https://doi.org/10.33271/nvngu/2025-1/063

A. O. Shchesniak[*1],
orcid.org/0009-0009-3726-592X,
P. V. Bosak[1],
orcid.org/0000-0002-0303-544X,
N. P. Kovalchuk[2],
orcid.org/0000-0003-3632-4253,
S. O. Sokolov[3],
orcid.org/0000-0001-9704-0938

1 – Lviv State University of Life Safety, Lviv, Ukraine
2 – Lutsk National Technical University, Lutsk, Ukraine
3 – Luhansk Taras Shevchenko National University, Poltava, Ukraine
[*] Corresponding author e-mail: sesnakalina2@gmail.com

ENVIRONMENTAL SAFETY ASSESSMENT OF SOILS IN KHMELNYTSKYI REGION BASED ON CHEMICAL COMPOSITION AND ACIDITY ANALYSIS

Purpose. Environmental safety assessment of Khmelnytskyi region based on a comprehensive analysis of soil chemical composition and acidity for identifying potential environmental risks.

Methodology. For soil quality assessment, soil samples were collected and analyzed in accordance with established and approved methods. X-ray fluorescence spectrometry (XRF) was used to determine the chemical content of the soil. The acidity of the soil was determined by measuring the actual acidity in the water extract and the potential acidity in the salt extract. Sampling was carried out on the territory of Derazhnyanska ATC, considering different types of land use. The pollution index (PI) was calculated to assess the level of soil pollution, which compares the actual concentration of chemical elements with the reference values. The spatial variability of chemical element concentrations and acidity indicators was investigated, and appropriate cartographic models of these parameters distribution were created within the study area.

Findings. The research of light gray podzolized soils of the Derazhnyanska ATC of Khmelnytskyi region was used to determine the chemical content and acidity of the selected samples. The analysis of the chemical composition of the soil using XRF analysis revealed significant spatial variability in the concentrations of elements, but their content did not exceed the maximum permissible limits. Measurements of the actual acidity in the water extract showed a predominantly neutral or close to neutral reaction of the medium (pH 6.9–7.9), which is favorable for most crops. However, the determination of potential acidity in the salt extract revealed a wider range of pH values (4.5–7.2), including samples with an acidic reaction, which may indicate the need for liming of some areas. The calculation of the pollution index showed that most of the studied elements are in the moderate pollution category ($1 < PI \leq 3$), with the highest values for Ti, V and Pb, indicating potential environmental risks and further monitoring is required.

Originality. The first comprehensive assessment of the environmental safety of soils in the Derazhnyanska ATC of Khmelnytskyi region was conducted on the basis of a complex analysis of chemical composition and acidity. A methodology for assessing environmental risk, which takes into account the correlation between the concentration of chemical elements, soil acidity, and environmental safety, was developed and tested.

Practical value. The investigation of environmental safety based on the analysis of the chemical composition and acidity of soils in Khmelnytskyi region is important for the sustainable development of the region and environmental protection. The obtained data provide an opportunity to assess the level of anthropogenic pressure on the ecosystem and develop effective measures to improve the ecological state of soils. Identification of areas with high content of pollutants and abnormal acidity allows for targeted environmental protection measures and optimization of agricultural activities, considering environmental risks.

Keywords: *Khmelnytsky region, environmental safety, soils, chemical elements, X-ray fluorescence spectrometry, acidity*

Introduction. Land is the most valuable natural resource in our time. It is the basis for the sustainable development of human life and society [1]. The Earth's soils were formed in a long-term cumulative interaction of soil-forming factors (rocks, climate, relief and organisms), resulting in the formation of various natural and historical layers that differ in morphology, composition, properties, functional regime and fertility characteristics. Soil should be considered as a fundamental resource for primary crop production, which accounts for about 95 % of the world's food and is a raw material for many industries, primarily because of its unique ability to provide plants with water, nutrients, and other conditions necessary for their normal growth and development [2].

Both natural and anthropogenic factors affect soil condition and quality. Natural factors include climatic conditions (temperature, precipitation, wind), topography, vegetation and organisms. Anthropogenic factors include agricultural activities, urbanization and industrial development of the territory, pollution with heavy metals and other toxic substances, erosion due to unsustainable land use and changes in the hydrological regime [3].

Russia's invasion of Ukraine has led to serious environmental risks and negative impacts on the environment, including pollution and soil degradation [4]. Although the war is still ongoing, severe air pollution and greenhouse gas emissions have been detected as a result of intense hostilities. Moreover, the fighting took place near the Zaporizhzhia Nuclear Power Plant (the largest in Europe) and the Chornobyl Nuclear Power Plant, and the occupation forces built fortifications in the Red Forest, which significantly increased the risk of radiation leakage. Due to deforestation and habitat destruction, biodiversity has been severely affected. Bombing, tunneling, and trenching have negatively affected soil degradation and the morphological structure of the landscape. This is especially important as Ukraine has one of the most fertile soils in the world, black soil, influencing food production. Water quality is changing due to the destruction and damage of infrastructure and the transfer of pollutants into water sources. Ecosystem services are being seriously damaged as deforestation reduces the potential of ecosystems [5].

Soil degradation due to armed attacks includes compaction, erosion, pollution, physical destruction of soil and loss of biodiversity. Explosions release toxic chemicals and metals that remain in the environment and affect the quality of soil and water resources. The impact on human health is already significant. However, it can be even more significant due to the serious consequences of environmental pollution and unsanitary conditions [5, 6].

Hostilities lead to massive soil contamination with heavy metals, oil products, and other toxic substances from ammunition explosions and equipment damage. Furthermore, the military operations destroy soil structures resulting from shell bursts, movement of heavy equipment, and construction of fortifications. Mines impede land cultivation, leading to the desertification of agricultural land and a decrease in production [7].

Chemicals used in ammunition and explosives (e.g., compounds of chemical elements that are not degraded by living organisms) may contaminate soil and surface water, and subsequently have a negative impact on human health and large ecosystems around the world. The main sources of environmental pollution include areas of land, air and water space where military operations are conducted, followed by intense conflicts, areas where military trainings of various kinds are held, and places of disposal and production of ammunition and explosives that can cause destruction under the influence of external influences. The above pollutants include a significant amount of organic and inorganic substances contained in soil and water that pose a serious threat to public health and ecosystems. For example, most of the toxic elements that may be present in munitions are oxidized in the air after being released into the environment, especially in humid environments. Some chemical media increase their solubility, potentially allowing toxins to migrate or become available. These include damage to vital organs such as the respiratory tract, kidneys, and liver, biochemical and functional changes in red blood cells, and inflammation of epithelial tissue. For decades, large areas of military land have been contaminated with toxic compounds and residues of explosives and ammunition containing toxic substances such as stibium (Sb), lead (Pb), uranium (U), 2,4-dinitrotoluene, 6-trinitrotoluene (TNT), 5-trinitro-1,5-triazacyclohexane (RDX), and others, which have remained highly contaminated. As a rule, most of these chemical compounds are very resistant to biodegradation and purification, leading to their persistence in the biosphere and transformation into a source of pollution that can be harmful to human health and the environment due to their potential toxic effects [8].

As a result, under the influence of anthropogenic and natural factors, soils lose their fertility, useful properties and other organically related natural components, which ultimately leads to degradation and poses a serious threat to environmental safety. Today, soil degradation is a very important problem that needs to be addressed. In recent decades, soil degradation has become one of the major global issues as the threat of a global environmental crisis has increased. Its importance is due to the fact that without maintaining soil fertility and overcoming soil degradation, it is impossible to preserve vegetation, wildlife, water and air, affecting the normal functioning of the biosphere, the environmental well-being of people and the overall level of environmental safety [9].

The soils of Khmelnytskyi region were formed under the influence of climate, relief, vegetation, and human activity. The region is home to a variety of soil types: chernozems, dark gray and podzolic chernozems, sod-podzolic, light gray and gray podzolic, grassy bogs, and peat bogs. Each of these soil types has its own unique chemical composition and acidity, which has a direct impact on environmental sustainability and potential environmental risks.

Light gray and gray podzolic soils are present in the research area and have specific characteristics that affect their agricultural use. Light gray soils formed under dense forests are characterized by intensive development of podzolization processes, which are similar in nature to sod-podzolic soils. This leads to the formation of a compacted crust on the soil surface during rain, which negatively affects plant germination and growth, soil permeability and aeration, increases the risk of erosion, and changes the hydrological regime of the territory. In gray podzolic soils formed under more sparse forests, podzolic phenomena are less pronounced. Gray soils are characterized by a higher nutrient content than light gray soils, but have lower levels of total and mobile nitrogen and potassium due to lower humus content and acidic reaction. This prevents the processes of nitrification and nitrogen fixation, and may lead to an imbalance of nutrients in the soil and leaching of excess elements into the water system, threatening environmental safety [10].

A comprehensive study of the chemical content and acidity of soil resources in Khmelnytskyi is an important factor in assessing the environmental safety of the region and ensuring sustainable land use. Effective strategies for improving soil fertility, optimizing land use, and implementing environmental protection measures in the region's agriculture require a detailed analysis of soil quality indicators, including chemical composition and acidity. These data are key to assessing the environmental status of Khmelnytskyi region's soils and developing measures for improving environmental safety.

Literature review. The issue of soil chemical composition and environmental safety has been widely explored in the modern scientific literature. Many scientists have devoted their research to studying the chemical composition and acidity of soils in anthropogenically disturbed areas that lead to degradation.

Among such works, it is worth noting the research of Boyko T., Skladannyi D., Zaporozhets Y. and Plashikhin S. [11], who explored the environmental safety of soil pollution by an industrial enterprise. They studied the geofiltration process as a complex of individual physical and physicochemical processes, assessing the impact of soil type on the overall results of filtration processes.

Vorotyntseva L. and Panarina R. [12] evaluated the long-term effect of irrigation with water of different quality on the salt content and exchangeable cations of the soil absorption complex of chernozem soils.

Holoborodko S. and Dymov O. [13] were engaged in the scientific substantiation of the current landscape and ecological state of agricultural fields and the development of agrobiological measures for increasing the fertility of degraded dark chestnut soils of the southern steppe zone of Ukraine.

Ponomarenko O., Nikiforov V., and Yakovenko V. [14] conducted a comparative analysis of the chemical composition and microstructure of modern chernozem samples with 130-year-old samples, revealing significant differences in the genesis of natural and agrogenic edaphotopes.

Sheiko V. I., Kuchmenko O. B., Gavii V. M., Pasichnyk S. V. [15] considered modern aspects of the infrared spectroscopy application for soil research, emphasizing the advantages of spectroscopic methods in determining the soil composition.

In the international context, it is worth noting the study by Zhang J., Xue K., Chen K. F. [16], who studied the characteristics of heavy metal contamination and assessed the environmental quality and safety of soils of agricultural facilities in China.

Guo W., Wu T., Jiang G. [17] investigated the spatial distribution, environmental risk, and zoning of safe use of heavy metals in the soils of agricultural fields in subtropical China, that is important for the development of effective pollution control strategies.

The issue of a comprehensive assessment of the environmental safety of soil resources in Khmelnytskyi region, namely the Derazhnyanska territorial community, in terms of chemical composition and acidity, for the purpose of developing measures for their rational use and conservation, which is crucial for ensuring environmental safety, remains relevant.

The research is based on the importance of soil resources for agriculture and necessity of their conservation. The chemical composition and acidity of the soil is one of the key factors that determine its fertility and suitability for growing various crops. For agricultural purposes, the soil should include not only humus and minerals within acceptable limits, but also have an appropriate pH level and be free of organic pollutants and heavy metal cations. Heavy metals enter the soil in a variety of ways, including the atmosphere, direct physical pollution, fertilization processes, and wastewater discharges. In the atmosphere, most heavy metal ions are in a stable oxidized state, but their accumulation in soils can lead to serious environmental problems [18].

Increasing agricultural productivity in the field is usually achieved by introducing large amounts of fertilizers that accumulate in the soil and have a long-term effect, but this leads to undesirable consequences such as soil contamination with heavy metals, which pose a serious threat to ecosystems and human health [19].

Soil contamination with heavy metals is a rather urgent problem in agriculture, as they can transfer from soil to plants and then to food, impacting human health. It is important to note that heavy metals have a dual role: on the one hand, they can be toxic, and on the other hand, they serve as important quantitative indicators for assessing various soil properties. Moreover, excessive levels of heavy metals and toxic chemicals in the soil may become one of the reasons for degradation in the future. Due to the insufficient absorption capacity and porosity of the soil profile, heavy metals migrate vertically to the parent rock [20]. An excessive amount of the chemicals can lead to changes in the physical and chemical properties of the soil, a decrease in fertility, and an imbalance of nutrients.

Acidity, which is closely related to the chemical composition of the soil, is crucial for the availability of nutrients to plants and the activity of soil microorganisms. It affects the solubility of minerals, including heavy metal compounds, thereby predetermining their mobility and assimilation by plants [21].

The lands of Derazhnyansky district are mostly represented by the following soil types: gray podzolized forest soils, subtypes of which are light gray, gray, and dark gray. These soils were formed under broadleaf oak and hornbeam forests on loess and carbonate rocks in a rather warm and not too humid climate [22]. Furthermore, these soils are characterized by susceptibility to acidification, which can negatively affect fertility. Moreover, they have a relatively low humus content and require regular organic fertilization to maintain fertility. They are also often affected by nutrient leaching, especially in the case of intensive farming, and special agronomic measures are required to maintain their quality.

Thus, the processes of erosion, drying, acidification, and heavy metal contamination can contribute to the degradation of gray forest soils, resulting in environmental hazards. Therefore, measurement of soil chemical composition and acidity is of particular importance as a tool for monitoring and assessing the degradation of land.

Unsolved aspects of the problem. Although numerous studies have been conducted on the chemical composition and acidity of soils in different regions of Ukraine, a comprehensive assessment of the environmental safety of soil resources in Khmelnytsky region, including the Derazhnyanska ATC, using modern analytical methods has not been conducted yet. Most of the available data relates to individual indicators or is based on outdated analytical methods, not allowing a full assessment of environmental risks.

The level of soil contamination with heavy metals and other toxic elements can negatively affect environmental safety, namely soil fertility, and pose a threat to the environment and public health. Heavy metals are common soil contaminants, such as arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), lead (Pb), copper (Cu), zinc (Zn), and nickel (Ni). This type of pollution is biologically toxic, widely present in the soil environment and persists for a long time, threatening the environment and public health [23].

The intensification of agriculture in Khmelnytskyi region causes significant changes in the chemical, physicochemical properties of the soil, directly affecting environmental safety. For instance, changes in soil structure due to intensive farming and pesticide use not only accelerate the leaching of organic matter and nutrients and reduce fertility, but also disrupt the natural balance of soil chemistry. This leads to a change in soil acidity, which is an important indicator of the ecological condition of the soil. In addition, intensive land use may contribute to the accumulation of pesticide residues and heavy metals, changing the chemical profile of the soil and threatening local environmental safety. The lack of systematic monitoring of these changes complicates the assessment of the actual environmental safety of the region's soils and the development of effective measures for their conservation and restoration.

Accurate agriculture is based on a set of methods and techniques developed to assess the spatial variability of soil and plant properties and to facilitate and optimize soil management, which often requires the use of many variables to support decision-making. However, in some cases, a large number of soil variables are required to assess land quality. Since some of these variables are redundant, identifying key parameter variables will reduce the time and cost of field and laboratory analyses and optimize models and procedures for spatial and temporal soil assessment [24].

Purpose. The purpose of the research is to assess the environmental safety of soil resources in Khmelnytskyi region based on the analysis of their chemical composition and impact on the environment and human health, and to develop recommendations for ensuring environmentally safe agricultural use of soils.

The objectives are:

1. To collect soil samples from 7 test sites on the territory of Derazhnyanska ATC in Khmelnytsky region between the villages of Slobidka and Kalnia, taking into account permanent and temporary land use.
2. To prepare samples to determine the chemical composition and acidity of the soil.
3. To determine the chemical composition of the selected soil samples using a method of X-ray fluorescence spectrometry (XRF).
4. To determine the actual and potential acidity of the soil by measuring the pH in water and salt extracts using litmus tests and a pH meter.
5. To analyze changes in the concentrations of chemical elements and acidity indicators in the study area. To determine the similarity of soils by chemical composition and acidity, as well as to find certain differences between samples.
6. To calculate and compare the soil pollution index.
7. To assess the ecological condition of soils based on the obtained data and develop recommendations for their rational use and improvement.

Methodology description. The investigation was carried out in the area between the forest and the pond in Derazhnyanska ATC of Khmelnytsky region. This area is located between the villages of Kalnia and Slobidka, which are about 900 and 500 m away, respectively.

The study area is located in Khmelnytsky region, which belongs to the forest-steppe natural zone of Ukraine. The forest-steppe occupies approximately 34 % of the country's territory and is characterized by various soil and climatic conditions that determine the peculiarities of soil cover formation in different parts of the country. The soil cover of the zone is characterized by considerable diversity and is represented by gray forest soils, podzolized chernozems, regraded chernozems, and typical chernozems [25]. In the Derazhnyanska ATC of Khmelnytsky region, gray podzolized forest soils prevail, formed under the influence of forest and steppe vegetation in a temperate continental climate. However, intensive agricultural activities may lead to degradation of these soils and changes in their properties.

To determine the quality of the soil in the area, a comprehensive analysis of the chemical composition and acidity of the soil was conducted. This provided a detailed overview of the current state of soil resources and identified potential threats to their degradation. The analysis included determining the content of macro- and microelements, heavy metals, and assessing the current and potential acidity of the soil.

Seven sites were selected for soil sampling within the study area. Sampling was carried out using the "envelope" method (Fig. 1). This method provides a characterization of the sample and allows for spatial variation of soil properties: points *1, 2, 3*, *4* and *5* used the "envelope" method, and points *6* and *7* were located at a distance of 50 and 150 m from point *5*.

This site was chosen for the investigation because of the signs of ecological imbalance, manifested in reduced soil fertility and insufficient crop yields. These signs may indicate potential environmental problems, such as heavy metal contamination of the soil, microbiological disruption, or degradation of the soil structure.

After sampling, the soil was analyzed comprehensively in the laboratory using modern analytical methods.

Portable X-ray fluorescence spectrometers are used to measure the chemical composition of soils and provide a quick and accurate way to determine the concentration of a wide range of chemical elements. The accuracy of the analysis is very high, with analytical errors varying from 0.1 to 0.3 % in some cases. XRF analyzers are characterized by high performance, capable of analyzing several hundred elements per hour, and almost complete automation [26, 27].

Soil acidity was determined by two methods: a pH meter and litmus tests were used to measure the acidity of water and salt extracts, which increased the reliability of the results.

The calculation of pollution indices (PI) is a widespread method for assessing soil pollution and identifying potential

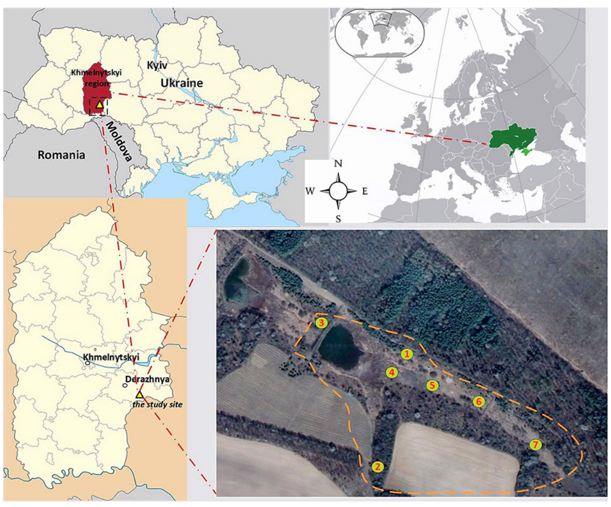

Fig. 1. Geographical location and soil sampling sites

environmental risks [28]. The index quantifies the degree of accumulation of chemical elements in the soil compared to background values. The pollution index is calculated using the following formula

$$PI = \frac{C_i}{S_i}, \qquad (1)$$

where C_i is the actual concentration of a chemical element in the soil under study, mg/kg; S_i is the reference value of chemical elements, mg/kg.

Summary of the main scientific results. Khmelnytsky region belongs to the forest-steppe zone. The soil cover of the forest-steppe is dominated by podzolic chernozems, as well as gray forest soils of varying degrees of podzolization. The light gray podzolized soils that dominate the territory of Derazhnyanska ATC were formed under the influence of deciduous forests and steppe vegetation in a temperate continental climate. These soils are characterized by low nutrient content, acidity and low fertility. In terms of environmental safety, the chemical composition of these soils may have a significant impact on the environment and public health. The acidic reaction of soils contributes to the mobility of heavy metals, all of which are easily leached into groundwater and surface water bodies. This creates a risk of contamination of drinking water sources and accumulation of toxic elements in the food chain. Moreover, due to their low buffering capacity, these soils are vulnerable to anthropogenic pollution, potentially rapidly degrading the quality of agricultural products and the overall environmental condition of the area.

According to the results of the research, the content of chemical elements in the selected soil samples from Derazhnyanska ATC was determined (Table 1).

The analysis of the presented data allows concluding that the content of chemical elements in the studied soil samples does not exceed the maximum permissible concentrations established by national standards in accordance with the order of the Ministry of Health of Ukraine [29, 30]. However, there are significant spatial variations in the concentrations of chemical elements depending on the sampling location. Particularly noticeable fluctuations are observed for Fe and Ti, while Cu content remains relatively stable. It is interesting to note that V is present only in the first four samples, and Zn is absent in sample No. 5, which may indicate local geochemical features of the study area. In general, the distribution of elements reflects the natural variability of soil composition, while remaining within the permissible concentrations.

Even if the detected chemical elements do not exceed the reference values, their accumulation in the soil can negatively affect the development and productivity of plants. High doses of trace elements can inhibit plant growth, disrupt photosynthesis, respiration, and nutrient transfer. In addition, they can endanger human and animal health if they enter the nutrient

Table 1

Chemical composition of the soil sample according to XRF analysis, mg/kg

Metals	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Ti	5,421	5,689	5,652	5,313	6,206	6,754	6,439
V	73	140	91	61	–	–	–
Mn	721	486	804	905	751	883	958
Fe	24,938	30,729	24,559	21,513	19,007	22,786	18,497
Ni	23	31	22	29	18	24	20
Cu	15	15	15	10	13	15	12
Zn	52	56	53	40	–	47	41
Sr	89	97	89	72	93	93	94
Pb	22	23	25	20	25	28	22

chain. Therefore, monitoring the content of chemical elements in the soil is an important issue for ensuring environmental safety.

Soil acidity is an important factor that affects the availability of nutrients for plants and overall soil fertility. This indicator determines the intensity of biochemical processes in the soil and affects the development of microorganisms and the root system of plants.

Measurements were made in aqueous and salt extracts to assess actual and potential acidity. The actual acidity of the soil samples in the aqueous extract is shown in Fig. 2, and the potential acidity values measured in the salt extract are shown in Fig. 3.

Fig. 2 shows the results of the pH measurement of seven soil samples using two different methods.

Analysis of this graph shows that the pH values of all tested soil samples are in the range of neutral to slightly alkaline. The acidity of most of the samples is around *7* or slightly higher, indicating suitable conditions for growing most crops.

Notably, there are small but noticeable differences between the results of different measurement methods. In most cases, the pH meter shows slightly higher values than the litmus test, probably due to the greater accuracy of the electronics. This difference is especially noticeable in samples *4* and *5*, where the discrepancy between the methods is the largest.

The first three samples have the highest pH values, approaching *8* on the pH meter scale, indicating a slightly alkaline soil reaction. Samples *4* and *5*, on the other hand, have the lowest pH values of all the tested samples, especially approaching the neutral value according to the litmus test.

The general trends observed in the figure indicate that neutral and slightly alkaline reactions prevail in the tested soils. These pH values are optimal for most cultivated plants.

It is worth noting that, despite the slight differences between the measurement methods, both approaches show similar trends in all samples, which confirms the reliability of the data obtained. This visualization enables a quick assessment of the acidity of different soil samples and a comparison of the performance of the two pH measurement methods.

Fig. 3 shows the results of two methods of measuring the potential acidity of soil samples in the salt extract: a pH meter and litmus paper.

In contrast to the previous measurement of the actual acidity of the aqueous extract, the range of pH values on this graph is very wide, which indicates the diversity of the potential acidity of the studied soils. Some samples show an acidic reaction at pH below 6.5, indicating that these soils need to be calcified to optimize their acid-base properties.

The data analysis shows that samples Nos.1 and 3 exhibit a neutral or near-neutral reaction, with pH values in the range of 6.7 to 7.2 measured with a pH meter. These results are consistent with the data obtained using litmus paper, confirming the reliability of both analyzes for neutral soils.

However, samples Nos. 2, 4, 5, 6 and 7 were acidic, with pH values ranging from 4.5 to 5.8 according to the pH meter. These values correspond to a slightly acidic or almost acidic soil reaction. Notably, the results of the litmus test for these samples were slightly different, indicating a more slightly acidic reaction (pH around 5–6). This discrepancy can be explained by the lower sensitivity of litmus paper to an acidic reaction compared to more accurate instrumental methods for measuring acidity.

The graph clearly shows that for some samples, such as Nos. 2, 4 and 5, there is a significant discrepancy between the pH meter and litmus test. These differences emphasize the importance of using accurate instrumental measurement methods to assess soil acidity. In particular, on acidic soils, even small changes in pH can have a significant impact on the nutrient supply to plants.

The difference between aqueous and salt extracts lies in the fact that they are used to measure different forms of soil acidity. Aqueous extracts reflect the actual acidity (active acidity) of the soil. It indicates the concentration of free hydrogen ions in the soil solution at the time of measurement. This indicator is important for understanding the current state of the soil and its impact on plants, but does not take into account possible changes in acidity due to change in conditions.

Salt extracts indicate the potential acidity of the soil. When salt solutions (usually KCl or $CaCl_2$) are added to the soil, cations are exchanged between the soil colloids and the solution. The potassium and calcium ions in the saline displaces hydrogen and aluminum ions adsorbed on the surface of soil particles. Saline solutions also affect the buffering capacity of the soil. Buffering capacity is the ability of the soil to withstand rapid changes in pH. It depends on the organic matter content, type of clay minerals, and other factors. The saline solution partially neutralizes this buffering capacity, allowing for the detection of "hidden" acidity that is not visible in aqueous extracts.

Another factor affecting this difference is the change in ionic strength of the solution. Salt solutions have a higher ionic strength than water, which increases the activity of hydrogen ions and leads to a lower pH.

Therefore, the pH values of salt leachate solutions are usually lower than water, especially in soils with a high content of organic matter and clay minerals. This difference is especially noticeable in soils with a high buffer capacity and a high content of exchangeable cations.

A pollution index was calculated to assess the level of anthropogenic impact on the tested samples and determine the degree of contamination with various chemical elements (Table 2). The index allows quantifying the deviation of the element concentration in the sample from its background value. For assessing soil contamination with heavy metals, it is necessary to establish their background content, which is typical for the study area. The background values were based on the regional averages of trace elements determined for the soils of the forest-steppe zone of Ukraine. When setting the background values, the natural features of soil formation and geochemical characteristics of the region were taken into account. These indicators reflect the natural content of trace elements in soils that have not been subjected to significant anthropogenic impact and serve as a baseline for assessing the degree of pollution in the study area.

Table 2 shows the results of the pollution index (PI) test of Khmelnytsky region soils with various chemical elements, which is an important factor in assessing environmental safety.

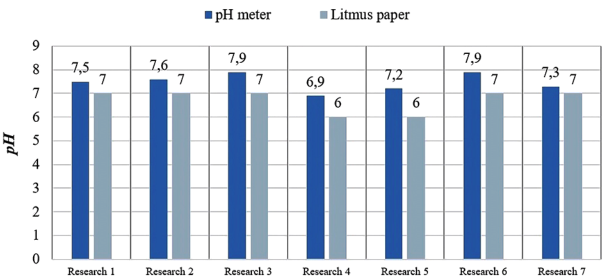

Fig. 2. Estimation of the pH of the aqueous extract of soil samples using pH meter and litmus paper data

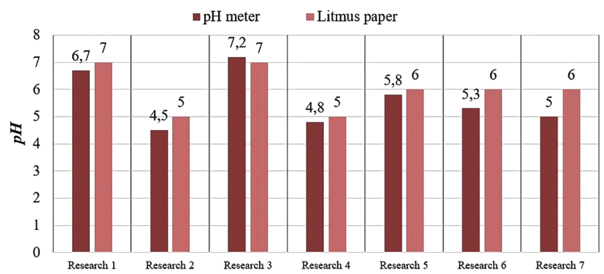

Fig. 3. Estimation of the pH of the salt extract of soil samples using pH meter and litmus paper data

Table 2

Pollution index of the samples

Metals	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Ti	2.073	2.176	2.162	2.032	2.374	2.583	2.463
V	1.921	3.684	2.394	1.605	–	–	–
Mn	0.951	0.641	1.06	1.193	0.99	1.164	1.263
Fe	1.473	1.815	1.45	1.27	1.122	1.345	1.092
Ni	1.045	1.409	1	1.318	0.818	1.09	0.909
Cu	1.034	1.034	1.034	0.689	0.896	1.034	0.827
Zn	0.928	1	0.946	0.714	–	0.839	0.732
Sr	0.754	0.822	0,754	0.61	0.788	0.788	0.796
Pb	2.2	2.3	2.5	2	2.5	2.8	2.2

The table presents data for nine chemical elements: titanium (Ti), vanadium (V), manganese (Mn), iron (Fe), nickel (Ni), copper (Cu), zinc (Zn), strontium (Sr), and lead (Pb). The contamination indices are presented for seven different soil samples, allowing for an assessment of the variability of contamination in different locations in the region.

The PI values for each contaminated soil were categorized according to the following criteria: practically uncontaminated soils ($P \leq 1$), moderately contaminated soils ($1 < P \leq 3$), or highly contaminated soils ($P > 3$).

Analysis of the data shows that contamination levels vary between elements and samples. Some elements show consistently high levels in all samples, while others are more variable. Some samples show high levels of contamination for certain elements, which may indicate localized sources of contamination. Such exceedances can negatively affect ecosystems, reduce soil fertility, inhibit plant growth, and disrupt natural soil processes. For the human population, the main risks are associated with the possible ingestion of these elements through the food chain and the environment, which can lead to a number of health problems.

Conclusions. Investigation of the chemical composition and acidity of soils in the Derazhnyanska ATC of Khmelnytskyi region revealed a problematic environmental condition of the region's soil resources. Analysis of the spatial variability of chemical element concentrations reflected the natural heterogeneity of the soil cover and indicated a potential risk of accumulation of some elements, including titanium, iron, and lead. Although the content of the studied elements did not exceed the maximum permissible concentrations, their accumulation may pose a long-term threat to the environmental safety of the area.

Assessment of soil acidity revealed a predominance of neutral and slightly alkaline reactions in water extracts. However, the analysis of salt extracts showed a wide variation in potential acidity, with some samples showing a tendency toward acidification. This indicates that the acid-base balance of soils needs to be carefully monitored and adjusted to maintain environmental sustainability and productivity.

The calculation of the pollution index (PI) revealed a moderate level of pollution by some elements in the studied soils, in particular titanium, vanadium, and lead. This indicates the presence of anthropogenic impact on the soil ecosystem and the need to take measures to minimize the intake of these elements into the soil to ensure environmental safety of the territory. Particular attention should be paid to heavy metal content control. It is due to the fact that even moderately excessive concentrations of heavy metals can have a cumulative effect, negatively affecting the quality of agricultural products and public health.

The revealed heterogeneity in the chemical composition and physicochemical properties of soils in relatively small areas highlights the importance of a differentiated approach to land use and a need to develop locally adapted soil management strategies. This includes the use of organic fertilizers, crop rotation with legumes, and the implementation of agroecological practices aimed at maintaining optimal acid-base balance, including liming the soil where necessary.

Acknowledgements. *The results of the study were performed using the equipment of the Centre for Collective Use of Scientific Equipment: Laboratory of New Technologies, Creation and Physicochemical Analysis of New Substances and Functional Materials of Lviv Polytechnic National University.*

References.

1. Supreme Council of Ukraine (2003). *On land protection*: Law of Ukraine of 19.06.2003 No. 962-IV. Retrieved from https://zakon.rada.gov.ua/laws/show/962-15#Text.

2. Pankiv, Z. (2016). Soil resources: value and functions. Bulletin of Odesa National University. *Geographical and Geological Sciences, 20*(2), 84-95. https://doi.org/10.18524/2303-9914.2015.2(25).60132.

3. Huang, S., Yang, Y., Cheng, C., Ren, Z., Zhi, G., Lu, Y., Guo, L., & Kang, P. (2021). Interactive effects of natural and anthropogenic factors on heterogenetic accumulations of heavy metals in surface soils through geodetector analysis. *Science of The Total Environment, 789,* 147937. https://doi.org/10.1016/j.scitotenv.2021.147937.

4. Solokha, M., Dmytruk, Y., Romanova, S., Zadorozhniuk, N., Kharchenko, O., Viatkin, K., & Paliienko, O. (2023). Russian-Ukrainian war impacts on the environment. Evidence from the field on soil properties and remote sensing. *Science of The Total Environment*, *902,* 166122. https://doi.org/10.1016/j.scitotenv.2023.166122.

5. Pereira, P., Francos, M., Lopes, M.A.S., & Brevik, E.C. (2022). Russian-Ukrainian war impacts the total environment. *Science of The Total Environment, 837,* 155865. https://doi.org/10.1016/j.scitotenv.2022.155865.

6. Romanova, S., Dmytruk, Y., & Zhukova, Y. (2024). Soil monitoring infrastructure in response to war. *International Journal of Environmental Studies, 81*(1), 1-10. https://doi.org/10.1080/00207233.2024.2314892.

7. Kucher, A., & Kucher, L. (2023). Impact of War on Soils: a Bibliometric Landscape. *17th International Conference Monitoring of Geological Processes and Ecological Condition of the Environment, 2023*, 1-5. https://doi.org/10.3997/2214-4609.2023520212.

8. Broomandi, P., Guney, M., Kim, J.R., & Karaca, F. (2020). Soil Contamination in Areas Impacted by Military Activities: A Critical Review. *Sustainability, 12*(21), 9002. https://doi.org/10.3390/su12219002.

9. Voloshchuk, M.D. (2017). Soil degradation is a global environmental problem. *Bulletin of Lviv University. Geographical series*, *51*, 63-70. https://doi.org/10.30970/vgg.2017.51.8738.

10. Veremeenko, S., Furmanets, O., Trusheva, S., Pinchuk, A., & Semenov, O. (2021). Influence of Climate Changes on Hydrothermal Regime of Dark Gray Podzolized Soil of Western Forest Steppe. *Scientific Horizons, 24*(12), 46-54. https://doi.org/10.48077/scihor.24(12).2021.46-54.

11. Bojko, T., Skladannyy, D., Zaporozhets, J., & Plashykhin, S. (2019). Application of simulation modeling for assessment of environmental safety of soils. *Technology Audit and Production Reserves, 1, 3*(51), 25-30. https://doi.org/10.15587/2312-8372.2020.198785.

12. Vorotintseva, L., & Panarin, M. (2023). Agrogenic changes in the physicochemical properties and health of chernozem soils under long-term irrigation. *Bulletin of Agrarian Science, 101*(12), 17-25. https://doi.org/10.31073/agrovisnyk202312-02.

13. Holoborodko, S., & Dymov, O. (2021). Current state and ways to improve soil fertility in the southern steppe zone of Ukraine. *Bulletin of Agricultural Science, 99*(4), 13-19. https://doi.org/10.31073/agrovisnyk202104-02.

14. Ponomarenko, O., Nikiforov, V., & Yakovenko, V. (2022). Changes in chemical and micromorphological properties of soils in Poltava region of Ukraine over the past 130 years. *Ukrainian Geographical Journal, 117*(1), 18-26. https://doi.org/10.15407/ugz2022.01.018.

15. Sheiko, V., Kurdiukova, O., Tyshchenko, A., & Kurdiukova, O. (2018). Modern aspects of the use of infrared spectroscopy for soil research. *Ecological Sciences, 50*(5), 108-113. https://doi.org/10.32846/2306-9716/2023.eco.5-50.15.

16. Zhang, J., Xue, Q., Chen, Q.F., Zhao, C.S., Liu, W., & Li, Q. (2023). Heavy metal pollution characteristics and assessment of environmental quality and safety of facility agriculture soil in Shouguang. *Environmental Science and Pollution Research, 30,* 1234-1245.

17. Guo, W., Wu, T., Jiang, G., Pu, L., Zhang, J., Xu, F., Yu, H., & Xie, X. (2022). Spatial Distribution, Environmental Risk and Safe Utilization Zoning of Soil Heavy Metals in Farmland, Subtropical

China. *International Journal of Environmental Research and Public Health, 19*(3), 1268. https://doi.org/10.3390/land10060569.
18. Sheyko, V., Astakhova, L., Hamula, Y., & Utevsky, A. (2023). Chemical composition and physicochemical properties of soils as indicators of their fertility and pollution. *Biodiversity, Ecology and Experimental Biology, 25*(1), 60-64. https://doi.org/10.34142/2708-5848.2023.25.1.06.
19. Liu, Z., Rong, Q., Zhou, W., & Liang, G. (2017). Effects of inorganic and organic amendment on soil chemical properties, enzyme activities, microbial community and soil quality in yellow clayey soil. *PLOS ONE 12*(3), e0172767. https://doi.org/10.1371/journal.pone.0172767.
20. Popovych, V., Stepova, K., Voloshchyshyn, A., & Bosak, P. (2019). Physico-Chemical Properties of Soils in Lviv Volyn Coal Basin Area. *E3S Web of Conferences, 105,* 02002. https://doi.org/10.1051/e3sconf/201910502002.
21. Razanov, S. F., Tkachuk, O. P., Ovcharuk, V. V., & Ovcharuk, I. I. (2021). The impact of green manure on soil fertility. *Balanced nature management, 4,* 144-152. https://doi.org/10.33730/2310-4678.4.2021.253101.
22. Voitkiv, P. S., Moroz, G. B., Ivanov, E. A., & Popyk, O. O. (2024). Results of agrochemical assessment of dark gray podzolized clayey soils of Vinnytsia nature and agricultural region (case study of experimental field No. 27 of Dashkivtsi PJSC). *Slobozhanskyi naukovyi vestnik, 1,* 116-124. https://doi.org/10.32782/naturalspu/2024.1.16.
23. Zhao, H., Xia, B., Qin, J., & Zhang, J. (2022). Comprehensive assessment of harmful heavy metals in contaminated soil in order to score pollution level. *Scientific Reports, 12*(3552). https://doi.org/10.1038/s41598-022-07602-9.
24. Abdel-Fattah, M. K., Helmy, A. M., & Mohamed, A. A. E. (2021). Quantitative Evaluation of Soil Quality Using Principal Component Analysis: The Case Study of El-Fayoum Depression Egypt. *Sustainability, 13*(1824), 1-19. https://doi.org/10.3390/su13041824.
25. Davydiuk, H., Borodai, V., & Khomenko, O. (2022). The influence of anthropogenic human activity on the components of the environment in a rural settlement of the Khmelnytsk region. *Agriculture and Plant Sciences: Theory and Practice, 4*(6), 31-38. https://doi.org/10.54651/agri.2022.04.04.
26. United States Environmental Protection Agency (n.d.). *SW-846 Test Method 6200: Field Portable X-Ray Fluorescence Spectrometry for the Determination of Elemental Concentrations in Soil and Sediment*. Retrieved from https://www.epa.gov/hw-sw846/sw-846-test-method-6200-field-portable-x-ray-fluorescence-spectrometry-determination.
27. Silva, S. H. G., Weindorf, D. C., Faria, W. M., Pinto, L. C., Menezes, M. D., Guilherme, L. R. G., & Curi, N. (2020). Soil texture prediction in tropical soils: A portable X-ray fluorescence spectrometry approach. *Geoderma, 362*, 114136. https://doi.org/10.1016/j.geoderma.2019.114136.
28. Kharytonov, M. M., Stankevich, S. A., Titarenko, O. V., Doležalová Weisssmannová, H., Klimkina, I. I., & Frolova, L. A. (2020). Geostatistical and geospatial assessment of soil pollution with heavy metals in Pavlograd city (Ukraine). *Ecological Questions, 31*(2), 47-61. https://doi.org/10.12775/EQ.2020.013.
29. State Standard of Ukraine (2016). Soil quality. *Indicators and parameters of the soil and meliorative state of irrigated lands* (No. 7856:2015). Retrieved from https://online.budstandart.com/ua/catalog/doc-page?id_doc=62738.
30. Ministry of Health of Ukraine (2020). *On approval of the Hygienic Regulations for the permissible content of chemicals in soil*. Order No. 1595. Retrieved from https://zakon.rada.gov.ua/laws/show/z0722-20#Text.

Оцінка екологічної безпеки ґрунтів Хмельниччини на основі аналізу хімічного складу та кислотності

А. О. Щесняк[*1], *П. В. Босак*[1], *Н. П. Ковальчук*[2], *С. О. Соколов*[3]

1 – Львівський державний університет безпеки життєдіяльності, м. Львів, Україна
2 – Луцький національний технічний університет, м. Луцьк, Україна
3 – Луганський національний університет імені Тараса Шевченка, м. Полтава, Україна
[*] Автор-кореспондент e-mail: sesnakalina2@gmail.com

Мета. Оцінити рівень екологічної безпеки Хмельницької області на основі комплексного аналізу хімічного складу й кислотності ґрунтів для виявлення потенційних екологічних ризиків.

Методика. Для оцінки якості ґрунтів був здійснений відбір проб ґрунту та проведене дослідження відповідно до встановлених і затверджених методик. Зокрема, був використаний метод рентгенофлуоресцентної спектрометрії (РФС) для визначення хімічного складу ґрунту. Кислотність ґрунту визначалася шляхом вимірювання актуальної кислотності у водній витяжці та потенційної кислотності у сольовій витяжці. Відбір проб здійснювався на території Деражнянської ОТГ з урахуванням різних типів землекористування. Для оцінки рівня забруднення ґрунту розраховувався індекс забруднення (PI), що порівнює фактичну концентрацію хімічних елементів з еталонними значенням. Встановлена просторова варіабельність концентрацій хімічних елементів і показників кислотності, а також створені відповідні картографічні моделі розподілу цих параметрів на досліджуваній території.

Результати. На основі проведених досліджень світло-сірих опідзолених ґрунтів на теріторії Деражнянської ОТГ Хмельницької області були встановлені вміст хімічних елементів і показники кислотності у відібраних зразках. Аналіз хімічного складу ґрунту за допомогою РФС-аналізу виявив значну просторову мінливість концентрацій елементів, проте їх вміст не перевищував гранично допустимих норм. Вимірювання актуальної кислотності у водній витяжці показало переважно нейтральну або близьку до нейтральної реакцію середовища (pH 6,9–7,9), що є сприятливим для більшості сільськогосподарських культур. Однак, визначення потенційної кислотності у сольовій витяжці виявило більший діапазон значень pH (4,5–7,2), включаючи зразки з кислою реакцією, що може свідчити про необхідність вапнування деяких ділянок. Розрахунок індексу забруднення показав, що більшість досліджених елементів знаходяться в категорії помірного забруднення ($1 < PI \le 3$), з найвищими показниками для Ti, V та Pb, що вказує на потенційні екологічні ризики та необхідність подальшого моніторингу.

Наукова новизна. Уперше проведена комплексна оцінка екологічної безпеки ґрунтів Деражнянської ОТГ Хмельницької області на основі комплексного аналізу хімічного складу й кислотності. Розроблена та апробована методика оцінювання екологічного ризику, що враховує взаємозв'язок між концентрацією хімічних елементів, кислотністю ґрунтів та екологічною безпекою.

Практична значимість. Дослідження екологічної безпеки на основі аналізу хімічного складу й кислотності ґрунтів Хмельницької області має важливе значення для сталого розвитку регіону та охорони навколишнього середовища. Отримані дані дають змогу оцінити рівень антропогенного навантаження на екосистему та розробити ефективні заходи щодо поліпшення екологічного стану ґрунтів. Виявлення ділянок із підвищеним вмістом забруднюючих речовин та аномальною кислотністю дає змогу проводити цілеспрямовані природоохоронні заходи та оптимізувати сільськогосподарську діяльність з урахуванням екологічних ризиків.

Ключові слова: *Хмельницька область, екологічна безпека, ґрунт, хімічні елементи, рентгенофлуоресцентна спектрометрія, кислотність*

The manuscript was submitted 20.08.24.