable of depositing pollutants that come to its surface with atmospheric precipitation, aerosol emissions, household and industrial waste. A characteristic feature of soil pollution in large cities is the accumulation of a complex multicomponent chemical mixture in it, among which heavy metals take up a significant share.

Modern environmental monitoring includes standard tools for assessing the quality of the environment. However, the use of only physical-chemical research methods, despite their high accuracy, cannot provide a complete picture of the ecological situation. A special place among methods for assessing the state of the environment is occupied by monitoring using plant test systems. Bioindicative methods make it possible to determine the integrated effect of all pollutants present in environmental objects; in addition, they are highly sensitive and sufficient for adequate assessments of the state of the environment. Accordingly, urban vegetation can also act as a depositor of pollution. Therefore, modern environmental monitoring should include not only a chemical analysis of the level of pollution but also an ecological assessment carried out by the methods of biomonitoring, biotesting, and bioindication. This will make it possible to determine the level of ecological danger of the territory and to develop appropriate environmental protection measures for the restoration of contaminated soils, which in turn will minimize the impact of pollution on the environment and restore the ecological balance. Therefore, research aimed at studying the deposition of heavy metals in edaphotopes and vegetation is an urgent issue.

2. Literature review and problem statement

In scientific circles, the development of methodological approaches to assessing the degree of ecological adaptation of plant groups, which play a diverse role in the formation of urban geocenoses, is gaining more and more popularity. Since plants are sensitive phyto indicators of pollution and register the impact of not only static environmental factors but also their rhythm and dynamics, they can act as indicators of the early total effect of air, water, or soil pollution.

Study [1] is aimed at determining the distribution of heavy metal ions (Cd, Cr, Cu, Ni, Pb, and Zn) in the soil and grass cover of the roadside zone of highways. It was determined that the distance to the road affects the content of heavy metals in the surface layer of the soil. As the distance to the highway increases, the concentration of heavy metal ions decreases both in the soil and in the investigated plant samples. However, when describing the general trend of changes in the level of pollution, the authors did not conduct a study of soil properties, the state of vegetation, and did not take into account local meteorological and topographical conditions.

Paper [2] provides an assessment of the phytoremediation potential of perennial herbaceous plants, in particular *Calamagrostis epigejos*, in relation to heavy metal ions from various anthropogenically degraded areas. *Calamagrostis epigejos* grasses have been found to exhibit high potential for phytostabilization of metals by absorbing a significant portion of the available fraction of heavy metals in the soil and storing it in their root system. However, the authors did not study the above-ground vegetative organ of plants (stems, leaves, or buds) and did not take into account the dynamics of polluting components in atmospheric air.

Paper [3] reports results of the study into the phytoabsorption capacity of roadside plant species in relation to solid particles and heavy metals. A significant positive correlation was established between the content of heavy metals in the leaf and the amount of dust on the surface of the leaf, which indicates the absorptive capacity of the leaves relative to toxic metals after the deposition of dust particles on the leaf surface. It was found that *Nerium indicum* accumulates a significant amount of Cd, Pb, and Zn ions, which are mainly absorbed from the atmosphere. It was noted that the ability of plant leaves to retain solid particles and heavy metals is determined by the plant species and is related to the features of the microstructure of the leaf. However, it should be noted that the work lacks information about the physical and chemical properties of the soil. However, these properties can influence the absorptive capacity of plants, regulate the availability of elements and their solubility in the soil.

Study [4] was aimed at evaluating the possibilities of using the leaves and bark of the two most common tree species – *Ficus nitida* and *Eucalyptus globulus* in the industrial zone of Minya governorate, Upper Egypt, as bioindicators of atmospheric air pollution. Determination of the content of heavy metal ions was carried out in samples of leaves and bark of trees with subsequent correlation with the content of heavy metals (Pb, Cu, Cd) in the soil and atmosphere. Sampling was carried out in the winter and summer seasons. It was established that the concentrations of heavy metal ions in the leaves and bark of *Ficus nitida* and *Eucalyptus globulus* have the same trend: Pb>Cu>Cd. At the same time, it was noted that the highest concentration of cadmium, lead, and copper ions was found precisely in the leaf plate, and not in the tree bark samples. The authors note that their results can confirm the theory that the source of heavy metal ions is atmospheric dust. The justification of the authors is based on a high statistical correlation between the ratio of the concentration of heavy metal ions in the atmospheric air and in the leaf plate of both types of trees (regardless of the growing season). However, it should be noted that the cited study is limited mostly to plants prevailing in the tropical climate zone, and accordingly cannot be used as bioindicators in temperate climates.

In [5], an assessment of the impact of vehicle emissions on the adaptation potential of roadside trees *Grevillea robusta* and *Mangifera indica* planted along roads in the capital of Uttarakhand, India was carried out. The study was conducted by comparing the properties of trees grown in the control area in relation to roadside areas. The control plot was part of a protected forest where human intervention is controlled, and anthropogenic activity is prohibited. It was found that the intensity of vehicles affects the anatomical, morphological, physiological, and biochemical characteristics of trees, in particular, air pollution affects the functioning of stomata and the thickness of leaves of urban plantations. Emissions from transport affect the process of photosynthesis, transpiration, stomatal conductance, proline content and the concentration of copper ions in plant tissue. Air pollution negatively affects the photosynthetic pigment and, as a result, reduces its productivity. However, when describing the general trend of the impact of pollution levels on tree plantations, the authors did not take into account local meteorological conditions, seasonal studies, as well as the growing season of plants.

The authors of [6] evaluated the influence of traffic flow intensity and the amount of industrial emissions on the concentration of heavy metals (Fe, Mn, Cu, and Ni) in the aerial parts of *Polygonum aviculare L*. To evaluate the bioindicative capacity of *Polygonum aviculare L*., several groups of sites were selected: urban, suburban, rural, industrial, and roadside. A direct dependence of the concentrations of heavy metals on the place of sampling of plant samples was found. The highest concentrations of Fe, Mn, Cu, and Ni were recorded in cities, then a significant load was recorded near roadside areas, the lowest concentrations of metals were recorded in rural areas. The adsorption capacity of *Polygonum aviculare L*. in relation to heavy metals was ranked from the highest to the lowest as follows: Fe>Mn>Cu>Ni. The results of the cited study show that *Polygonum aviculare L*. has a differential ability to accumulate heavy metals and can be used as a bioindicator of pollution and metal contamination in anthropogenic ecosystems. However, it should be noted that the study is limited to the analysis of the aerial parts of *Polygonum aviculare L*. for the content of heavy metals (Fe, Mn, Cu, and Ni). In addition, the selection of plant material was carried out in different periods of time (for part of the experimental plots, sampling was carried out in June, for others – in September and October), which can significantly affect the results obtained.

In [7], the bioindicative abilities of the herbaceous plant *Polygonum arenastrum Bor* were investigated for F, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Zn. 90 localities near six industrial enterprises, which are the biggest polluters of the city's environment, were selected for assessment. To compare the absorption capacity of plants, the studied samples were selected at different distances from the emission sources, in particular at a distance of 0.75, 1.5, 3, and 4.5 km from each of the pollutants. The results of the study of the concentration of Cr, Cu, Fe, Pb, and Zn in the shoots and roots of the plant showed a positive correlation with the concentrations of these metals in the soil. The authors concluded that *Polygonum arenastrum Bor* can be used as an indicator of pollution in industrial areas and used as an early warning system for increased environmental toxicity. However, in addition to industry, the level of pollution of the urban environment is also significantly influenced by motor vehicles, the emissions of which also contain heavy metals, which was not taken into account by the researchers. In addition, the arrival of heavy metals is limited only to the study of soil cover and plant material and does not take into account indicators of atmospheric air quality. Accordingly, it is not possible to clearly establish the routes of entry of heavy metals into the plant (a part could have been absorbed by the leaf plate from atmospheric air).

In [8], the bioaccumulation capacity of the invasive species *Solidago gigantea* in relation to toxic metals (Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) was investigated. 30 sites with varying degrees of anthropogenic influence were selected for the study. The content of heavy metals was determined both in soil cover and in plant material (leaves, stems, and roots). The results showed that the distribution of the species *Solidago gigantea* was observed to a greater extent in heavily polluted areas. High bioaccumulation factor but low translocation factor values for Cd, Cu, Cr, Fe, Ni indicate that *Solidago gigantea* absorbs heavy metals from soil. The authors note that the obtained results confirm the possibility of using the invasive species *Solidago gigantea* as a bio monitor of metal pollution, in particular Cd, Cu, Cr, and Zn. However, it should be noted that the authors did not conduct a study of the physical and chemical properties of the soil, which directly affects the absorptive capacity of plants.

It should be noted that most studies are focused exclusively on the study of adsorption and permeability of heavy metals in above-ground vegetative organs of plants (stems or leaves). However, they do not take into account the properties of the soil of the studied areas, the intensity of man-made load, as well as the seasonality and meteorological conditions of the studied areas. Therefore, the integral assessment of the deposition of heavy metals in the edaphotopes and vegetation of an industrially developed city is an urgent issue that needs to be studied.

3. The aim and objectives of the study

The purpose of our work was to determine the features of the deposition of heavy metals in edaphotopes and spontaneous vegetation in the city of Cherkasy. This will make it possible to assess the impact of techno genesis on the state of the urban ecosystem and the possibilities of phytoindicative use of the plant *Polygonum aviculare L*. in ecological monitoring of the anthropogenic transformation of the city's ecotopes.

To achieve the goal, it is necessary to solve the following tasks:

– to analyze air-anthropogenic sources of pollution of urban landscapes in the city of Cherkasy with heavy metals;

– to assess the impact of meteorological conditions on urban ecosystem pollution;

– to evaluate the physical and chemical properties of the city's edaphotopes;

– to determine the level of heavy metal contamination of the ground cover of the territory in the city of Cherkasy;

– to determine the content of heavy metals in samples of plant material of the species *Polygonum aviculare L*. and to establish correlations of translocation.

4. The study materials and methods

The object of our research was the ecosystem components of the industrially developed city of Cherkasy – atmospheric air, soil, and vegetative organs (roots and shoots) of the herbaceous plant *Polygonum aviculare L*. – a typical representative of ruderal and segetal vegetation.

According to ecotopic features and the extent of man-made load, the study area includes several localities (industrial, transport, recreational zones). The background area (recreational area) – Naberezhna Street (Dakhnivskyi microdistrict) (Fig. 1).

The following methods were used for research: field, physical-chemical, atomic-adsorption, and statistical.

Sampling of soil and plant material and their subsequent research was carried out in accordance with current regulations. Soil samples were taken from experimental plots in accordance with methodological recommendations and current standards: DSTU 4287:2004, DSTU ISO 10381-5:2009, DSTU ISO 10381-4:2005, DSTU GOST 17.4.4.02:2019; DSTU 7670:2014 was used for plants.

The basic physical and chemical properties were determined for the studied soil samples. The content of mobile potassium compounds was determined by the Chirykov modification method in accordance with DSTU 4115:2002. The content of total humus was determined by the Tyurin method in the CINAO modification according to DSTU 4289:2003. The content of exchangeable calcium and magnesium – according to DSTU 7861:2015 in the modification of the Sokolovsky NNC IGA, pH-water indicator – according to DSTU 8346:2015.

The selected samples were analyzed for the content of mobile forms of heavy metals by the method of atomic absorption spectrophotometry on an atomic spectrometer (SM-115M1-PK). The content of mobile forms of VM in the soil was determined according to DSTU 4770.2:2007, DSTU 4770.3:2007, DSTU 4770.6:2007, DSTU 4770.9:2007, in plant samples in accordance with methodological recommendations with preliminary mineralization of plant material by the method of dry ashing [9].

The extent of man-made load on the soil cover and the possibility of migratory transition to plants were determined by calculating the main geochemical and ecological indicators, in particular the concentration coefficient (K_c). This indicator characterizes the degree of accumulation of heavy metals in the components of the urban system relative to the background sample and is an indicator of the activity of radial migration of the element:

$$K_{C_i} = \frac{C_i}{C_f}, \quad (1)$$

where C_i is the concentration of the *i*-th element in the components of the urban system under study,

C_f – background content [10].

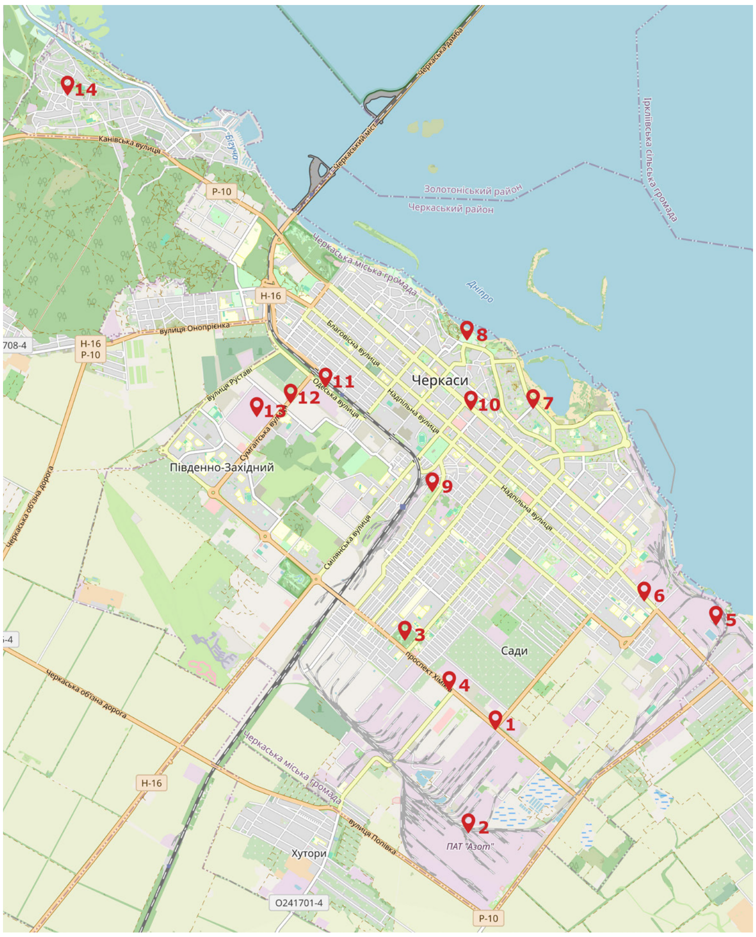

Fig. 1. Location map of expeprimental plots

Since anthropogenic soil pollution is multicomponent, the concentration coefficient (K_c) is not informative enough; therefore, additional information is needed on the toxic effect of individual metals and their multi-element combinations on plants. Therefore, the sanitary and hygienic assessment of the state of the soil was carried out according to the total pollution index – (Z_c), which is the cumulative sum of the content of elements above their background levels and characterizes the effect of the association of metals [10]:

$$Z_{C_j} = \sum_{i=1}^{n} K_{C_i} - (n-1). \quad (2)$$

The pollution load index (*PLI* – pollution load index), which shows how many times the concentration of heavy metals in the soil exceeds the background level, was calculated using the following formula [10]:

$$PLI = \sqrt[n]{K_{C_1} \cdot K_{C_2} \cdot \ldots K_{C_i}}, \quad (3)$$

where K_c is the ratio of the metal content in the sample to the background content;

n is the number of metals.

A value of $PLI>1$ indicates that the surface sediments are polluted, $PLI<1$ indicates the absence of pollution [11].

To determine the availability of mobile forms of metals in the soil for the plant of the test object and the ability of its vegetative organs (root, shoot) to accumulate, the biological absorption coefficient (*BAC*) was determined. This is an indicator that determines the extent of use of a certain element, and also makes it possible to evaluate the entire system of translocation transition: soil – heavy metals – (roots, shoot) of an annual plant, the calculation was performed according to the formula:

$$BAC = \frac{C_s}{C_p}, \quad (4)$$

where C_p is the concentration of the pollutant in the phytomass of the plant, mg/kg;

C_s is the concentration of the pollutant in the soil, mg/kg [12].

To calculate correlation indicators, the Pearson correlation coefficient calculation technique was used, which makes it possible to establish the depth of connection between the analyzed arrays for a small number of observations according to the formula:

$$r_{xy} = \frac{\sum d_x \cdot d_y}{\sqrt{\sum d_x^2 \cdot \sum d_y^2}}, \quad (5)$$

where x and y are correlated indicators;

d_x and d_y are deviations of each of the numbers of these indicators from the average.

Since each indicator in most cases actually depends on a whole series of other indicators (the so-called multiple correlation), in practice the relationship between two of the remaining ones was studied taking into account the partial coefficient (partial correlation) according to the formula:

$$r_{ab} = \frac{r_{ab} - r_{ac} \cdot r_{bc}}{\sqrt{\left(1 - r_{ac}^2\right) \cdot \left(1 - r_{bc}^2\right)}}, \quad (6)$$

where a, b, c are the numerical expressions of correlated indicators.

5. Results of research into the content of heavy metals in the urban ecosystem of the city

5. 1. Results of investigating air-technogenic pollution of urban landscapes of the city of Cherkasy by heavy metals

In the set of anthropogenic factors contributing to the influx of heavy metals into urban landscapes, air-technogenic pollution occupies a special place in terms of its significance and degree of impact on the environment. As a result of techno genesis, geochemical anomalies of heavy metals in urbosems are formed, their self-cleaning ability, physicochemical conditions of pollutant migration, etc., change.

According to data from the Department of Ecology and Natural Resources of the Cherkasy Regional State Administration regarding the concentration of pollutants and air quality, the city of Cherkasy is one of the most polluted cities of this oblast. This is evidenced by the results of a study of the air pollution index, which ranges from 5.21 to 7.36 (Fig. 2).

The Cherkasy industrial agglomeration is represented by several enterprises, which are the main polluters of atmospheric air. In particular, the largest share is contributed by PrAT "Azot" with a gross emission of 3.8 thousand tons, PraT "Cherkaske Khimvolokno" VP "Cherkaska TPP") – 13.9 thousand tons, and TOV "Cherkasky zavod avtohimiya". In addition, enterprises such as "Cherkasky Plywood Combine" TOV, "Cherkasky Paintwork Plant" TOV, and "Cherkassky Plant of Reinforced Concrete Products" TOV exert an additional influence.

Emissions from motor vehicles are also added to the emissions of enterprises, which, together with production equipment, make up about 56 % of the gross receipts of pollutants. The emissions of all these sources contain a significant volume of heavy metals that have mutagenic and carcinogenic properties. Heavy metals are able to be transported into environmental objects with soil and rainwater and be carried by wind over long distances together with dust from contaminated soil.

According to the Main Department of Statistics in the Cherkasy Region, the gross emissions of heavy metals have slightly decreased but they are recorded only from stationary sources (Fig. 3).

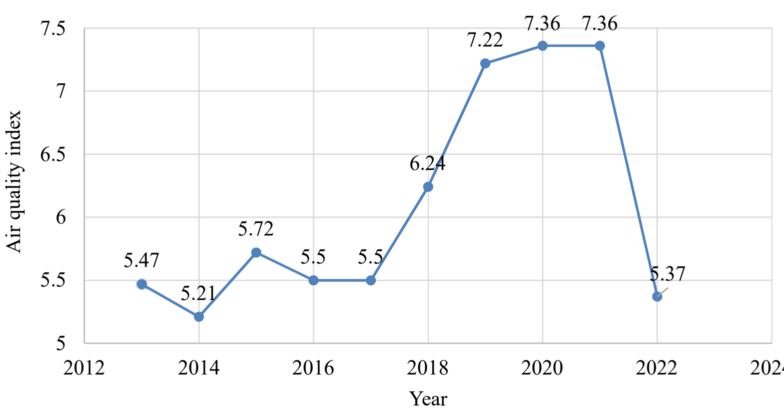

Fig. 2. Dynamics of changes in the air pollution index in the city of Cherkasy

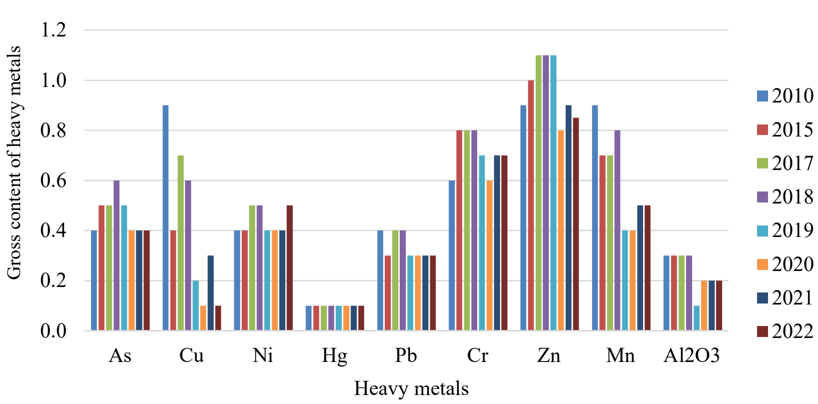

Fig. 3. Dynamics of gross emissions of heavy metals into the atmosphere from stationary sources, t

The data in Fig. 3 testify to the entry into urban landscapes of a number of toxic pollutants of various hazard classes. In particular, such as mercury, with a gross emission of 0.1 t, arsenic – 0.4–0.6 t, chromium – 0.6–0.8 t, nickel – 0.4–0.5 t., lead – 0.3–0.4 t, etc., which belong to the first class of danger. Also, iron, zinc, copper, and aluminum, which belong to the second and third class of danger. At the same time, cadmium, which has the greatest permeability and is contained in the exhaust gases of motor vehicles, is not registered.

5. 2. Results of investigating the influence of meteorological conditions on pollution in the urban ecosystem

An important role in the formation of the ecological situation in the city of Cherkasy is also played by natural factors, in particular, the meteorological features of the territory. The transfer and dispersion of impurities is carried out according to the laws of turbulent diffusion, and its intensity depends on many factors, such as the wind regime (direction and speed), temperature regime, amount of precipitation, etc. However, it is worth noting that the influence of each of these factors during the year is not the same. If atmospheric processes change rapidly, self-cleaning of the surface layers of the atmosphere accelerates. With the low-active development of atmospheric processes and stagnant phenomena in the atmosphere, conditions are created for the accumulation of harmful substances.

Throughout the year, winds from the north-west, south-west and north-east directions prevail in the city of Cherkasy (Fig. 4). The significant recurrence of north-west and north-east winds is associated with the activity of cyclones, which are one of the main forms of atmospheric circulation in the cold season. In the warm period of the year, especially in summer and autumn, the predominant form of atmospheric circulation is westerly.

At the same time, it is necessary to take into account not only the direction but also the speed of the wind since the highest concentration of impurities in cities is observed mainly in the surface layer with weak winds, with a wind speed of 0–1 m/s. According to data from the Cherkasy Regional Center for Hydrometeorology, Cherkasy is characterized by weak winds (up to 5 m/s) (Fig. 5).

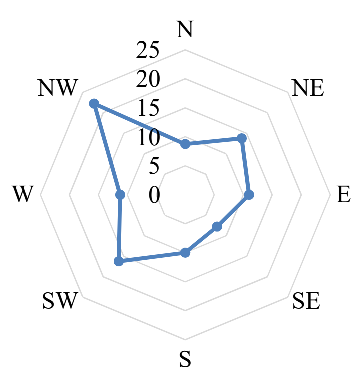

Fig. 4. Scheme of the average annual wind rose in the city of Cherkasy (numerical values indicate the percentage of recurrence of winds in the specified directions)

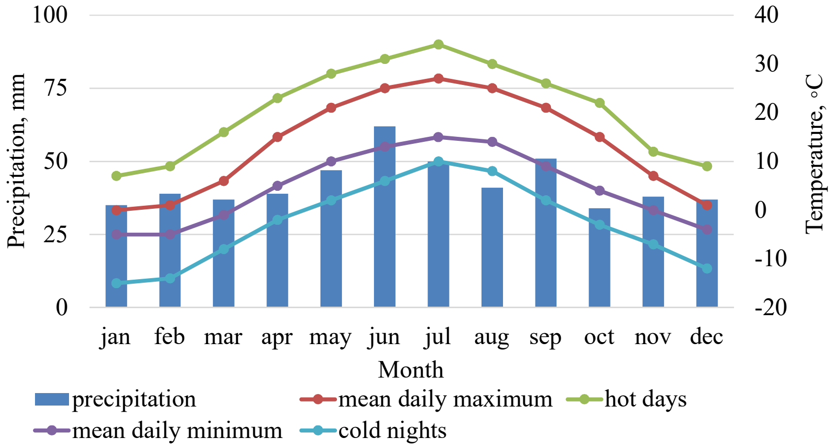

Fig. 5. Average temperatures and precipitations in Cherkasy [13]

The summer months (from June to September) are characterized by the lowest speeds – the wind speed does not exceed 3–4 m/s, in winter we observe a tendency to increase this indicator, the average wind speed reaches 4.5–4.8 m/s. The repeatability of wind speeds up to 1 m/s and 2–5 m/s, on average, is 30 % of the total number of cases, and in summer – up to 40 %.

A great danger is the so-called "stagnation" of air (calm weather), which is characterized by a weak wind speed of 0–1 m/s. In this case, harmful substances cannot rise to the upper layers of the atmosphere and accumulate near the emission source. For the city of Cherkasy, such conditions make up 20 % of the total number of days, in summer – 1.5–2 times more.

With the daily distribution, the maximum wind speed occurs in the afternoon, which is associated with the development of thermal convection and the strengthening of atmospheric turbulence. In the winter months, the average wind speed in the afternoon is 4.2–5.1 m/s, and in the warm period – 3.4–3.8 m/s. The minimum wind speed is observed at night.

The accumulation of impurities in the atmosphere is also observed in the presence of inversions and fogs. According to the weather station in the Cherkasy region, on average, there are 35 to 70 foggy days per year, mainly in the autumn-winter period.

Precipitation is a meteorological indicator that contributes to the purification of atmospheric air from pollutants. In the multi-year regime, the recurrence of precipitation during the year in the city of Cherkasy (Fig. 5) is distributed almost evenly with a slight increase in June and a decrease in February.

5. 3. Results of investigating the physical and chemical properties of the city's edaphotopes

The soil cover of the city is formed for a long time, and therefore urban soils inherit both certain characteristics of zonal soils and reflect the intensity and nature of the industrial development of the city. Therefore, when studying soils, it was taken into account that the soil-forming process in cities takes place under the influence of combined natural and man-made factors. The results of investigating the physical and chemical properties of urban soils are given in Table 1.

The wide range of presented values is probably due to different economic uses of urban areas and different degrees of contamination of the sampling sites.

According to the obtained data, the pH of the upper soil layer (0–20 cm) varies in the range from 6.25 to 8.00. The soils of the industrial zone and the roadside transport zone are characterized by a slightly alkaline and alkaline reaction of the environment (7.35–8.00), and in the recreational zone the pH value is in the range of 6.75–6.85.

The humus content has a small range of values: from 0.56 to 3.01 %, which is explained by the light mechanical composition of these soils (with a predominance of coarse and medium sand). This humus content is classified as low.

Soils are characterized by heterogeneity in terms of potassium content, but they are mostly sufficiently supplied with this important element of plant nutrition.

Table 1

Physical-chemical properties of urban soils in the city of Cherkasy

Site No.	Subzone	pH	Humus content, %	Mg^{2+} exchangeable, mg-equiv per 100 g of soil	Ca^{2+} exchangeable, mg-equiv per 100 g of soil	K^+ soluble, mg-equiv per 100 g of soil
1	Industrial	7.50	2.30	4.50	9.02	1.108
2		7.65	2.00	2.80	6.40	0.475
11		7.40	1.53	1.80	6.80	0.489
12		7.75	0.82	1.40	6.60	0.622
4	Roadside	7.35	0.86	4.90	5.28	0.218
6		8.00	0.86	6.90	7.70	0.391
8		7.55	0.84	0.10	9.90	0.331
10		7.80	0.56	3.80	6.16	0.290
13		7.80	1.32	3.80	7.20	0.474
5	Recreational	6.85	1.54	2.40	6.60	0.633
3		6.75	2.40	3.00	6.60	0.271
7		6.80	1.27	4.70	5.06	0.674
9		6.70	1.61	2.60	5.94	0.228
14		6.25	3.01	7.20	5.94	0.342

According to the results of the studied soils, the ratio of the concentration of exchangeable calcium and magnesium cations is not optimal. It is believed that the exchangeable soil-absorbing complex of an ideal soil should contain 65 % Ca and 10 % Mg. Probably, the violation of the optimal ratio of exchangeable calcium and magnesium is due to the leaching of these ions from the soil-absorbing complex in the processes of neutralization of hydrogen ions in the soil solution. Also, this may be due to the use in winter of an anti-icing mixture, which includes magnesium chloride and sodium chloride. Mg^{2+} ions are important for plant growth and development, as well as Ca^{2+} ions. At the same time, a high concentration of Mg^{2+} can negatively affect the water resistance of soil aggregates, limit the supply of Mn^{2+} for plants, the deficiency of which leads to chlorosis and necrosis of leaves and stems.

5. 4. Results of the study of heavy metal contamination of the ground cover of the territory in the city of Cherkasy

The level of heavy metal content in urban soils is an indirect indicator of the degree of man-made load and potential danger to the health of the population in a specific area. The research results revealed the presence of heavy metals in all research areas (Table 2).

Compared to the background territory, the city's soils were characterized by increased concentrations of heavy metals. The concentration of mobile forms of Cu varied in the range from 9 to 50 mg/kg with an average value of 25.1 mg/kg, which is 9.3 times higher than the background content. The range of fluctuations of Zn concentrations in soils varies from 38.8 to 319.0 mg/kg, exceeding the background indicator (6.8 mg/kg) by 5.5–47 times. A similar situation with indicators of Pb concentrations, with a background content of 5.2 mg/kg, we observe its content in the city territory ranging from 11.7 to 94.0 mg/kg, with an excess of 2.1–18 times.

Table 2

Values of concentration coefficients (K_c) and concentrations of mobile forms of heavy metals in urban soils of Cherkasy

No..	Cu		Zn		Pb		Cd		Z_c	*PLI*
	C, mg/kg	K_c	*C*, mg/kg	K_c	*C*, mg/kg	K_c	*C*, mg/kg	K_c		
1	31.2±0.7	11.5	221.0±1.3	32.5	83.3±0.5	16.0	0.35±0.2	2.1	83.1	10.59
2	20.0±0.4	7.4	311.0±1.3	45.7	38.1±0.4	7.33	0.75±0.1	4.4	61.8	10.22
3	17.8±0.4	6.6	74.0±0.6	9.4	13.3±0.6	2.1	0.32±0.2	1.8	16.9	3.91
4	50.0±0.6	18.5	99.2±0.7	12.7	18.5±0.4	3.0	0.40±0.2	2.3	33.5	6.35
5	20.0±0.4	7.4	38.8 ±0.4	4.9	11.7±0.2	1.8	0.25±0.1	1.4	12.5	3.09
6	25.0±0.7	9.3	244.0±0.6	35.9	32.0±0.4	6.15	0.50±0.2	2.9	51.3	8.78
7	18.6±0.4	6.9	46.5±0.4	6.8	12.5±0.2	2.4	0.20±0.1	1.1	14.2	3.34
8	21.4±0.5	7.9	40.2±0.4	5.1	12.1±0.1	1.9	0.25±0.2	1.5	13.4	3.27
9	25.0±0.4	9.2	44.2±0.3	5.6	14.1±0.5	2.3	0.30±0.2	1.8	15.9	3.82
10	34.0±0.5	12.6	176.0±0.5	25.9	40.0±0.4	7.7	0.25±0.1	1.5	44.7	7.84
11	9.0±0.6	3.3	50.0±0.6	7.4	15.0±0.5	2.9	0.50±0.2	2.9	13.6	3.79
12	11.0±0.6	4.1	51.0±0.6	7.5	20.0±0.4	3.8	0.50±0.2	2.9	15.3	4.29
13	37.0±0.5	13.7	319.0±0.4	46.9	94.0±0.5	18.1	1.25±0.1	7.4	54.1	7.13
14	2.7±0.2	1.0	6.8±0.3	1.0	5.2±0.1	1.0	0.17±0.1	1.0	1.0	1.00

High concentrations of heavy metals in urban soils are the result of their long-term accumulation. The differentiation of pollutants in the environment and the accumulation of heavy metals in the surface layers of urban soils are determined by the specifics of emission sources and their composition.

A comparison of the total indicators Z_c of contamination of the soils of the study sites revealed the following: the maximum value of the indicator is typical for soils near industrial enterprises. So, near the main polluter of the city (plot No. 1) – thermal power station – Z_c=83.1, plot No. 2 – PrAT "Azot" – Z_c=61.8, which puts these soils in the "dangerous" category. A similar situation is observed for the soils of roadside strips (plots #4, 6, 10, and 13), where the indicator Z_c varies within 34–54. The soils of other areas, which are mostly classified as recreational areas, have a moderate level of pollution (Z_{cj}<16).

A very high index of anthropogenic load on the soil (indicator *PLI*=10.59 and *PLI*=10.22, respectively) was established for experimental sites No. 1 and No. 2, which confirms the dominance of heavy metal concentration processes due to aerogenic pollution by emissions of industrial enterprises. In addition, the soils of roadside lanes with high traffic intensity (plots No. 4, 6, 10, and 13) approach the soils of the industrial district of the city in terms of the level of anthropogenic load (6.0≥*PLI*≤8.8). The soils of other areas, most of which belong to the recreational zone, are characterized by a moderate level of anthropogenic load.

5. 5. Results of accumulation of heavy metals in *Polygonum aviculare L.* and determination of translocation correlations

Shoots and roots of common mustard (*Polygonum aviculare L.*) were used as a bioindicator of heavy metal accumulation because the prevalence of the species was previously recorded in all study areas. The results of the content of heavy metals in samples of plant material are given in Table 3.

As with soils, the highest concentrations of heavy metals in samples of plant material of the species *Polygonum aviculare L.* were found in experimental plots located near industrial enterprises and highways. Their content in the roots and shoots of plants varies according to the timing of the experimental site of the edaphotope and indicates the amount of man-made load. The content of heavy metals in different parts of plants is determined by their physiological ability to uneven accumulation of these toxicants in the root and aerial mass. It also depends on the level of supply and chemical form of these elements and their presence in the soil. The resulting variations in bioaccumulative capacity are shown in Fig. 6, 7.

The results of our calculation of the biological absorption coefficient (Fig. 6, 7) showed that the plants from all experimental plots accumulated copper and zinc in the largest amount, lead was in second place in terms of intensity of accumulation, followed by cadmium.

It is worth noting that, in general, biological absorption was observed more intensively in the root system, compared to the aerial part of the plant (Fig. 6, 7).

Table 3

Concentration of heavy metals in samples of plant material of *Polygonum aviculare L.*

Site No.	Content, mg/kg							
	Cu		Zn		Pb		Cd	
	Root	Sprout	Root	Sprout	Root	Sprout	Root	Sprout
1	27.103	5.6976	183.26	25.838	6.428	2.684	0.1834	0.0693
2	14.834	4.9418	136.25	23.994	7.8051	4.8366	0.1558	0.0819
3	13.504	2.5426	49.483	24.604	5.7462	3.2687	0.0934	0.0256
4	18.284	3.9317	51.389	31.356	6.6481	4.7256	0.0846	0.0226
5	8.0451	1.7195	21.336	18.442	5.2814	2.8684	0.0586	0.0258
6	14.601	3.1578	171.28	126.25	7.9382	4.6327	0.0627	0.0228
7	12.616	2.0648	32.241	27.564	6.4211	3.0764	0.0324	0.0289
8	14.721	2.8548	31.544	24.254	6.6115	3.6934	0.1254	0.0868
9	13.407	4.7011	26.335	24.845	6.234	3.9282	0.0844	0.0203
10	14.612	3.6453	128.23	78.612	6.524	3.6855	0.0842	0.0225
11	7.706	2.5347	37.062	23.631	5.404	3.8248	0.0842	0.0269
12	6.1082	2.9153	37.656	29.052	6.944	3.6421	0.0524	0.0257
13	16.275	4.9956	124.24	27.547	7.455	5.2112	0.1275	0.06
14	1.8051	1.2589	4.525	2.311	3.551	2.8236	0.0522	0.0256

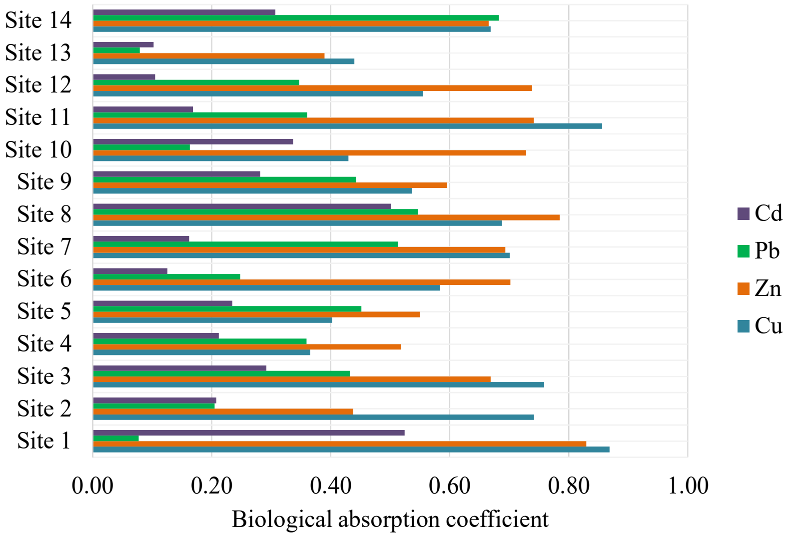

Fig. 6. Value of the biological absorption coefficient (BAC): translocation transition – mobile forms of heavy metals in the soil and roots of *Polygonum aviculare L.* (mg/kg dry weight) from the localities in the city of Cherkasy

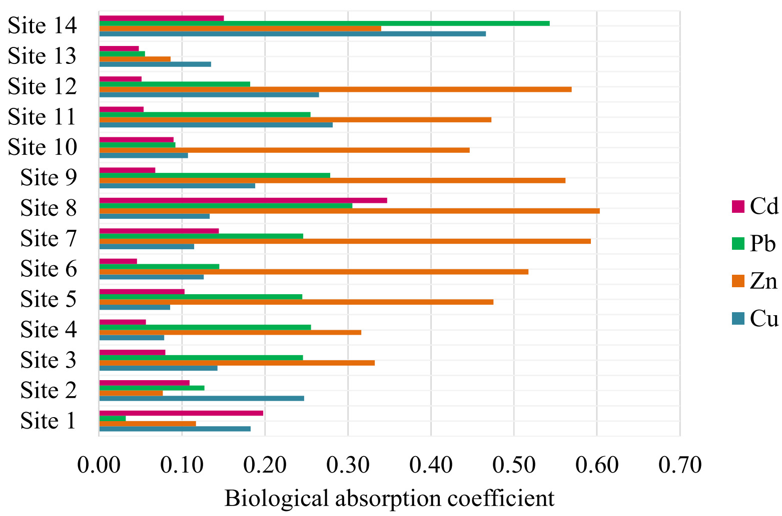

Fig. 7. Value of the biological absorption coefficient (BAC): translocation transition – mobile forms of heavy metals in the soil and shoot of *Polygonum aviculare L.* (mg/kg dry weight) from the localities in the city of Cherkasy

The values of the coefficient of biological absorption for localities with intense influence of man-made factors (sanitary and protective zones of industrial facilities and roadside strips) are in the range of 0.6>BAC<0.85, which indicates an active translocation of trace elements from the soil to the roots.

Regarding the aerial phytomass of *Polygonum aviculare L.*, our results indicate that the shoots accumulate heavy metals 2–3 times less than the roots (Fig. 7). The largest coefficients were established for sanitary protection zones at industrial facilities and roadside strips of experimental sites.

To confirm the probable migration of heavy metals in the research objects, correlation coefficients were calculated to establish the relationship between the phases: "soil-plant" and "atmosphere-plant" (Table 4).

The calculated partial correlation coefficients indicate that the dependence of toxicants entering plants through the soil is the highest, and the entry of heavy metals through plant shoots from the atmosphere is somewhat lower.

Correlation indices for copper and zinc, which are 0.75 and 0.89, respectively, in the system "soil-plant root system" can be characterized as strong, with lead and cadmium – as weaker, but still significant.

Table 4

Partial correlation coefficients

Element	System type		
	"Atmosphere-plant"	"Soil-plant"	
		Root	Sprout
Cu	0.45	0.75	0.63
Zn	0.35	0.89	0.52
Pb	0.32	0.67	0.56
Cd	0.28	0.58	0.36

6. Discussion of the phytoindicative potential of *Polygonum aviculare L.* for assessing the destructive impact of urban techno genesis

Cherkasy is an industrially developed city with a significant level of air pollution (Fig. 2). The main anthropogenic factors in the formation of an unfavorable ecological situation in the city are the high development of the territory, the development of polluting industries, the intensive process of urbanization, as well as natural conditions.

Our analysis of the sources of pollution showed that the main polluter of the urbocenosis with heavy metals, which come in air-technogenic way, is a thermal power plant, the emissions of which contain Cu, Zn, Pb, As, Ni, Cr, Al. In addition, a significant share of inputs to the environment of such elements as Cu, Cr, Ni, Cr, Cd are contributed by VAT "Photoprilad" and VAT "Azot". The reason for the increase in the volume of emissions of heavy metals from stationary sources (Fig. 3) in recent years is the increase in the share of coal and fuel oil in the fuel consumed at the Cherkasy Thermal Power Plant due to the increase in natural gas prices. Motor vehicles are an active polluter of the city's natural landscapes with heavy metals. According to the amount of Pb emissions, it ranks first, Cu – second. It should be noted that there is a tendency to decrease the amount of Pb emitted by vehicles. This fact is explained by the decrease in the share of leaded gasoline used by drivers.

Thus, among the anthropogenic factors of changes in the natural environment and the formation of the ecological situation in Cherkasy, industrial enterprises, power plants, and motor vehicles have the greatest negative impact, the emissions of which contain, in particular, heavy metals.

Analyzing the set of natural processes (Fig. 4, 5), which determine the stability of the natural complex and the ability to self-cleansing and self-recovery, meteorological conditions deserve attention. Analysis of the wind regime (Fig. 4) proves that one of the main polluters of the city's environment is the southeastern industrial hub, the winds of the southern and eastern directions direct the smoke plume to the residential area and form the prevailing conditions of pollution in the city. With moderate and strong stability of the south-west direction of the wind, emissions of harmful substances from VAT "Khimvolokno VP "Cherkaska TPP"" and VAT "Azot" (experimental sites No. 1 and No. 2) are transferred to the localities in the city of Cherkasy. In addition, with persistent stratification and weak winds, a situation of significant air pollution by vehicle emissions may arise in the city. According to our analysis, the meteorological conditions in Cherkasy can be defined as those that do not contribute to the dispersion of impurities from high and low emission sources.

The main indicators of the physical and chemical properties of soils belong to the number of conservative soil properties. However, the impact of urbanization on soils is so intense and long-lasting that changes occur even in the most stable properties, which is confirmed by research conducted for different cities [14, 15].

One of the characteristic directions of the transformation of urban soils under modern conditions is the change in their acidity, which plays an important role in the formation of the ecological state of the soil environment. The actual acidity of soils in experimental areas in the city of Cherkasy ranges from 6.25 to 8.00 with an average value of 7.40 (Table 1). Most of the soils studied have a slightly alkaline or alkaline environment. Soil alkalinization probably occurs due to man-made carbonate inclusions (concrete, cement, and other mixtures that are destroyed by wind or water erosion and enter the environment). Alkalinity can also be caused by the use of sand-salt mixtures in winter when there is ice and emissions from enterprises and vehicles, which fall into the soil with precipitation over time. Alkalinity of soils disrupts the assimilation of nutrients by plants and can lead to the deterioration of the condition of green areas and their failure to fulfill their functions [16]. The lowest pH value was observed in the soils selected in the recreational zone of the studied site No. 14, which is located near a pine forest. This is due to the fact that the decay products of pine needles have an acidic reaction.

The content of humus in the urban soils in the city of Cherkasy (Table 1) has a small range of values: from 0.56 to 3.01 %, which is explained by the light mechanical composition of these soils (with a predominance of coarse and medium sand). This humus content is classified as low.

There are certain regularities in the spatial distribution of the content of organic matter. In the area of the eastern and central parts of the city, especially in the areas of high-rise buildings, the value of this indicator is the lowest. This may be due to the fact that they were created on alluvial sands and in the territories that have been functioning for the longest time under the influence of urban factors (industrial zone and residential zone of multi-story buildings). Physical-chemical indicators (mechanical composition with a predominance of the sand fraction, low humus content, absence of carbonate ions capable of binding heavy metals in insoluble forms) provide grounds for predicting a decrease in the sanitary function of these soils.

An imbalance of nutrients in the soil, as well as an alkaline environment, can have a significant impact on the development of the city's green spaces. It is known from the literature [17–20] that when the concentration of any element in the urban pedosystem changes, the concentration of all other elements necessarily changes, which affects the functional state of the entire urban ecosystem.

The functional zones of the city have slight differences in the level of heavy metals in the soils (Table 2). This is due to the interspersed locations of industrial enterprises, fuel and energy complex and machine-building complexes on the territory of the city. Therefore, it is difficult to separate the impact of industrial emissions from the emissions of energy enterprises, small fuel plants, private furnace heating, motor vehicles due to overlapping areas of their influence. In addition, the presence of the Dnipro River is a factor in the occurrence of local convection movements of air masses that affect the redistribution of pollutants.

At the same time, it is worth noting that the greatest contamination of soils with heavy metals is characteristic of the soils of the industrial zone (Table 2). This is especially clearly demonstrated by the concentration indicators of Zn and Pb. The most ecologically unfavorable situation regarding the content of the studied metals in the soil cover was formed within the southern part of the city. Here is located the sanitary and protective zone of "Cherkasy TPP" and the transport highway (experimental section No. 2 and No. 3) and the sanitary and protective zone of VAT "AZOT" (experimental section No. 1)). Zinc-lead-copper-cadmium geochemical anomalies were formed in this part of the city. Concentrations of heavy metals exceeded background values by 1.5–15.6 times (Table 2).

The significant content of heavy metals in the soil cover of the southern part of the city is associated with the influence of the Cherkasy TPP. This enterprise is the main source of air-technogenic inflow of pollutants. In addition, the increase in the dispersion halo of polluting substances occurs due to the emissions of mobile sources under adverse wind conditions.

In accordance with the interval of the total index of chemical pollution (Z_C=13.4–15.9), the central part of the city is characterized as slightly polluted. According to the content of heavy metals, the concentration exceeds background indicators by 1.2–9.2 times. Accordingly, the formation of a zinc-copper-lead-cadmium geochemical anomaly is followed. There is a tendency to approach the category of medium pollution, which is associated with emissions of industrial facilities in the southern and eastern industrial hubs with unfavorable wind conditions, significant traffic load, and unsatisfactory capacity of transport junctions.

The soil cover of the north-western part of the city has an excess of background indicators of the content of heavy metals by 1.3–7.5 times. On the territory of the model site, zinc-lead-copper-cadmium and zinc-copper-lead-cadmium geochemical anomalies were formed. In accordance with the interval of the total index of chemical pollution (Z_C=13.6; 15.3), this territory can be classified as lightly polluted.

In the industrial zone, the accumulation of these elements is determined by their presence in the chemical composition of emissions from enterprises of various industries. Localization of heavy metal anomalies in urban industrial zones has been noted in many works [21–26].

The ability to accumulate heavy metals by the vegetative organs and root system of *Polygonum aviculare L.* was studied at different localities in the city of Cherkasy, depending on the degree of anthropogenic influence. Just as for soils, the highest concentrations of heavy metals in samples of plant material of the species *Polygonum aviculare L.* were found at experimental sites located near industrial enterprises and highways (Table 3). Concentrations of heavy metals are indicated in Table 3 and indicate the processes of their accumulation in plant material during the growing season. Compared to the vegetative organs of *Polygonum aviculare L.*, the root system accumulates heavy metals most actively (Fig. 6, 7).

The indicators of increase in the content of Zn, Cu, Pb, Cd (times) in relation to the stem are Zn – 7.3; Cu – 4.7; Pb – 2.7; Cd – 1.4. The values of the coefficient of biological absorption for localities with intense influence of man-made factors (sanitary and protective zones of industrial facilities and roadside strips) are in the range of 0.6>BAC<0.85, which indicates an active translocation of trace elements from the soil to the roots. The limited mobility of elements between roots and shoots indicates the resistance of *Polygonum aviculare L.* to the negative effects of heavy metals [27].

As a result of the calculations of correlation coefficients (Table 4), indicators were obtained that establish a clear dependence of the accumulation of heavy metals in the "soil-plant" system. Correlation indicators are somewhat lower at the "atmosphere-plant" boundary, but the probability of these pollutants entering through different environments turned out to be quite high. This indicates the prospect of using the studied plants as cumulative indicators of metal pollution of urban technogenic ecosystems and their high phytoremediation value under conditions of environmental pollution with heavy metals.

Thus, our results indicate that *Polygonum aviculare L.* is able to accumulate heavy metals in the tissues of the root system. Accordingly, this indicates the resistance of *Polygonum aviculare L.* to the negative impact of heavy metals. These properties can be used for ecological and geochemical assessment of territory pollution, as well as for phytoremediation of soils contaminated with heavy metals.

In contrast to studies [1–8], which considered only the adsorption and permeability of heavy metals in aboveground vegetative organs of plants, our results make it possible to more accurately assess the combined effect of pollutants from various sources and identify the most dangerous areas of the city. As well as determine the possibilities of phytoindicative use of the plant *Polygonum aviculare L.* in ecological monitoring of the anthropogenic transformation of the ecotopes of the city.

The lack of determination of the dependence of the accumulation of heavy metals on the growing season of the plant may be considered a disadvantage of the study. As well as the absence among the studied areas of localities belonging to the settlement subzone. But this was beyond the scope of our study and may be the topic of subsequent one.

This study has limitations due to the differences in the physical and chemical properties of urban edaphotopes, in particular, acidity and humicity indicators, which affect the migration properties of heavy metals.

Our results from the integrated assessment of the deposition of heavy metals in edaphotopes and synanthropic vegetation can be important for making effective management decisions in the field of environmental protection. An in-depth study of the condition of urban edaphotopes and an assessment of the possible consequences of harmful effects on the city ecosystem and the health of the population is necessary.

7. Conclusions

1. In the set of anthropogenic factors that negatively affect the environment, man-made atmospheric pollution occupies a special place in terms of significance and degree of impact on the environment. Among the anthropogenic factors of changes in the natural environment and the formation of the ecological situation in the city of Cherkasy, industrial enterprises, power plants, and motor vehicles have the greatest negative impact, the emissions of which contain, in particular, heavy metals.

2. Analysis of meteorological conditions reveals that the processes of accumulation of pollutants prevail in the region, rather than their dispersion, which causes air-technogenic pollution of the city's environment.

3. Our analysis of edaphic indicators of soils revealed their heterogeneity. The studied soils have a slightly alkaline and alkaline environment (6.25≥pH≤8.00), a low content of humus (from 0.56 to 3.01 %), and a high content of exchangeable Mg^{2+}. The obtained indicators characterize the soils as anthropogenically and technogenically urbanized.

4. According to the results of analyzed data on the content of heavy metals in the soil cover in the city of Cherkasy, the highest indicators of concentration coefficients, total indicators of chemical pollution were established for the model areas of the southern part of the city. The data indicate the consequences of man-made changes in the chemical composition of soils and allow us to make assumptions about the formation of a changed biogeochemical soil province with a moderately dangerous level of chemical pollution.

5. A comparative assessment of the spatial heterogeneity of the content of heavy metals in the vegetative organs (root, shoot) of *Polygonum aviculare L.* indicates high biological availability in relation to the accumulation of toxicants of technogenic origin in the phytomass of *Polygonum aviculare L.* Analysis of the concentration dependences of the content of heavy metals in the "soil-plant" system of *Polygonum aviculare L.* confirms the possibility of using plants as a bioindicator of environmental pollution with heavy metals. The revealed regularities could be used in forecasting the processes of accumulation of heavy metals in plant coenoses, which is an important component of modeling the geo-ecological state of the territory of the settlement.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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