

**РОЗДІЛ 1. ХІМІЧНА, РАДІАЦІЙНА ТА ЕКОЛОГІЧНА БЕЗПЕКА
В УМОВАХ ВІЙНИ ТА ТЕХНОГЕННОГО НАВАНТАЖЕННЯ**

**CHAPTER 1. CHEMICAL, RADIATION, AND ENVIRONMENTAL
SAFETY IN WARTIME CONDITION AND TECHNOGENIC STRESS**

**ASSESSMENT OF SOIL ENVIRONMENT TRANSFORMATION UNDER
POTENTIAL MILITARY AND TECHNOGENIC IMPACT**

**ОЦІНКА ТРАНСФОРМАЦІЇ ҐРУНТОВОГО СЕРЕДОВИЩА В УМОВАХ
ПОТЕНЦІЙНОГО ВОЄННОГО ТА ТЕХНОГЕННОГО ВПЛИВУ**

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Abstract. The study investigates the transformation of the soil environment within the territories of Kharkiv Oblast under conditions of potential military and technogenic impact. The physicochemical parameters of 11 soil samples collected from areas characterized by increased anthropogenic pressure and possible consequences of military activity were analyzed. The study included the determination of soil pH, moisture content, and FTIR identification of potentially hazardous chemical compounds using the portable Thermo Scientific TruDefender analyzer. The investigated soils were found to be predominantly alkaline, with pH values ranging from 8.0 to 9.2. A pronounced spatial heterogeneity of soil moisture indicators was identified, indicating local changes in the physicochemical state of the surface soil horizon. FTIR analysis revealed spectral matches with potentially hazardous compounds, including mercury sulfate, sodium fluoroborate, palladium oxide, and several nitrogen-containing compounds. The obtained results indicate signs of transformation in the chemical composition of the soil environment and confirm the feasibility of using portable FTIR analyzers for rapid environmental monitoring of potentially hazardous territories. Spatial modeling performed in the Surfer software environment made it possible to identify local zones of increased technogenic pressure and spatial heterogeneity of soil physicochemical characteristics. The practical significance of the study lies in the possibility of applying the obtained results for environmental risk assessment, forecasting degradation processes, and improving environmental monitoring systems for territories affected by military and technogenic factors.

Keywords: soil environment, military impact, technogenic pressure, FTIR analysis, environmental monitoring, soil transformation, acid-base balance, spatial analysis, Kharkiv Oblast, potentially hazardous substances, Thermo Scientific TruDefender, municipal waste landfills.

Анотація. У роботі досліджено трансформацію ґрунтового середовища територій Харківської області в умовах потенційного воєнного та техногенного впливу. Проаналізовано фізико-хімічні показники 11 зразків ґрунту, відібраних у межах територій із підвищеним антропогенним навантаженням та можливими наслідками бойових дій. У процесі дослідження визначено кислотно-

лужну реакцію середовища, вологість ґрунтів та проведено FTIR-ідентифікацію потенційно небезпечних хімічних сполук із використанням портативного аналізатора Thermo Scientific TruDefender. Встановлено, що досліджувані ґрунти характеризуються переважно лужною реакцією середовища, при цьому значення рН змінювалися у межах 8,0–9,2. Зафіксовано виражену просторову неоднорідність показників вологості ґрунтів, що свідчить про локальні зміни фізико-хімічного стану поверхневого горизонту. За результатами FTIR-аналізу виявлено спектральні відповідності потенційно небезпечним сполукам, зокрема сульфату ртуті, фторборату натрію, паладій оксиду та окремим азотовмісним компонентам. Отримані результати свідчать про ознаки трансформації хімічного складу ґрунтового середовища та підтверджують доцільність використання портативних FTIR-аналізаторів для оперативного екологічного моніторингу територій потенційного ризику. Просторове моделювання результатів у програмному середовищі Surfer дозволило виявити локальні зони підвищеного техногенного навантаження та просторову неоднорідність фізико-хімічних характеристик ґрунтів. Практична цінність дослідження полягає у можливості застосування отриманих результатів для оцінки екологічних ризиків, прогнозування деградаційних процесів та удосконалення систем екологічного моніторингу територій, що зазнають впливу воєнних і техногенних чинників.

Ключові слова: ґрунтове середовище, воєнний вплив, техногенне навантаження, FTIR-аналіз, екологічний моніторинг, трансформація ґрунтів, кислотно-лужний баланс, просторовий аналіз, Харківська область, потенційно небезпечні речовини, Thermo Scientific TruDefender, полігони побутових відходів.

INTRODUCTION

Modern military conflicts are accompanied by large-scale transformation of the natural environment and the emergence of new environmental risks, among which soil degradation occupies a special place. Mechanical destruction of surface horizons, accumulation of combustion products, explosive residues, fuels and lubricants, and other toxic components lead to changes in the physicochemical properties of soils, disruption of biogeochemical cycles, and destabilization of natural ecosystems¹. Under martial law conditions, particular importance is attached to assessing soil environment transformation within territories exposed to combined technogenic and military pressure.

Soils are among the key components of ecosystems, as they regulate the migration of chemical elements, accumulate organic matter, maintain biodiversity, and ensure the stability of landscape systems. Disturbances in acid-base balance, changes in moisture content, and accumulation of toxic substances directly affect the mobility of heavy metals, sorption properties of soils, and bioavailability of hazardous compounds². Under such conditions, secondary contamination processes intensify and may pose a threat to surface and groundwater systems, vegetation cover, and human health.

Recent studies indicate that territories affected by military activities are characterized by significant spatial heterogeneity of soil physicochemical properties and the formation of local zones of toxic substance accumulation³. Explosive processes, infrastructure destruction, and deposition of combustion products alter

¹ Solokha M. Soil Degradation and Contamination Due to Armed Conflict. Land. 2024. Vol. 13(10). P. 1614. <https://doi.org/10.3390/land13101614>

² Alloway B. J. Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability. Springer. 2023. <https://doi.org/10.1007/978-94-024-1222-2>

³ Broomandi P., Guney M., Kim J. R., Karaca F. Soil contamination in areas impacted by military activities: A critical review. Sustainability. 2020. Vol. 12(21). P. 9002. <https://doi.org/10.3390/su12219002>

the mineral composition of the surface soil horizon, disrupt sorption processes, and intensify the migration of potentially hazardous compounds.

Assessment of spatial heterogeneity of contamination and the application of rapid environmental monitoring methods have become particularly important in modern ecological research⁴. Spatial analysis enables the identification of local zones of soil transformation and assessment of territories with elevated levels of potential environmental risk.

One of the promising approaches for rapid environmental monitoring is the application of portable FTIR analyzers, which provide the possibility of express identification of chemical compounds directly under field conditions⁵. Fourier Transform Infrared Spectroscopy (FTIR) makes it possible to analyze the spectral characteristics of substances and identify signs of transformation in the chemical composition of soils⁶.

Modern approaches to assessing environmental and technogenic hazards involve combining physicochemical soil analysis with geoinformation and spectroscopic research methods. Such an integrated approach enables rapid identification of local environmental risk zones, assessment of edaphotope transformation, and prediction of potential degradation processes⁷. The importance of comprehensive assessment of technogenically transformed territories is also confirmed by recent studies on environmental risks associated with municipal waste landfills and disturbed lands⁸.

The aim of the study is to assess soil environment transformation based on physicochemical indicators and FTIR identification of potentially hazardous substances within territories of Kharkiv Oblast exposed to potential military and technogenic impacts.

METHODOLOGY

Within the framework of the study, 11 soil samples collected from the territory of Kharkiv Oblast in areas exposed to potential military and technogenic impacts were analyzed. Sampling was carried out within territories characterized by anthropogenic pressure, possible consequences of military activities, local zones of technogenic transformation, and potential deposition of combustion products and chemical compounds into the soil environment. Spatial referencing of sampling locations was performed at the administrative-territorial level without indicating exact geographic coordinates due to security restrictions under martial law conditions.

Soil samples were collected from the surface soil horizon, which is most actively affected by atmospheric deposition of pollutants, combustion products, and technogenically transformed components. The selection of the surface layer was determined by the fact that this horizon is characterized by intensive accumulation of toxic compounds and the formation of primary physicochemical transformations of the soil environment⁹.

During field investigations, the main physicochemical characteristics of soils were determined, including temperature, moisture content, and acid-base reaction (pH). Soil temperature was recorded

⁴ Hou D., O'Connor D., Nathanail P. et al. Integrating GIS and machine learning for soil contamination assessment and spatial analysis: A review. *Science of the Total Environment*. 2023. Vol. 857. P. 159321. <https://doi.org/10.1016/j.scitotenv.2022.159321>

⁵ Liu Y., Ma X., Wang Y. Portable spectroscopy for environmental monitoring and contaminant assessment: Recent advances and applications. *Environmental Research*. 2022. Vol. 214. P. 113834. <https://doi.org/10.1016/j.envres.2022.113834>

⁶ Griffiths P. R., De Haseth J. A. *Fourier Transform Infrared Spectrometry*. Wiley. 2021. <https://doi.org/10.1002/9781119450464>

⁷ Popovych V. V., Apenko I., Dziubenko B. Optimization of fire station locations to increase ecosystem efficiency during natural ecosystems. *Environmental Research, Engineering and Management*. 2022. Vol. 78(2). P. 47–57

⁸ Korol K. A., Popovych V. V., Shuplat T. I. *Ecological and Technogenic Hazards of Municipal Waste Landfills in Lviv Region*. Lviv: LSU LS, 2025

⁹ Solokha M. Soil Degradation and Contamination Due to Armed Conflict. *Land*. 2024. Vol. 13(10). P. 1614. <https://doi.org/10.3390/land13101614>

directly during field surveys under stable weather conditions. Soil moisture was determined as a percentage parameter, since it significantly influences the migration of dissolved compounds, the intensity of physicochemical processes, and the sorption properties of the soil environment¹⁰.

The acid-base reaction of soils was determined using the potentiometric method with repeated measurements for each sample followed by calculation of average pH values. Soil pH is considered one of the most informative indicators for assessing soil transformation processes because changes in acid-base balance directly affect the mobility of heavy metals, bioavailability of toxic compounds, and intensity of biogeochemical processes¹¹.

Rapid identification of potentially hazardous chemical compounds was performed using the portable FTIR analyzer Thermo Scientific TruDefender. The instrument operates based on Fourier Transform Infrared Spectroscopy (FTIR), which enables rapid field identification of unknown substances according to their spectral characteristics¹².

The operational principle of the FTIR analyzer is based on recording infrared absorption spectra of investigated substances. The obtained spectra were compared with the reference spectral library integrated into the Thermo Scientific TruDefender software, enabling preliminary identification of chemical compounds and determination of spectral matches. The analysis was conducted directly under field conditions, allowing rapid assessment of the possible presence of technogenically transformed components within the soil environment¹³.

The FTIR analysis results were interpreted as indicative signs of the possible presence of certain chemical substances or compounds with similar spectral characteristics. The obtained spectral matches were not interpreted as quantitative concentration measurements because portable FTIR analyzers are primarily intended for qualitative rapid identification of substances under field conditions. Particular attention was focused on identifying spectral features of potentially hazardous compounds capable of affecting soil physicochemical properties and forming local environmental risks.

During interpretation of the obtained results, special attention was paid to the analysis of changes in soil acid-base balance, spatial variability of moisture indicators, and possible signs of technogenic transformation of the surface horizon. The integrated approach combining physicochemical assessment and FTIR identification enables a more objective evaluation of the ecological condition of territories affected by military and technogenic factors¹⁴.

Comparative analysis of physicochemical indicators and descriptive environmental assessment methods were applied for generalization of the obtained results. Visualization of spatial heterogeneity of the studied parameters was performed using thematic maps, graphical models, and interpolation surfaces generated in the Surfer software environment. Spatial modeling allows identification of local zones of soil transformation, determination of gradients of physicochemical parameter changes, and assessment of territories characterized by elevated levels of potential environmental hazard¹⁵.

¹⁰ Hou D., O'Connor D., Nathanail P. et al. Integrating GIS and machine learning for soil contamination assessment and spatial analysis: A review. *Science of the Total Environment*. 2023. Vol. 857. P. 159321. <https://doi.org/10.1016/j.scitotenv.2022.159321>

¹¹ Alloway B. J. *Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability*. Springer. 2023. <https://doi.org/10.1007/978-94-024-1222-2>

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¹⁵ Popovych V. V., Apenko I., Dziubenko B. Optimization of fire station locations to increase ecosystem efficiency during natural ecosystems. *Environmental Research, Engineering and Management*. 2022. Vol. 78(2). P. 47–57

RESULTS

The results presented in Figure 1 demonstrate pronounced spatial variability of the acid-base condition of the soil environment within the studied territories of Kharkiv Oblast. The highest pH values were associated with specific local areas located in the eastern and northeastern parts of the investigated territory. The formation of such anomalies may be related to the heterogeneous nature of technogenic pressure, local accumulation of combustion products, deposition of ash residues, and changes in the mineral composition of the surface soil horizon caused by military and anthropogenic impacts. Similar patterns of spatial heterogeneity of edaphotopes have been described in studies devoted to technogenically disturbed territories and municipal waste landfill environments, where local physicochemical anomalies are formed due to uneven accumulation of pollutants and transformation of soil structure.

Analysis of pH values demonstrated that all investigated samples were characterized by predominantly alkaline conditions. The average pH values ranged from 8.0 to 9.2, exceeding neutral conditions and indicating possible transformation of the natural acid-base balance of the soil cover¹⁶.

The highest pH values were recorded in samples No. 4, No. 6, and No. 7, where the indicators exceeded 9.0. Such alkalinity levels are not typical for stable natural soil systems and may indicate active transformation processes within the surface soil horizon. Elevated pH values are often associated with the accumulation of combustion products, ash residues, fragments of concrete and construction materials, as well as mineral components entering the soil environment due to infrastructure destruction and explosive processes¹⁷.

Changes in acid-base balance directly affect the ecological stability of soils. Under alkaline conditions, transformation of sorption properties occurs within the surface layer, migration capacity of certain chemical elements changes, and the functioning of soil microbiota may be disrupted. Elevated pH values may also contribute to the formation of local zones of toxic compound accumulation and influence the bioavailability of heavy metals¹⁸.

Under conditions of increased alkalinity, the physicochemical behavior of numerous pollutants changes substantially. Heavy metals may form both insoluble precipitates and mobile complex compounds depending on environmental conditions, moisture regime, and mineral composition of soils. Disturbance of the natural acid-base equilibrium may also reduce biological activity of soil microorganisms and negatively affect nutrient cycling processes within the ecosystem. Long-term alkalization of soils may therefore become one of the factors contributing to degradation of ecological functions of the soil environment.

The identified spatial heterogeneity of pH values additionally indicates that transformation processes occur unevenly across the investigated territories. Such variability may be associated with differences in the intensity of local military impact, deposition of combustion residues, destruction of infrastructure objects, and accumulation of technogenic materials within specific sectors of the studied territory. Localized alkaline anomalies may therefore serve as indirect indicators of zones subjected to increased anthropogenic and military-related pressure.

The obtained results confirm that physicochemical indicators of soils can be effectively used for rapid environmental assessment of territories affected by technogenic and military impacts. Changes in pH values represent an important diagnostic criterion reflecting the intensity of transformation processes within the surface soil horizon and the degree of disturbance of natural geochemical conditions.

¹⁶ Alloway B. J. *Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability*. Springer. 2023. <https://doi.org/10.1007/978-94-024-1222-2>

¹⁷ Broomandi P., Guney M., Kim J. R., Karaca F. Soil contamination in areas impacted by military activities: A critical review. *Sustainability*. 2020. Vol. 12(21). P. 9002. <https://doi.org/10.3390/su12219002>

¹⁸ Alloway B. J. *Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability*. Springer. 2023. <https://doi.org/10.1007/978-94-024-1222-2>

The results of the spatial distribution of soil pH values are presented in Figure 1.

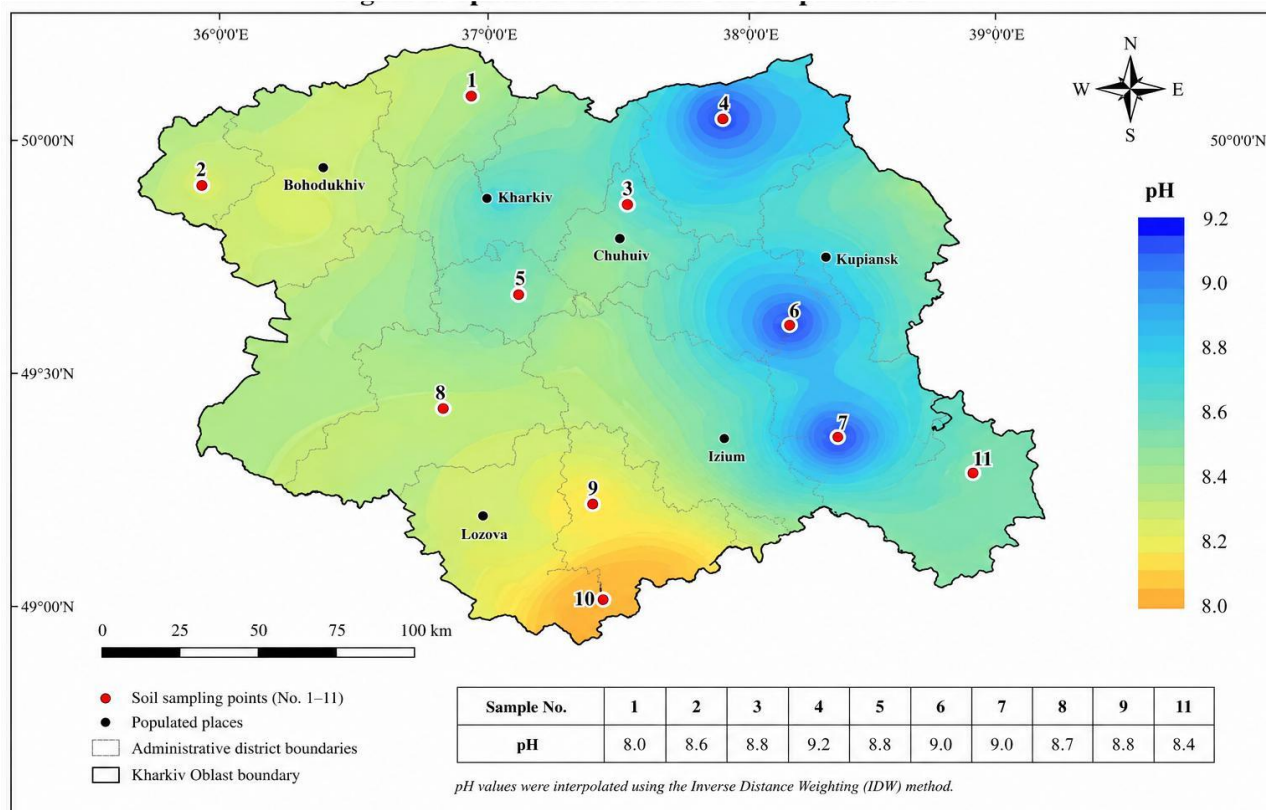


Figure 1. Spatial Distribution of Soil pH Values in the Studied Samples

The results presented in Figure 1 demonstrate pronounced spatial variability of the acid-base condition of the soil environment within the studied territories of Kharkiv Oblast. The highest pH values were associated with specific local areas located in the eastern and northeastern parts of the investigated territory. The formation of such anomalies may be related to the heterogeneous nature of technogenic pressure, local accumulation of combustion products, deposition of ash residues, and changes in the mineral composition of the surface soil horizon caused by military and anthropogenic impacts. Similar patterns of spatial heterogeneity of edaphotopes have been described in studies devoted to technogenically disturbed territories and municipal waste landfill environments, where local physicochemical anomalies are formed due to uneven accumulation of pollutants and transformation of soil structure.

Elevated pH values observed in several investigated samples indicate the disturbance of the natural acid-base balance of soils and may reflect intensive physicochemical transformation processes occurring within the surface horizon. Under alkaline conditions, the mobility of individual chemical elements and toxic compounds changes significantly, while the sorption capacity of soils may be altered. Such transformations can affect the intensity of biogeochemical processes, disrupt the functioning of soil microbiota, and contribute to the formation of local zones characterized by increased environmental risk. In addition, long-term shifts in acid-base conditions may influence nutrient availability and lead to deterioration of ecological stability within disturbed ecosystems.

Soil moisture indicators were also characterized by considerable heterogeneity. Moisture values ranged from 28.5% to 48.6%, indicating different moisture conditions within the surface soil layer and varying intensity of physicochemical processes across the investigated territories. The highest moisture levels were recorded in samples No. 1 and No. 11, whereas the lowest values were observed in samples No.

2 and No. 10. Such variability demonstrates that the investigated territories differ significantly in their hydrological regime and water-retention characteristics.

Spatial heterogeneity of moisture distribution may be associated both with local natural conditions and with disturbances in the structure of the surface soil horizon caused by mechanical and technogenic impacts. Soil compaction, destruction of natural aggregation, alteration of granulometric composition, and accumulation of technogenic materials may substantially affect infiltration processes and the capacity of soils to retain water. In territories exposed to military activities, additional factors influencing soil moisture conditions include crater formation, destruction of vegetation cover, changes in surface runoff patterns, and accumulation of combustion residues within depressions of the microrelief.

Elevated moisture levels create favorable conditions for intensified migration of dissolved compounds, including potentially toxic substances and mobile forms of heavy metals. Increased water content may enhance vertical and horizontal migration of contaminants through the soil profile and facilitate their transport into adjacent environmental components, particularly groundwater and surface water systems. Under such conditions, even local contamination sources may contribute to broader environmental degradation processes and increase ecological risks for neighboring territories.

The combination of elevated moisture content and alkaline environmental conditions may contribute to the transformation of sorption processes, changes in the migration capacity of toxic compounds, and the formation of unstable geochemical conditions within the surface soil horizon. Under alkaline conditions, some heavy metals may become less mobile, while others may form soluble complexes capable of migrating within the soil environment. Simultaneously, changes in soil moisture significantly influence the intensity of physicochemical reactions, dissolution of mineral components, and redistribution of contaminants between solid and liquid phases.

The obtained results indicate that the investigated territories are characterized by active local transformation processes associated with technogenic and potentially military-related impacts. Spatial variability of pH and moisture indicators demonstrates that soil transformation occurs unevenly and depends on the intensity of local disturbances, physicochemical composition of deposited materials, and hydrological conditions of individual sites. Such heterogeneity complicates environmental assessment of disturbed territories and confirms the necessity of applying spatial analysis methods for identifying local ecological anomalies.

Under conditions of prolonged technogenic and military pressure, the identified physicochemical transformations may become one of the key factors contributing to degradation of soil ecosystems, reduction of biological productivity, disturbance of natural migration barriers, and intensification of secondary contamination processes. Therefore, monitoring of physicochemical soil parameters represents an important component of environmental assessment systems aimed at identifying potentially hazardous territories and forecasting further degradation processes.

To visualize the spatial heterogeneity of soil moisture, a corresponding graphical model was developed (Figure 2).

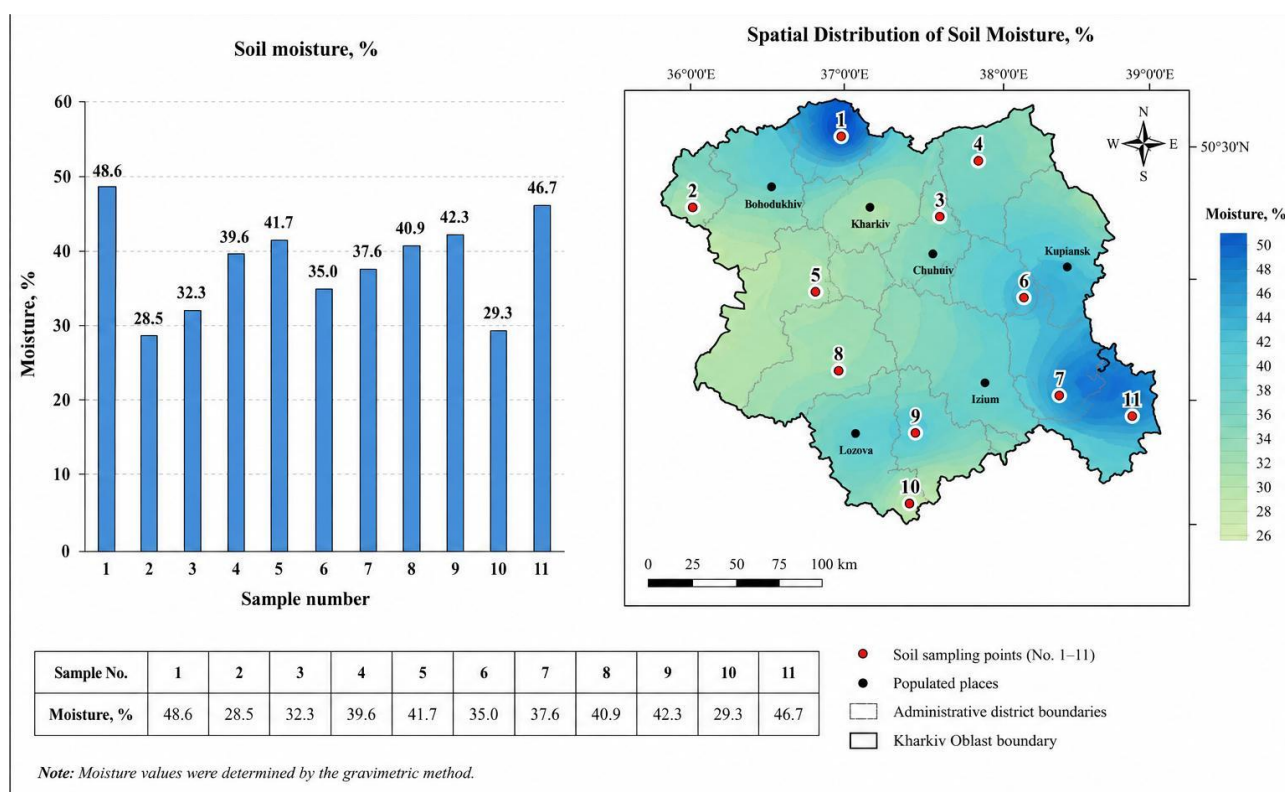


Figure 2. Variability of Soil Moisture in the Studied Samples

The results presented in Figure 2 demonstrate substantial spatial heterogeneity of soil moisture within the studied territory. The most humidified areas were confined to the northern and eastern parts of the investigated region, whereas local zones characterized by reduced moisture levels were observed in the southern sector. Such a distribution pattern may indicate uneven influence of technogenic processes, alteration of the physical structure of soils, and disturbance of the natural hydrological regime of the surface soil horizon.

The obtained results indicate the presence of local transformation processes within the studied territories. The combination of elevated pH values and significant variability of soil moisture may suggest disturbance of the natural functioning of the soil environment under conditions of potential military and technogenic impact.

CONCLUSION

As a result of the conducted research, it was established that the soil environment of the studied territories within Kharkiv Oblast is characterized by signs of physicochemical transformation under conditions of potential military and technogenic impact. Analysis of physicochemical indicators demonstrated the predominantly alkaline nature of the investigated soils, with pH values ranging from 8.0 to 9.2. The highest pH values were recorded in samples No. 4, No. 6, and No. 7, indicating the local formation of technogenically transformed zones within the surface soil horizon. Such changes may be associated with the accumulation of combustion products, mineral components, construction debris, and other substances capable of altering the natural acid-base balance of the soil environment.

Significant spatial variability of soil moisture indicators was also identified, reflecting heterogeneity of the surface horizon functioning and different intensities of physicochemical processes within the investigated territories. Moisture values ranged from 28.5% to 48.6%, with the highest values observed in samples No. 1 and No. 11. The obtained results indicate disturbance of the natural hydrological regime of soils and changes in their water-retention properties. The combination of elevated moisture levels and

alkaline environmental conditions creates favorable conditions for intensified migration of dissolved compounds, transformation of sorption processes, and formation of local zones of secondary contamination.

The results of spatial analysis confirmed pronounced heterogeneity in the distribution of physicochemical indicators across the studied territories. Local zones characterized by elevated pH and moisture values were identified, which may indicate different intensities of technogenic pressure and uneven transformation of the soil environment. Such spatial variability represents an important indicator of disturbed natural functioning of edaphotopes and confirms the feasibility of applying geoinformation approaches for environmental monitoring of disturbed territories.

According to the FTIR analysis results obtained using the portable Thermo Scientific TruDefender analyzer, spectral matches corresponding to potentially hazardous compounds were identified in several investigated samples, including mercury sulfate, sodium fluoroborate, palladium oxide, triacetoxyborine, and certain nitrogen-containing compounds. Detection of such spectral features may indicate transformation of the chemical composition of the surface soil horizon and the introduction of technogenically altered components into the soil environment. Particular environmental concern is associated with substances characterized by potential toxic effects and the ability to accumulate within environmental components.

The obtained results confirm that the use of portable FTIR analyzers represents a promising direction for rapid environmental monitoring of potentially hazardous territories. The integration of physicochemical soil analysis with spectroscopic technologies enables comprehensive assessment of soil environment transformation, identification of local zones of potential environmental hazard, and evaluation of spatial heterogeneity of contamination.

The practical significance of the conducted research lies in the possibility of applying the obtained results to improve environmental monitoring systems for territories affected by military activities and technogenic processes. The identified patterns of soil environment transformation may be used for environmental risk assessment, prediction of degradation processes, identification of priority ecological control zones, and development of measures aimed at ensuring environmental safety of disturbed territories.