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WATER QUALITY IN DRINKING WATER SOURCES IN DNIPROPETROVSK REGION DURING HOSTILITIES

Kateryna Akhmetova[1]✉, Iryna Kochmar[1], Kateryna Stepova[1], Iryna Fediv[1], Aušra Mažeikienė[2]

[1] Department of Environmental Safety,
Lviv State University of Life Safety,
35, Kleparivska Str., Lviv, 79007, Ukraine
[2] Department of Environmental Protection and Water Engineering,
Faculty of Environmental Engineering,
Vilnius Gediminas Technical University,
11, Saulėtekio Al., Vilnius, 11 10223, Lithuania
ira.arnaut94@gmail.com

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Abstract. Military actions in Ukraine have severely affected water sources, mainly due to the destruction of dams, pumping stations, treatment facilities, canals, and the seizure of water infrastructure. These events damaged water supply systems and contaminated drinking sources, reducing reserves in certain areas. The issue is intensified in Ukraine due to the high industrialization of regions near active conflict zones. This study focuses on the impact of war on drinking water in the Dnipropetrovsk region, located 105–150 km from the front line. Further risks to water quality stem from missile attacks, where debris from rockets and drones targeting cities like Dnipro, Samara, and Kamianske may alter the chemical state of nearby aquatic ecosystems. To evaluate water safety, we conducted a physicochemical analysis of 16 indicators, including pH, oxidation, alkalinity, conductivity, metals (iron, copper, cadmium, zinc), and nitrogen compounds. Results were benchmarked against national sanitary standards (DSanPiN 2.2.4-171-10, 2010) applicable to well and spring waters. Exceedances of pH and permanganate oxidizability were found in Kocherezhky and Novotroitske villages, while nitrate exceedance was recorded only in Bulakhivka. Water quality classes were determined using DSTU 4808:2007 standards. The poorest quality was in Bulakhivka's well, where 5 of 13 parameters fell into the 4th class (mediocre), while Kocherezhky's pump room showed the best quality, with 10 of 13 indicators rated as 1st class (excellent).

Keywords: drinking water quality, war impact, water pollution, environmental monitoring, sustainable development.

1. Introduction

One of the main challenges of the 21st century is the pollution of surface waters, which are essential for modern society as they provide clean drinking water for the population, as well as water for domestic and industrial use. In 2015, the United Nations General Assembly adopted Resolution ""Transforming our World: The 2030 Agenda for Sustainable Development" (United Nations, 2024), which outlines the Global Sustainable Development Goals. Among them, Goal 6 – "Clean Water and Sanitation" –aims to enhance water quality by 2030. This includes reducing

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sources of pollution, prohibiting unauthorized waste discharge, limiting the spread of hazardous substances, decreasing the share of untreated wastewater, and greatly expanding the safe reuse and recycling of water resources worldwide.

Modern wars, since the First World War, are believed to have a greater impact on ecosystems than previous, less industrialized wars because of the higher potential of modern weapons to cause environmental damage. The consequences of war can materialize both directly, by damaging water resources and polluting the environment with weapon remnants, and indirectly, by increasing the frequency or intensity of harmful processes. Such processes can be natural, such as erosion, or man-made, such as industrial pollution (Popovych et al., 2025).

Research on environmental contamination during armed conflicts has highlighted multiple potential pathways through which pollutants enter ecosystems. For example, during the Gulf War, Kuwait's water resources were heavily polluted by oil spills after attacks on oil fields (Literathy, 1992), which led to increased concentrations of trace elements along the Gulf coast and affected regional aquaculture (Buolayan et al., 1998). During the civil war in Syria, the discharge of untreated wastewater into the environment, both intentional and accidental, degraded water quality in the affected areas (Faour & Fayad, 2014). After the civil war in Sri Lanka, explosive remnants of war, such as landmines, remained scattered across the landscape. Research (Gunawardana et al., 2018) reports higher than standard concentrations of heavy metals, fluoride, and calcium in groundwater in these areas. Other possible sources of contamination include hazardous waste from industrial plants and landfills, pathological waste from hospitals damaged during the conflict, unregulated burning of household waste, and the use of chemical weapons (Literathy, 1992).

Contamination of water resources due to infrastructure damage is a recurring theme in conflict impact studies. Specific examples include the damage to wastewater treatment plants in the Gaza Strip during Israel's military operations Cast Lead in 2008 (Mason et al., 2011) and Protective Edge in 2014 (Weinthal & Sowers, 2019), which leaked untreated wastewater, as well as damage to sewer lines and treatment plants in Israel during the 2006 Lebanon War, which resulted in large volumes of silt being released directly into the Mediterranean Sea (Zeitoun et al., 2014).

Unfortunately, large volumes of insufficiently treated wastewater from industrial enterprises continue to flow into Ukraine's surface waters. In parallel, military activities across the country have signifycantly exacerbated water quality issues. Between 2014 and 2025, the russian federation's armed aggression have caused extensive–and in many cases, irreversible–damage to essential infrastructure. This includes centralized water supply systems, municipal drainage networks, flood control facilities, and hydraulic components of irrigation systems. A substantial number of water treatment structures and irrigation canals were affected. Moreover, 22 instances of damage to urban water supply and sewage systems have been documented. These events led to repeated interruptions in the operation of water utilities and treatment plants, creating high risk for uncontrolled and acute contamination of natural water bodies (Denisov & Averin, 2017; Akhmetova & Kochmar, 2023). It should be noted that in general, the consequences of hostilities have exacerbated problems related to water quality and its natural environment.

The country has a large number of reservoirs and water storage facilities, and their destruction may lead to flooding of large areas and impede the population's access to drinking water. The hostilities have had a significant impact on Ukraine's water resources, causing pollution of water bodies with heavy metals and various chemicals, which are also released following the explosion of dams, pumping stations, treatment facilities and the seizure of water infrastructure. Damage to the water supply system and contamination of drinking water sources have reduced water supplies in some regions (Popovych et al., 2018).

A substantial portion of Ukraine's water infrastructure has already suffered destruction due to ongoing hostilities. This includes more than 1,947 kilometers of water distribution pipelines, 25 water treatment plants, and 182 pumping stations–primarily concentrated in the Kharkiv, Luhansk, and Donetsk regions. In addition, 159 wells have been either destroyed or severely damaged, with the majority located in the Kharkiv region. The conflict has also affected laboratory facilities responsible for monitoring and analyzing drinking water quality, leading to the loss or damage of many such institutions. Preliminary assessments indicate that over 582 kilometers of sewerage systems have been impacted, and at least 183 sewage pumping stations have been partially or entirely demolished, most of which are again situated in the Kharkiv region. Overall, 51 sewage treatment plants are believed to have been destroyed or damaged. This harms public health, causing increased morbidity among the population. The russian army regularly attacks critical infrastructure, including water pumping stations, water supply and treatment systems, and wastewater treatment systems. The loss of such infrastructure results in substantial challenges for environmental safety and public health (Tsyganenko-Dzyubenko et al., 2023).

Consequently, polluted wastewater discharges into the Dnipro River, leading to a marked decline in water quality, disturbing aquatic habitats, and fostering the growth of pathogenic microorganisms.

Pollution of the environment and water resources due to a full-scale invasion is a danger that affects not only the areas of direct hostilities or areas adjacent to the front line, but also the whole of Ukraine, which is regularly subjected to missile strikes, UAV attacks, and pollution by ammunition and rocket fuel residues (Nikolajev & Stefurak, 2022). Therefore, assessing the environmental safety of drinking water sources is relevant today, as one of the greatest practical importance for humanity is the state of water bodies that perform important functions in the life of society.

The novelty of this study lies in the first assessment of decentralized drinking water sources in the Dnipropetrovsk region during hostilities. Unlike previous works focused only on general infrastructure damage, we provide empirical data from wells and springs located near missile impact areas. Applying DSTU 4808:2007 under war conditions and identifying exceedances of nitrates, orthophosphates, and alkalinity offer new baseline information for post-war monitoring.

The aim of this study was to assess the physicochemical quality of decentralized drinking water sources in the Dnipropetrovsk region, some of which are directly located near areas affected by military operations.

2. Materials and Methods

In January 2025, water samples were collected from selected drinking water supply sources using standardized sampling procedures (Fig. 1):

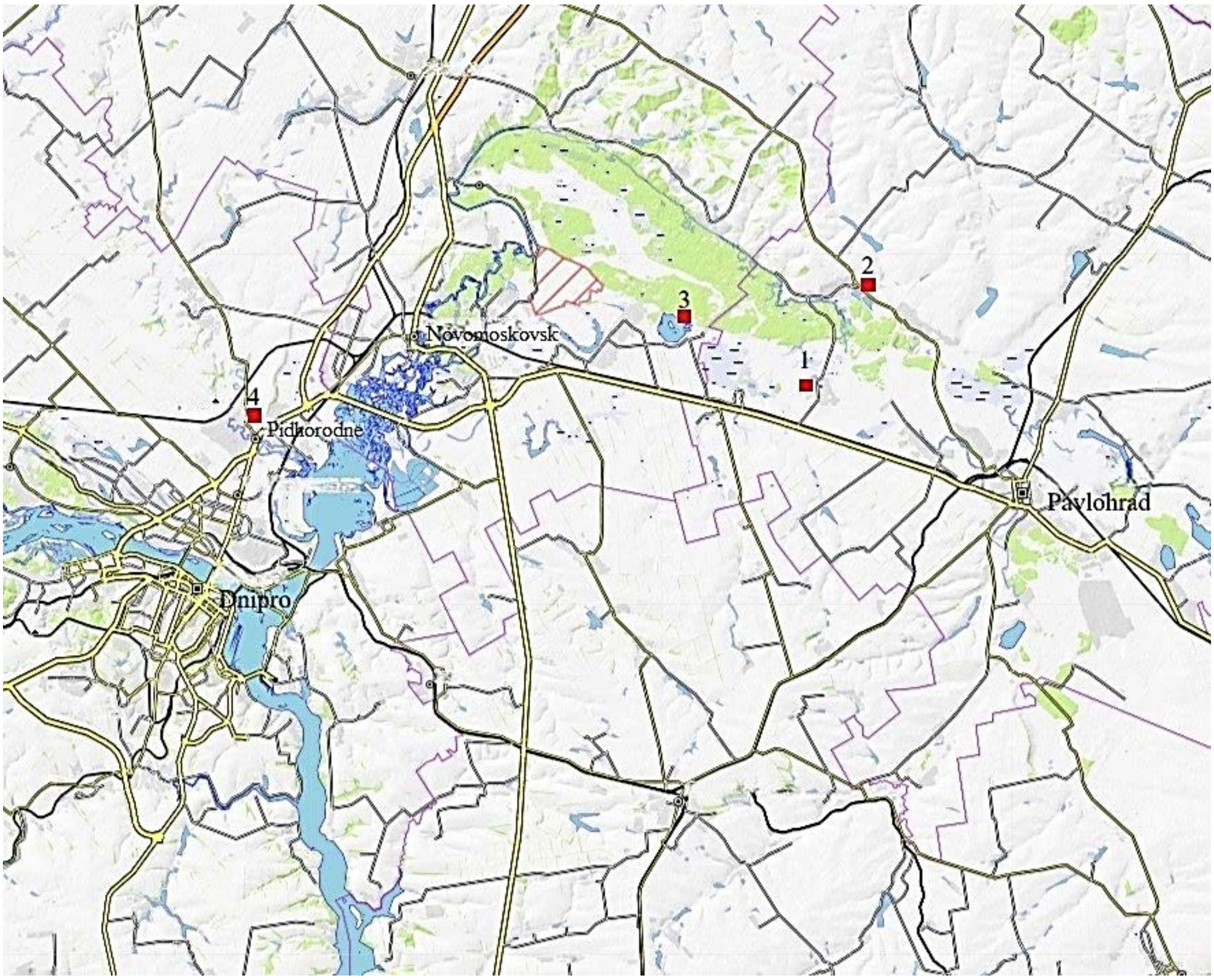

Fig.1. Map of water sampling points within the Dnipropetrovsk region: 1 – well in Bulakhivka village; 2 – pump room in Kocherezhky village; 3 – spring near Solonyi Lyman lake; 4 – well in Pidhorodne town (Lviv: karta, mapa, 2025)

1) Dushi Krynytsia, a private well located in the village of Bulakhivka, Pavlohrad district, Dnipropetrovska oblast. It is located 18 km from the city of Pavlohrad and 48 km from the regional center, the city of Dnipro. There is no centralized water supply in the village, so most residents have their own boreholes and wells or collect water from local wells (Dnipropetrovska oblasna rada, 2020). The water sampling point was chosen because of the fall of the wreckage of a cruise missile that was destroyed by air defense forces near the village of Balakhivka in March 2024.

2) A pump room in the village of Kocherezhky. The village is located on the right bank of the Samara River, 31 km northwest of the district center, the city of Pavlohrad. There is no centralized water supply in the village, so the locals use wells and boreholes to meet their own household needs, but most of the villagers use water from the drinking column. Water from the pump room was selected as a control point because the well pumps deep groundwater.

3) The source is situated near Solonyi Lyman Lake in the vicinity of Novotroitske village, within the Novomoskovsk district of Dnipropetrovsk region. There is a source of drinking water on the shore of the lake, which is visited by patients and military personnel who are treated in the physiotherapy hospital and military hospital in the village of Novotroitske (Dnipropetrovska oblasna rada, 2020). Near the lake, air defense forces are constantly destroying missiles and enemy UAVs heading for cities such as Dnipro, Samara, and Kamianske.

4) A well in the town of Pidhorodne, "Kozatska Krynytsia". The town is located in the central part of the Dnipropetrovsk region on the banks of the Kilchenia River and is a northern suburb of the city of Dnipro. On June 4, 2023, the russian army fired an Iskander missile at the suburbs of Dnipro, damaging the wastewater disposal system.

Water samples were collected in sterilized polyethylene bottles with a volume of 1–2 L. Before sampling, all containers were rinsed three times with the water to be tested. The samples were taken from a depth of 20–30 cm below the water surface, preserved at +4 °C, and delivered to the laboratory within 24 hours. The procedure was carried out according to the national standard DSTU ISO 5667-3:2001 "Water quality – Sampling – Part 3: Preservation and handling of water samples.

The physicochemical parameters of the water were determined using gravimetric, titrimetric, photocolorimetric, and conductometric methods. The analysis included pH, electrical conductivity, alkalinity, hardness, nitrates, nitrites, phosphates, chlorides, sulfates, and iron content. All methods followed national standards and guidelines for drinking water quality control.

Analysis of water quality parameters was carried out in the water testing laboratory of the "Osnova Chemical Factory" LLC. The parameters were determined according to standard methods, namely: hydrogen index was determined by DSTU 4077-2001, permanganate oxidation according to MBB 38433478.003:2023, total alkalinity, carbonate and hydrocarbonate content according to MBB 38433478.005:2023, electrical conductivity according to MBB 38433478. 001:2023, total iron content according to DSTU ISO 6332:2003, copper ion content according to MBB 38433478.0011:2023, cadmium ion content according to MBB 081/12-0787-11, sulfate content according to MBB 38433478. 008:2023, chloride content according to DSTU ISO 9297:2007, orthophosphate content according to MBB 38433478.009:2023, zinc ion content according to MBB 081/12-0787-11, nitrite, ammonia and ammonium ion content according to MBB 38433478.007:2023, nitrate content according to MBB 38433478.007:2023.

The measured values of drinking water quality parameters were evaluated against the regulatory limits established in Sanitary and Epidemiological Norms 2.2.4-171-10 "Hygienic Requirements for Drinking Water Intended for Human Consumption" for water from wells and capped springs (DSanPiN 2.2.4-171-10, 2010). The water quality of wells and spring capacities was determined by DSTU 4808:2007 (DSTU 4808:2007, 2007), according to which the range of water quality indicators (criteria) for surface and groundwater is divided into 4 classes: Class 1 – excellent, desirable water quality; Class 2 – good, acceptable water quality; Class 3 – satisfactory, acceptable water quality; Class 4 –mediocre, limitedly suitable, undesirable water quality.

The overall water quality was assessed using the Water Pollution Index (WPI) according to DSTU 4808:2007 "Sources of centralized drinking water supply. Hygienic and ecological requirements for water quality and rules of choice." The WPI was calculated as the arithmetic mean of the normalized concentrations (C_i/ MPC i) for the selected indicators, where C_i is the measured concentration of a parameter and MPC i is its maximum permissible concentration. Based on the obtained values, each sampling point was assigned to a water quality class ranging from "clean" to "extremely polluted."

3. Results and Discussion

The studied water samples from wells and spring catchments are characterized by different values of pH, permanganate oxidation and total alkalinity at all sampling points (Fig. 2). It should be noted that the pH value of the water does not meet the standard values of 6.5–8.5 in the village of Kocherezhky, where the water is acidic – pH 6.0, and in the village of Novotroitske, where the water is alkaline – pH 9.07. In the village of Bulakhivka, an excess of the integral indicator of permanganate oxidation was detected, which exceeds the MPC of 5.0 mg/L by 1.2 times. In accordance with DSanPiN 2.2.4-171-10, total alkalinity reflects the buffering capacity of water, primarily due to the presence of weak acid anions such as carbonates and bicarbonates. This parameter is not typically assessed for water extracted from wells or surface intakes, while for bottled drinking water, the acceptable limit is 6.5 mmol/L. In the analyzed samples, total alkalinity varied between 0.9 and 14.2 mmol/L, with the maximum value recorded in the sample collected from Bulakhivka village.

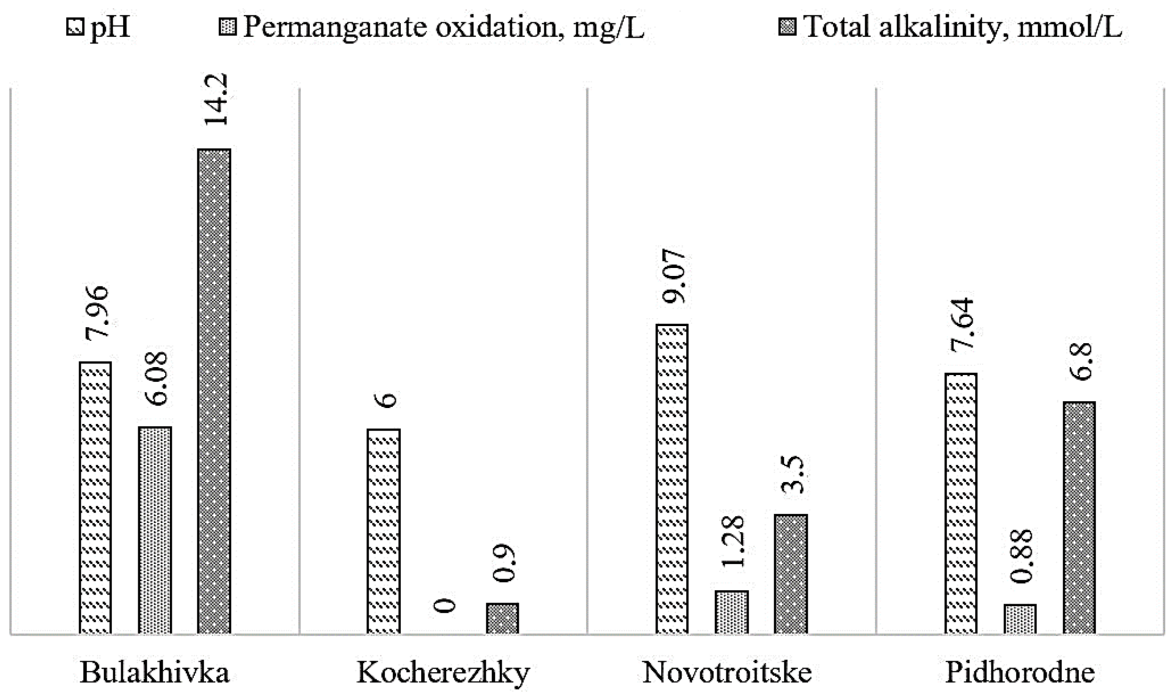

Fig.2. Characterization of general water quality indicators

Notably, the concentrations of hydrocarbonates, chlorides, sulfates, and nitrates varied considerably across the analyzed water samples (Fig. 3). Hydrocarbonate concentrations ranged from 54.9 to 866.2 mg/L, with the peak level observed in Bulakhivka village, showing a strong relationship with the water's total alkalinity. Chloride levels remained below the maximum permissible concentration (350 mg/L), fluctuating between 4.55 and 209.91 mg/L. The MPC for sulfates in water from wells and water captures is 500 mg/L; in the tested samples, they were detected in water from Bulakhivka village (16.13 mg/L) and Pidhorodne town (118.95 mg/L), while their content is within the normal range. Also, no exceedance of the MPC (3.3 mg/L) for nitrite content was detected in all sources of non-centralized water supply, and their content ranges from 0.003 mg/L in Kocherezhky village to 0.013 mg/L in Bulakhivka village. However, the nitrate content in the water from Bulakhivka village exceeds the MPC of 50 mg/L by 4.2 times, while in Kocherezhky, Novotroitske, and Pidhorodne samples nitrates remainned within the permissible limits. The electrical conductivity of the selected water samples, which depends mainly on the degree of mineralization (concentration of dissolved mineral salts), was also investigated and found to increase in the following order: Kocherezhky village, Novotroitske village (66.5 μS/cm) – Pidhorodne (1317 μS/cm) – Bulakhivka village (2740 μS/cm).

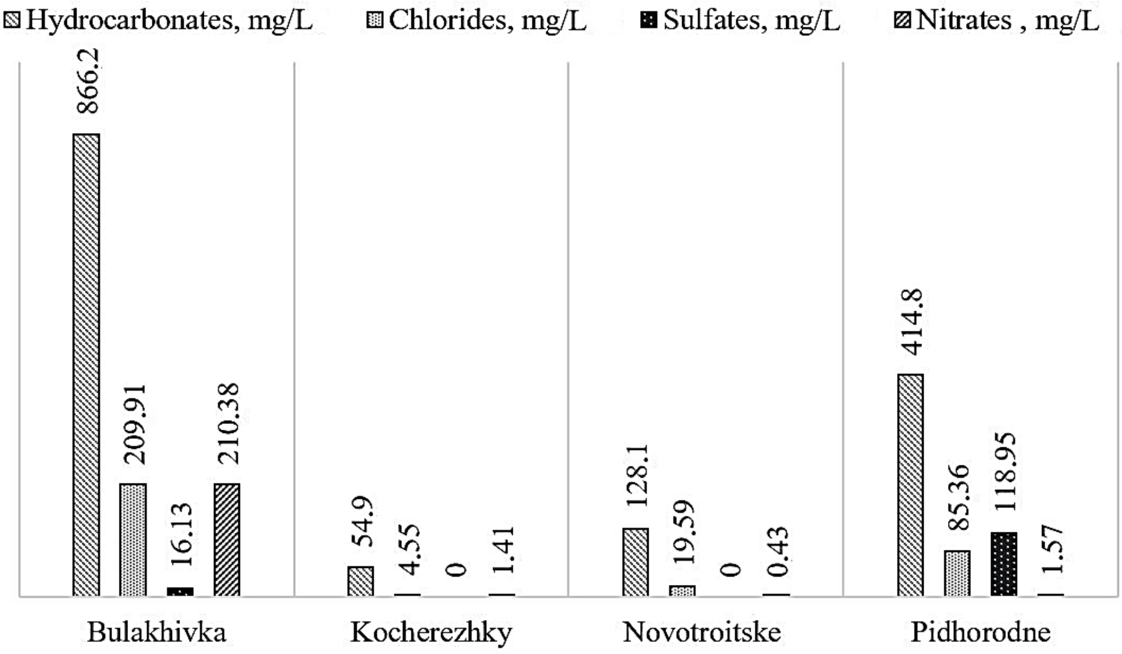

Fig.3. Anion content in water samples

Fig. 4 presents the findings for total iron, copper, and zinc concentrations; cadmium was absent in all analyzed samples. The data indicate that total iron levels remain below the maximum permissible concentration of 1.0 mg/L. Copper concentrations ranged between 0.01 and 0.06 mg/L, while zinc levels varied from 0.02 to 0.2 mg/L.

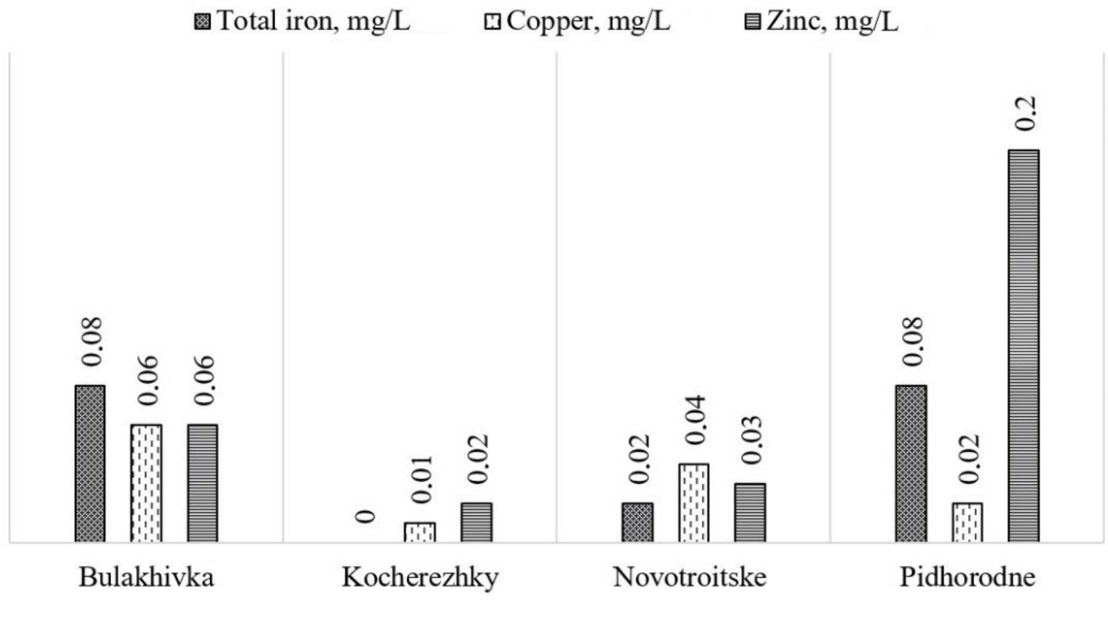

Fig.4. Cation content in water samples

To evaluate the condition of the water, the concentrations of eutrophication-related compounds were also analyzed in the collected samples. Ammonia and ammonium were absent in samples from Kocherezhky village, while the highest concentrations were recorded in Bulakhivka. Nonetheless, all values remained below the maximum permissible concentration of 2.6 mg/L. Orthophosphate levels varied from 0.06 mg/L in Pidhorodne to 1.23 mg/L in Bulakhivka's water supply.

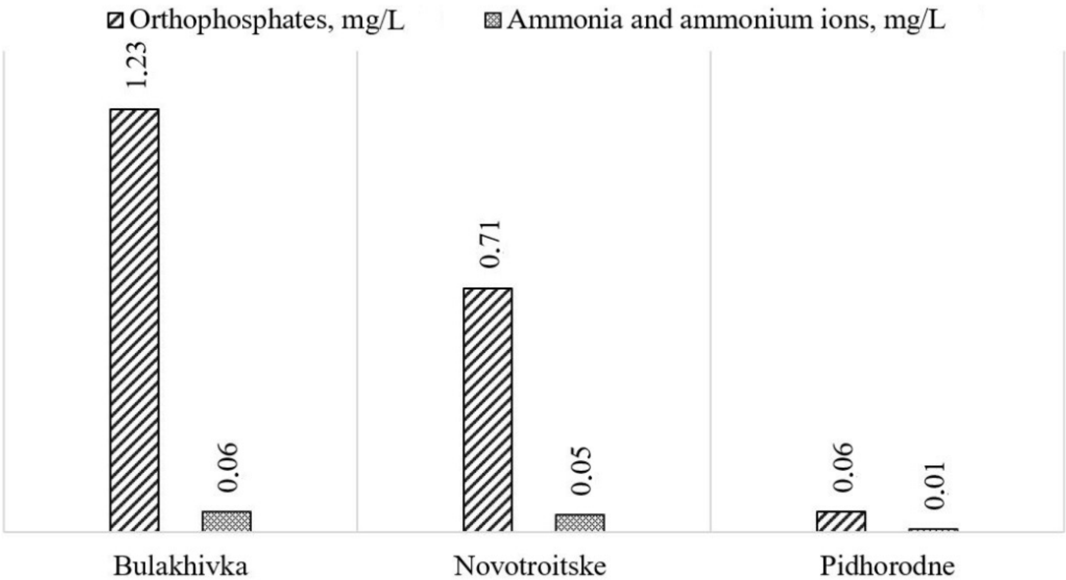

Fig.5. Eutrophic agents content in water samples

To assess the water quality of wells and spring capture, we used DSTU 4808:2007 (DSTU 4808:2007, 2007), which defines water quality classes for each study site according to individual indicators (Fig. 6).

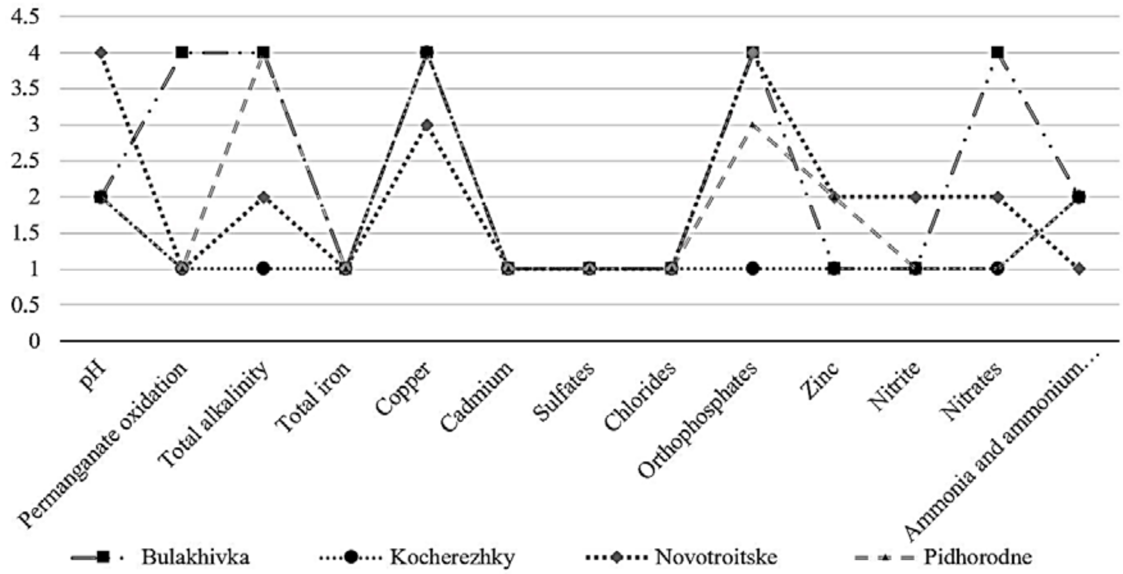

Fig.6. Distribution of water quality classes by individual indicators

The water quality in the pump room of Kocherezhky village predominantly corresponds to Class I standards, accounting for 76.9 % of the analyzed parameters. An additional 15.4 % of the indicators align with Class II, while only 7.7 % fall under Class IV, indicating isolated concerns regarding specific characteristics. The water from the spring near the Solonyi Lyman Lake in Novotroitske village corresponds to the 1st class of water quality in 46.1 % of the studied indicators, 30.77 % – to the 2nd class of water quality, 7.7 % – to the 3rd class of water quality, 15.4 % – to the 4th class of water quality. The water from the well in Pidhorodne corresponds to the 1st class of water quality in 53.8 % of the studied indicators, 23.1 % – to the 2nd class of water quality, 7.7 % – to the 3rd class of water quality, 15.4 % – to the 4th class of water quality. The worst water quality should be recognized as the well in the village of Bulakhivka, as 46.1 % of the studied indicators correspond to the 1st class of water quality, 15.4 % – to the 2nd class of water quality, 38.5 % – to the 4th class of water quality.

The analysis of nitrate and other parameters showed significant variation among the studied sites.

A more detailed analysis of the studied water sources demonstrates pronounced variation between sites. The control site in Kocherezhky village exhibited the best water quality, with almost all parameters well below the maximum permissible concentrations. The only deviation was a slightly acidic pH (6.00), which may affect taste and accelerate corrosion in pipelines, potentially releasing trace metals.

In Novotroitske village (spring near Solonyi Lyman Lake), the water showed generally favorable characteristics such as low mineralization (66.5 µS/cm) and reduced permanganate oxidation values. However, excessive alkalinity (pH 9.07), a high carbonate concentration (42 mg/L), and elevated orthophosphates (0.71 mg/L) pose risks of eutrophication and algal blooms.

In Pidhorodne, the local well water had high total mineralization (1317 µS/cm), with substantial hydrocarbonates (414.8 mg/L) and sulfates (118.95 mg/L), which may increase hardness and alter taste. Although nitrates and organic substances were absent, elevated mineral content may pose risks of chronic kidney stress.

The poorest quality was observed in Bulakhivka, where water was highly mineralized (2740 µS/cm), with high alkalinity (14.2 mmol/L) and hydrocarbonates (866.2 mg/L). Critically, nitrates exceeded the maximum permissible concentration by a factor of 4.2, creating a potential risk of methemoglobinemia in children. High permanganate oxidizability and orthophosphates also indicated organic contamination.

A summary of all measured parameters, their exceedances, classification according to DSTU 4808:2007, and potential health implications is presented in Table.

Summary of water quality indicators, exceedances, classes, and possible health risks in the Dnipropetrovsk region

Sampling site	Main exceedances / deviations	Water Quality Class (DSTU 4808:2007)	Exceedance of MPC	Possible health risk / impact
Bulakhivka well	Nitrates (×4.2 MPC), high alkalinity, orthophosphates, permanganate oxidizability	Class IV (poor)	Yes	Methemoglobinemia in infants; gastrointestinal disorders; unsuitable without treatment
Kocherezhky pump room	Slightly acidic pH (6.0), minor copper deviation	Class I (excellent)	No	Generally safe; minor corrosion risk due to low pH
Novotroitske spring (Solonyi Lyman)	Alkaline pH (9.07), orthophosphates ↑, elevated carbonates	Class II–III (satisfactory to good)	Partial	Risk of eutrophication, algal blooms; digestive irritation
Pidhorodne well	High mineralization, hydrocarbonates ↑, sulfates ↑, copper ↑	Class III (satisfactory)	Borderline	Kidney stress from high hardness; altered taste, possible chronic effects

Based on pH values, three of the four studied decentralized water sources–Bulakhivka, Kocherezhky, and Pidhorodne–fall into Class II, indicating good and acceptable water quality. In contrast, the sample from Novotroitske corresponds to Class IV, which denotes mediocre quality with limited suitability for use. With respect to permanganate oxidation, the water from Kocherezhky, Novotroitske, and Pidhorodne meets Class I standards, suggesting excellent quality, while the sample from Bulakhivka aligns with Class IV. Assessment of total alkalinity shows that water from Kocherezhky meets the criteria for Class I, Novotroitske ranks as Class II, and both Bulakhivka and Pidhorodne fall under Class IV, reflecting undesirable quality. For indicators such as total iron, cadmium, sulfates, and chlorides, all sampled locations demonstrate Class I quality, indicating high compliance with environmental norms. Copper concentrations vary: the sample from Novotroitske falls within Class III, whereas the others are categorized as Class IV due to elevated levels. General water quality evaluation shows that Kocherezhky maintains Class I status; Pidhorodne is rated as Class III, and both Bulakhivka and Novotroitske remain within Class IV. As for zinc, water from Bulakhivka and Kocherezhky corresponds to Class I, while Novotroitske and Pidhorodne are grouped under Class II, denoting good quality. Regarding nitrites, Novotroitske alone meets Class II standards, while the other three locations conform to Class I, indicating excellent quality. A different pattern emerges when examining nitrate levels: Kocherezhky and Pidhorodne meet Class I criteria, Novotroitske falls into Class II, and Bulakhivka, showing the poorest result, is rated as Class IV. Finally, the content of ammonia and ammonium ions places Novotroitske in Class I, while all remaining water sources are classified under Class II. Among the surveyed wells and spring catchments, the highest water quality was observed in Kocherezhky village, while Bulakhivka exhibited the most unfavorable parameters. Notably, the limiting tors for water quality in Bulakhivka include deviations in pH, elevated permanganate oxidation, increased total alkalinity, and higher concentrations of copper, orthophosphates, and nitrates. In Novotroitske, the constraints are related to pH and orthophosphates; in Pidhorodne – to total alkalinity and copper; and in Kocherezhky – primarily to copper levels. The elevated concentrations of these components may carry potential health risks for local populations relying on these water sources for drinking purposes.

The obtained results indicate that several exceedances of nitrates, orthophosphates, and heavy metals can be linked to the consequences of hostilities in the region. Intensive shelling and explosions release nitrogen oxides, which are further transformed into nitrates in water bodies. Damage to sewage infrastructure and fuel storage facilities may explain the increased levels of phosphates and petroleum-derived compounds. The detection of elevated iron and zinc concentrations in some wells can be associated with corrosion of damaged pipelines and military debris. Such processes are consistent with earlier observations in conflict zones such as Syria (Faour & Fayad, 2014) and Kuwait (Buolayan et al., 1998), where war-related pollution significantly affected groundwater quality.

Exceedances of nitrates above the maximum permissible concentration (MPC) pose a particular risk for infants, as they may cause methemoglobinemia (“blue baby syndrome”) (DSanPiN 2.2.4-171-10, 2010). Elevated phosphates and increased permanganate oxidation values indicate a high content of organic matter, which may lead to bacterial growth and gastrointestinal disorders (Popovych et al., 2018). The increased hardness and alkalinity observed in some samples may contribute to chronic kidney stress (Tsyganenko-Dzyubenko et al., 2023). Overall, the combination of these factors reflects a deterioration of drinking water safety during wartime conditions.

4. Conclusions

This article provides an evaluation of contamination levels in selected drinking water sources within the Dnipropetrovsk region. It reveals that water quality is influenced by multiple factors, including the geographical location of the source, environmental conditions of the surrounding area, proximity to pollution sources, and the sanitary-technical state of the water supply infrastructure. Importantly, the ongoing full-scale war in Ukraine, now in its fourth year, has severely damaged numerous water management facilities, such as sewage and wastewater treatment plants. These disruptions may significantly compromise the quality of surface and underground water sources in affected areas.

The obtained laboratory data allow for comparing water quality across the examined sites. The control site in Kocherezhky demonstrated the highest quality, with almost all parameters below maximum permissible concentrations except for slightly low pH (6.00), which may affect taste and increase pipeline corrosion. The spring near Solonyi Lyman Lake in Novotroitske showed low mineralization and reduced organic matter but had excessive alkalinity (pH 9.07), high carbonates (42 mg/L), and elevated orthophosphates (0.71 mg/L), posing risks of eutrophication. The well in Pidhorodne was marked by high mineralization (1317 μS/cm), hydrocarbonates (414.8 mg/L), and sulfates (118.95 mg/L), which may increase hardness and alter taste, though no nitrates or organic contamination were found. The poorest quality was in Bulakhivka, where water was highly mineralized (2740 μS/cm), with high alkalinity (14.2 mmol/L), hydrocarbonates (866.2 mg/L), and nitrates exceeding the MPC by 4.2 times, creating serious health risks, especially for children.

In summary, the primary contributors to the deterioration of drinking water quality in the context of ongoing military operations include the destruction of treatment plants, industrial sites, and civilian infrastructure. These damages have led to the release of sewage and hazardous substances into the environment, causing unintentional contamination of water sources. Although such pollutants as heavy metals have not yet been detected in the samples taken, it should not be forgotten that their impact on water is delayed and may manifest itself later. These findings emphasize the urgent need for systematic monitoring of decentralized water sources in conflict-affected areas, both during active hostilities and in the post-war period.

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ANALYSIS OF THE CAUSES AND CONSEQUENCES OF ANTHROPOGENIC PRESSURE ON THE ENVIRONMENT OF PRODUCTION OF CONSTRUCTION PRODUCTS

Anatolii Marfutin[1], Oleg Nahursky[1]✉, Halyna Krylova[1], Oksana Orobchuk[1], Michał Charlak[2]

[1]Lviv Polytechnic National University,
12, S. Bandery Str., Lviv, 79013, Ukraine
[2]Politechnika Lubelska,
38, Nadbystrzycka Str., Lublin, 20-501, Poland
oleg.a.nahursky@lpnu.ua

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Abstract. The article is devoted to the study of the causes and consequences of the anthropogenic impact of the construction industry on the environment, with a special emphasis on the use of radon-containing materials in the production of construction products. The key factors that cause environmental pressure, such as raw material extraction, technological processes, insufficient waste disposal technologies, and weak regulatory control, are analyzed. Risks to human health, including exposure to radon, a radioactive gas emitted from natural building materials such as granite and basalt, are discussed. It is shown that radon inhalation is an important factor in the development of lung cancer and other diseases. The article also describes the impact of radon on the environment, including its accumulation in the atmosphere, soil, and water resources, which threatens ecosystems. The authors emphasize the importance of monitoring radon levels in building materials, improving ventilation systems, waste management, and monitoring radioactivity at all stages of production. The authors propose a number of measures to minimize the negative impact of the construction industry, including the introduction of environmental standards, the use of innovative technologies, the use of alternative materials, and raising awareness among consumers and producers. Prospects for further research aimed at creating effective technologies to reduce radon emissions, as well as improving waste disposal methods and assessing their impact on ecosystems are outlined.

Keywords: radon, building materials, environmental safety, anthropogenic impact.

1. Introduction

In recent years, the environmental impact of building material production has become a major concern due to the significant role the construction industry plays in environmental degradation. This sector is one of the largest consumers of both renewable and non-renewable natural resources (Spence et al., 1995; Curwell et al., 1998). It heavily depends on the natural environment to extract raw materials such as wood, sand, and aggregates for construction.

According to the Worldwatch Institute (Worldwatch Institute, 2003), the construction industry consumes 40 % of the world's raw stone, gravel, and sand, as well as 25 % of virgin timber annually. Additionally, it uses 40 % of the total energy and 16 % of global water supplies. Dust and emissions generated in the production, transportation, and onsite application of materials contain toxic substances, including nitrogen and sulfur oxides and radioactive gases. These pollutants pose serious threats to the natural environment (Spence et al., 1995; Ofori et al., 1998; Rohracher, 2001).

The extraction of natural resources alters the environment not only in terms of ecology and aesthetics but also leads to the accumulation of pollutants in the

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atmosphere (Curwell et al., 1998; Ofori et al., 1998; Bernard, 2002). According to Levin, H., construction activities account for 40 % of air emissions, 20 % of wastewater, and 13 % of other emissions. The growth of this sector involves the intensive use of raw materials that contain naturally occurring radionuclides, such as radon. Radon is a colorless, odorless radioactive gas that forms from the decay of uranium, thorium, and radium found in soil, rock, and building materials. Elevated environmental radon levels pose a health risk, increasing the likelihood of respiratory diseases and cancers. Since radon enters the body primarily through inhalation, it is critical to monitor its presence in building materials.

The generally recommended maximum indoor exposure limit for radon is 100 Bq/m³ (Shoeib et al., 2014). Natural construction materials and their derivatives contain three key radionuclides: uranium-238 (238U), thorium-232 (232Th), and potassium-40 (40K) (Oloruntobi et al.,2023). Because high concentrations of these radionuclides can lead to significant indoor radiation exposure, it is necessary to implement radon control measures for construction materials and consider other contributing sources (Abdallah et al., 2012). Ventilation plays a significant role in radon concentration levels–poor ventilation contributes to higher radon exhalation rates and elevated indoor levels. Special attention should be given to the radioactivity of brick components in building structures (Pro skhvalennia Natsionalnoi stratehii upravlinnia vidkhodamy v Ukraini; Malanca et al., 1993; Hewamann et al., 2001).

Overall, the radon content in construction materials is not consistently taken into account. As a result, recent literature has increasingly focused on environmental radon monitoring (Khan, 1991; Ahmed, 1994; Jonsson, 1995; ICRP 65; O'Rirdan, 1996). Bernard L. Cohen (Bernard, 2002) emphasized that the most significant environmental impact of construction is the radiation exposure to the public caused by radon in both residential and occupational settings.Research and analysis of building materials provide the necessary information to develop and implement effective strategies for monitoring and controlling radon levels. Further research into this issue is critical to ensuring the safety and health of our communities in the future.

2. Theoretical part

The construction products industry imposes substantial negative anthropogenic pressure on the environment, stemming from both objective and subjective factors related to technology and legislation. These factors include the nature of raw materials used, the production processes, insufficient waste disposal technologies, and the inadequate development of legal regulations.

The use of raw materials that naturally contain radon is a widespread practice in the building materials industry due to the presence of natural radionuclides in certain minerals. Materials like granite, basalt, clay-based substances, and specific sandstones frequently contain trace amounts of uranium, thorium, or radium that decay and release radon gas. These materials are chosen because of their desirable physical and mechanical characteristics–such as durability, strength, and thermal insulation–which make them suitable for construction. Many rocks with radon content, like granite, offer excellent strength and abrasion resistance, making them suitable for wall components, façade panels, paving tiles, and other structural applications. Moreover, some radon-containing materials offer superior thermal insulation, aiding energy efficiency–particularly valuable in colder climates. These raw materials are often abundantly available and less expensive to extract and process, especially when sourced locally, which also helps reduce transport costs and enhances overall cost-efficiency.

However, using natural materials with radioactive elements increases radiation exposure risks during extraction, transportation, and processing. Rocks like granite are notable contributors to contamination risks (see Tabl. 1).

Table 1

Main Sources of Radon in Building Materials

Material	Radionuclides	Potential Radon Level	Usage Frequency
Granite	238U, 232Th	High	High
Basalt	238U	Medium	Medium
Phosphogypsum	Natural & Artificial	High	Low
Coal ash	226Ra	Medium	Increasing

Additionally, the construction sector incorporates substantial amounts of industrial waste. Recently, there has been a growing trend of incorporating new materials with either naturally elevated or artificially increased levels of radioactivity–examples include phosphogypsum, coal ash, oil shale ash, and rare minerals (Azlina et al., 2023; Kovler et al., 2002; Hanfi et al., 2022; Lope, 2011; Maxwell, 2018; Ravisankar et al., 2014; Rostamani et al., 2021; Sabbarese et al., 2021; Shoeib et al., 2014). Consequently, most building materials contain some amount of naturally radioactive elements, mainly potassium-40 (^{40}K), as well as isotopes from the uranium (^{226}Ra) and thorium (^{232}Th) decay series. Fig. 1 visualizes radon content in various building materials.

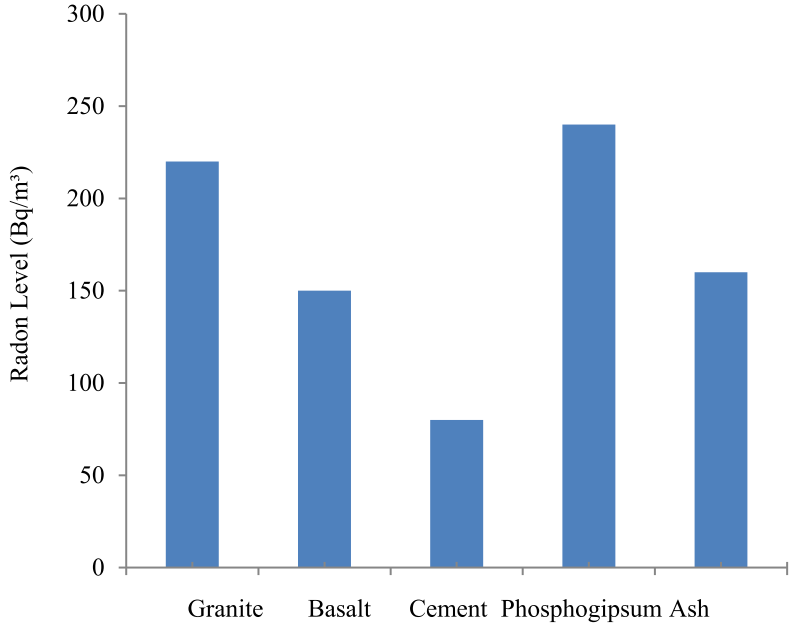

Fig.1. Radon Content in Various Materials (Bq/m³)

During the manufacturing of construction materials like concrete, bricks, and ceramics, radon may be emitted as the materials are processed or fired–causing localized air contamination both at production sites and in the general atmosphere. Radon release can begin at the raw material extraction phase, when resources such as stone, sand, clay, and industrial byproducts (e.g., ash, slag) are mined. These substances often contain uranium and thorium, the primary sources of radon. As these materials are mined and processed, radon gas is released. For instance, when granite or basalt–naturally rich in uranium–is crushed, more of its surface comes in contact with air, intensifying radon release. Additionally, crushing processes can generate dust particles infused with radon, which then become airborne. In enclosed processing environments, radon concentrations may become dangerously high, posing health risks to workers.

Subsequently, high-temperature processing stages such as drying or firing enhance radon emissions, particularly from materials like clay or cement. Heat accelerates radon release from uranium-bearing minerals. Even after products are manufactured, radon continues to emanate from materials such as concrete, ceramics, granite, marble, and other natural stones. Poorly ventilated storage areas may facilitate radon accumulation. Construction site storage and transportation of such materials can also contribute to elevated radon levels in the air.

During installation–whether of concrete blocks, tiles, or stone structures–radon release persists, especially in enclosed spaces like basements or poorly ventilated areas. Such spaces require vigilant monitoring, as radon accumulation presents serious risks for both workers and future occupants.

The absence of efficient technologies for recycling construction waste exacerbates environmental pollution, particularly where radon emissions are not managed.

Waste management in the construction materials industry is a pressing concern for both environmental protection and economic sustainability. If improperly handled, waste generated during the production of concrete, bricks, ceramics, and cement can pose significant environmental hazards. These wastes include dust, fragments, unused raw materials, slag, and ash–many of which may contain hazardous substances.

One key issue is the lack of effective recycling technologies. Although concrete waste can be processed into crushed stone, this requires specialized and often costly equipment. Furthermore, many types of construction waste are still not recycled due to technical and financial constraints, leading to reliance on landfilling–a practice detrimental to environmental conditions (Oloruntobi et al., 2023).

Toxic substances such as heavy metals, found in ash and slag, may leach into soil and water, further endangering ecosystems. Waste disposal processes must therefore be carefully regulated. Uncontrolled disposal poses a major threat to ecological integrity.

Compounding the problem is the low level of environmental awareness and weak governmental regulation regarding construction waste management. In many countries, including Ukraine, existing regulations for recycling building materials are insufficient, and construction companies often treat waste disposal as a low priority. This leads to uncontrolled waste accumulation or environmental discharge (Pro skhvalennia Natsionalnoi stratehii upravlinnia vidkhodamy v Ukraini).

Nonetheless, some positive developments are emerging. Certain companies are adopting innovative recycling techniques, thereby reducing environmental impact and lowering raw material costs. Using secondary raw materials–like recycled concrete or bricks–to produce new construction components is one promising approach. Ash and slag recycling for cement production or concrete aggregate use is also gaining traction.

Another major concern is the lack of strict environmental control over radioactivity levels in construction materials during production and sale. In Ukraine and several other countries, despite existing radiation safety legislation, enforcement is weak. As a result, materials with elevated radioactivity–like those containing natural uranium–may enter the market unchecked, increasing health risks for building occupants.

Inadequate inspection across the supply chain–from raw material extraction to processing and transport–means that radon-emitting materials can end up in residential construction without appropriate safety assessments. During crushing or firing of raw materials, radon emissions are difficult to track, making it essential to implement emissions control measures at all stages of production.

Another critical issue is the public's limited awareness of the risks associated with radon-containing construction materials. Most customers are unaware of potential radiation hazards and rarely demand certification or information on radioactivity levels. This ignorance allows unsafe materials to be used in residential projects, putting residents' health at risk.

The absence of standardized testing procedures for radioactive contamination in building products further compounds the problem. Manufacturers may exploit regulatory loopholes, often driven by economic motivations, as radioactive materials are usually cheaper. This financial incentive can lead to neglect of radiation safety protocols.

Lastly, the low level of environmental consciousness among both producers and consumers significantly contributes to the issue. If radon-emitting materials continue to be used irresponsibly, long-term health consequences may arise. The lack of widespread education and public outreach on radon-related risks worsens the situation.

3. Results and Discussion

The utilization of raw materials that contain radon in the production of building products poses significant threats to both human health and the environment. The primary health concern arises from radon inhalation. When radioactive radon particles are inhaled, they can settle in the lungs and undergo radioactive decay, releasing alpha particles that cause cellular damage (Tabl. 2).

Table 2

Health Effects of Radon Exposure

Exposure Type	Health Effect	WHO Estimated Risk (%)
Inhalation	Lung Cancer	3–14 %
Water Ingestion	Gastrointestinal Cancer	~1–2 %
Chronic Exposure	Immune Disorders	Insufficient Data

Such cellular damage may trigger mutations, ultimately increasing the risk of developing lung cancer. Radon ranks just after tobacco smoking as the second leading cause of lung cancer, and studies suggest that even non-smokers face a significantly heightened risk from radon exposure. According to the World Health Organization (WHO), radon is responsible for 3–14 % of global lung cancer cases. Long-term exposure to elevated radon levels is also associated with other severe conditions, including cardiovascular diseases, hematologic disorders, and immune system impairments. Fig. 2 illustrates how lung cancer risk correlates with radon exposure levels.

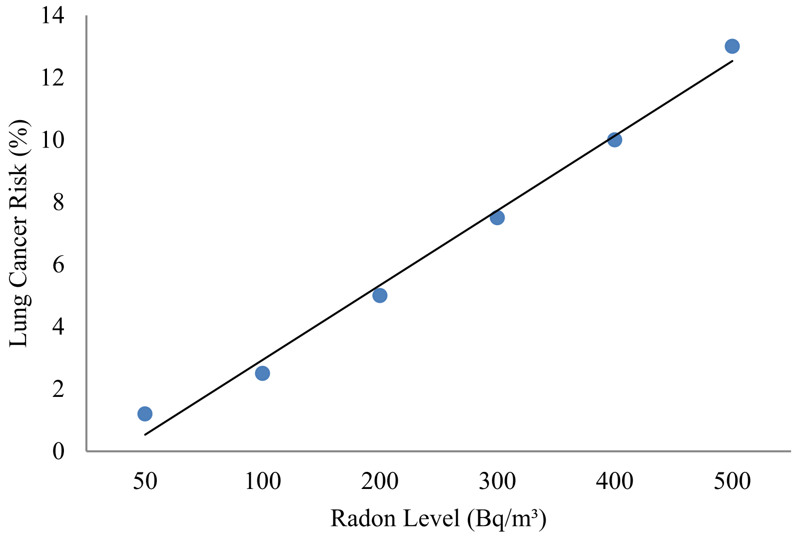

Fig.2. Lung Cancer Risk vs. Radon Exposure

Radon also presents serious environmental hazards. It can seep into the atmosphere as a gas and contaminate groundwater sources. If radon enters water supplies used for drinking, it can cause additional internal exposure upon i ngestion. Furthermore, radon released into the air contributes to atmospheric pollution, particularly near mining sites where uranium- or thorium-bearing materials are extracted. In construction, the use of radon-emitting materials can lead to indoor radon accumulation, particularly in areas with inadequate ventilation like basements, underground garages, or older structures with poor air circulation.

This can lead to concentrations that exceed safe thresholds.A particular danger is that radon can accumulate in interior spaces where preventive measures are insufficient, such as buildings with wall or floor cracks that allow gas to penetrate. Construction materials–such as stone, brick, concrete, or granite–may emit radon if they contain uranium or thorium and have not undergone appropriate radioactive testing. Consequently, structures built with such materials and lacking proper ventilation can accumulate dangerous levels of radon. Fig. 3 shows the proportionate contribution of various sources to indoor radon levels.

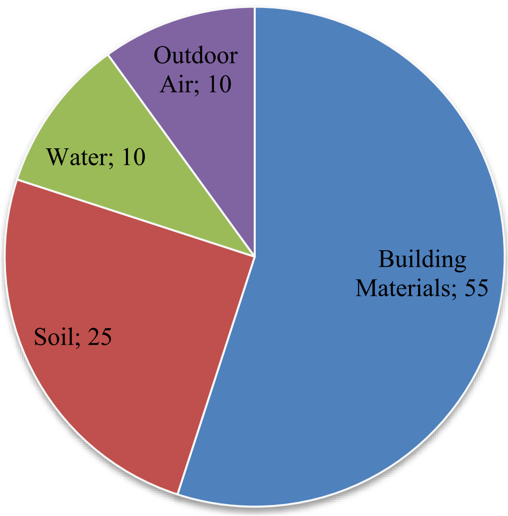

Fig.3. Contribution of Different Sources to Indoor Radon, %

Another important aspect is the economic impact of using radon-containing materials in construction. An additional concern is the economic impact of using radon-containing materials. Buildings with high indoor radon levels may necessitate expensive diagnostic evaluations and the installation of enhanced ventilation systems or radon mitigation infrastructure. The market value of such properties may decline due to health risks and associated remediation costs. Developers and construction firms may also face higher expenses when sourcing certified low-radiation materials, thereby inflating the total construction budget.

To mitigate the risks linked to radon-containing materials, several measures are essential. Firstly, consistent monitoring of radioactive elements like uranium and thorium in construction materials must be implemented. This will help restrict radon-laden materials from entering the market and ensure consumer safety. Technologies that minimize radon emissions or prevent its infiltration into indoor environments also play a critical role in reducing exposure. Furthermore, routine indoor radon level assessments are necessary to detect and address elevated concentrations in a timely manner.

Enhancing ventilation systems in buildings is another crucial strategy for reducing indoor radon levels. Properly designed systems can effectively disperse and remove accumulated radon, ensuring occupant safety.

Radon also has considerable environmental consequences. When radon and its decay products enter ecosystems, they can disrupt ecological balance. Radon initially disperses into the atmosphere but its radioactive progeny–including polonium-218, lead-214, and bismuth-214–can settle onto soil and plant surfaces. These particles can be absorbed by vegetation and further integrated into the food chain. In areas of intense accumulation, radon may infiltrate built environments and spread through waste and evaporation.

These radioactive byproducts can adversely affect living organisms by accumulating in soil or water systems. Polonium and other heavy metals may settle in the topsoil or contaminate aquatic environments, subsequently entering food chains. Over time, they accumulate in plant tissues, interfere with biological functions like photosynthesis and respiration, and reduce overall plant vitality. Symptoms of radon-induced stress in plants include reduced leaf size, stunted growth, and diminished crop yields. Moreover, toxic effects on root systems may hinder nutrient uptake, resulting in soil degradation and compromised agricultural productivity.

Animals residing in radon-rich zones or consuming contaminated vegetation also face health risks. Ingested or inhaled radioactive particles may collect in body tissues, leading to mutations, immune suppression, reproductive issues, and respiratory illnesses. In aquatic environments, rainwater or soil leaching can introduce radioactive elements into water bodies, where they may settle in sediments and aquatic organisms. This bioaccumulation disrupts aquatic food webs and can lead to species decline or extinction.

Humans, being at the top of the food chain, are ultimately exposed to these radioactive contaminants through consumption of affected produce, meat, and fish. Long-term ingestion increases the probability of cancer and other radiation-induced conditions. Water supplies contaminated with radon further amplify health risks. The accumulation of radon and its progeny within ecosystems heightens environmental radioactive contamination, intensifying adverse health outcomes over time. Prolonged exposure exacerbates these effects across all biological systems.

The use of radon-laden raw materials in the building sector also carries broader socioeconomic consequences. Radon is among the most dangerous radioactive elements and its implications span human health and economic domains. Prolonged use of such materials influences public health, healthcare expenditures, property markets, and construction industry practices (Tabl. 3).

Table 3

Socio-Economic Impact of Radon-Containing Materials

Category	Example of Impact
Economy	Real estate devaluation, ventilation costs
Health	Increased cancer cases, medical expenses
Environment	Soil, air and water pollution

To begin with, the presence of radon-containing materials in buildings can pose significant health risks to individuals residing in such structures. As a recognized carcinogen, prolonged exposure to radon through inhalation is linked to lung cancer and various other severe respiratory and systemic illnesses. A rise in the number of individuals suffering from cancers and chronic diseases associated with radiation exposure results in increased pressure on healthcare systems. Governments must allocate substantial funds not only for the direct treatment and rehabilitation of those affected but also for ongoing research and programs dedicated to monitoring radiation levels within inhabited buildings. Moreover, when radiation contamination is identified only after construction has been completed and the building is occupied, it may generate public concern and social unrest.

A notable socioeconomic repercussion involves the devaluation of real estate. When high levels of radon are discovered–whether during pre-sale inspections or post-occupancy evaluations–the market value of affected properties may drop considerably. Prospective buyers, worried about health risks, may avoid purchasing such homes or buildings. This reduction in demand depresses property prices and results in financial losses for owners. Furthermore, remedial actions necessitated by radon contamination–such as renovations, structural alterations, or even partial demolitions–can lead to significant unanticipated costs for property developers or owners seeking to reduce radon concentrations.

For companies involved in construction, sourcing and utilizing radon-emitting raw materials can drive up production expenses. These companies might be compelled to adopt new technologies aimed at lowering radon emissions, improve manufacturing processes, or secure additional material testing and certification. There may also be a need to invest in environmentally sound materials and modernize facilities to comply with safety standards. For small- and medium-sized enterprises, these requirements may prove financially burdensome, potentially reducing their ability to compete effectively within the industry.

On a broader scale, the economic implications tied to radon use in construction also touch upon labor and employment sectors. Elevated spending on healthcare services and environmental remediation could force both governmental bodies and private entities to reallocate budgets originally intended for other public priorities. This redirection of resources might cause reductions in funding for sectors like education, transportation, or urban development, thereby negatively affecting general societal well-being.

Nevertheless, there may also be beneficial outcomes associated with the identification of radon-related issues. Addressing these problems can promote the advancement of innovative, safe, and environmentally sustainable technologies in the construction field. Businesses might shift toward implementing novel production processes and opt for alternative, eco-friendly materials that meet stringent environmental standards. This evolution could spark the development of the green building sector, encourage job creation, and lead to cost savings in the long term by preventing environmental degradation and protecting public health.

Ultimately, government interventions–such as imposing restrictions on radon-rich materials, launching public education campaigns, and strengthening regulatory oversight–could significantly reshape the market for construction materials. As public awareness of environmental safety grows, so does the demand for safer, non-toxic materials. This trend could stimulate the expansion of environmentally responsible industries, including eco-construction, contributing positively to long-term socio-economic growth.

In conclusion, the socioeconomic consequences of using radon-bearing raw materials in construction are broad and multidimensional. They encompass increased healthcare and remediation expenditures but also pave the way for progress in technological development and ecological stewardship. Addressing these challenges demands a co ordinated effort involving public authorities, industry stakeholders, and civil society to effectively reduce risks and optimize the potential benefits of adopting safer construction practices.

4. Conclusions

Following the comprehensive examination of the origins and consequences of the anthropogenic environmental impact resulting from the production of construction materials–particularly those involving radon-containing raw inputs–it is possible to outline key strategies for mitigating these adverse effects. One fundamental measure involves rigorous control over the selection of raw materials, prioritizing those with minimal concentrations of radioactive elements. This approach would significantly lower the initial levels of radon present in construction products. Additionally, maintaining adequate ventilation throughout all phases of production, storage, and application is critical to preventing radon accumulation in the ambient air. Systematic radon level monitoring must also be implemented to enable early detection of elevated concentrations and ensure timely remedial actions. Furthermore, effective management of construction waste containing radon is essential to preventing environmental emissions, thereby supporting overall ecological safety.

To address the current deficiency in environmental oversight surrounding the production and use of radon-bearing construction materials, it is necessary to enforce more stringent environmental standards at every stage–from raw material processing to final sale. This entails regular inspections, mandatory certification of materials, and the systematic assessment of their radiological properties. Increasing transparency by providing consumers with accessible information regarding material safety is equally vital. Public education campaigns should be implemented to raise awareness about the potential health hazards associated with radon exposure and to emphasize the importance of selecting safe materials for building projects. Moreover, the advancement of technologies for efficient processing and disposal of radon-laden waste is imperative to reduce the release of harmful substances during both production and construction activities.

Reducing the environmental footprint of the construction sector–especially where radon-containing materials are involved–requires a multifaceted approach. This includes the enhancement of technological processes, the tightening of compliance with environmental standards, and increased investment in research related to safe alternatives. A holistic, integrated strategy is essential to safeguard both environmental integrity and public health against the detrimental effects of radon exposure.

Prospects for Further Research

Future efforts should focus on the development of more efficient and economically viable technologies for the production and processing of construction materials that emit minimal amounts of radon. Additionally, further investigation into the ecological impact of radon contamination is required, along with the establishment of standardized regulations to ensure the safe incorporation of such materials in construction activities.

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PROBLEM ASPECTS OF HAZARDOUS WASTE MANAGEMENT IN A TECHNOLOGICALLY LOADED REGION

Anna Titova[1]✉, Olena Kharlamova[1], Volodymyr Shmandiy[1], Lilija Bezdeneznych[1], Tetyana Rigas, Wojciech Lutek[2]

[1] Kremenchuk Mykhailo Ostrohradsky National University,
20, University Str., Kremenchuk, 39600, Ukraine
[2]Maria Curie Sklodowska University,
5, Maria Curie-Sklodowska Sq., Lublin, 20-031, Poland
office@kdu.edu.ua

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Abstract. We have assessed the environmental risks caused by the lack of hazardous waste treatment facilities in the industrial region. We have identified such environmental threats as the release of hazardous waste into the environment, uncontrolled flows of hazardous waste that may end up in municipal landfills as household or other hazardous waste. A critical analysis of the existing modern infrastructure in Ukraine, on the basis of which hazardous waste management is carried out, was conducted. The problem of generation and disposal of hazardous waste in the Poltava region was analyzed. A list of the most common hazardous wastes, which are generated in almost all areas of activity and require disposal, was determined. Measures are proposed to reduce the anthropogenic load on the environment by improving the existing waste management system in one of the industrial centers of the region.

Keywords: hazardous waste, management, waste disposer, environmental safety, anthropogenic impact.

1. Introduction

On July 9, 2023, the Law of Ukraine «On Waste Management» (Pro upravlinnja vidchodamy, 2022) came into force, launching a waste management reform aimed at aligning national legislation with that of the European Union. Reforming the waste management sector involves long-term changes to Ukrainian legislation, a revision of approaches based on best available techniques, and the development of infrastructure in this area. The law introduces a n ew permitting system, accounting and monitoring mechanisms, electronic reporting through the Waste Management Information System available on the Ministry of Environmental Protection and Natural Resources of Ukraine's online platform «EcoSystem», and multi-level planning.

Currently, regulatory acts have already been approved regarding the procedure for developing regional, local, and enterprise-level waste management plans. Regional plans are intended to identify waste disposal sites that can continue to be used and those that require reclamation, as well as to determine how many and what types of waste treatment facilities need to be constructed. Local plans include a set of interrelated tasks and measures, coordinated in terms of timing and resource provision with all relevant stakeholders, aimed at ensuring sustainable waste management in settlements within the territorial community. These plans are based on the principles of intermunicipal cooperation and are developed according to an assessment of the current state of the waste management system and previously established models. Enterprise, institution, and organization-level plans provide information on the current

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status of the waste management system at the enterprise, planning for system improvements, and monitoring of plan implementtation.

Regulatory acts (Pro zatverdzennja licenzijnych umov…, 2023; Pro zatverdzennja porjadku vydaci…, 2023; Rejestr ocinky vplyvu na dovkillja, 2024) have introduced procedures for obtaining permits for waste treatment, licensing conditions for hazardous waste management, and a s tandard waste accounting form via the «EcoSystem» platform. Although the services of the information system are not yet fully operational, permits such as licenses and waste treatment authorizations can already be obtainned through the «EcoSystem» platform. Additionally, registries of issued licenses and permits, the Environmental Impact Assessment (EIA) registry, and the service for issuing documents for transboundary waste shipments are accessible and functioning.

We have analyzed the implementation of the waste management reform in Poltava region using the example of the city of Kremenchuk. The analysis identified the lack of infrastructure as a major obstacle to the reform process, along with challenges related to the management of specific waste types. Possible solutions to these issues have been proposed.

2. Experimental part

2.1. Analysis of industrial infrastructure in the region

The city of Kremenchuk is considered the main industrial center of the Poltava region, playing a key role in the economic development of both the region and the country as a whole. The city concentrates major enterprises across various industrial sectors, with more than 86 i ndustrial enterprises, 58 construction organizations of various forms of ownership, and over 16,000 business entities operating there (Vykonavcyj komitet, 2020).

Kremenchuk's industrial sector encompasses nearly all major branches of production, forming the foundation of the region's economic stability:

– Oil refining and petrochemical industry – one of the most significant sectors, responsible for oil processsing and the production of a w ide range of petrochemical products. Key enterprises include PJSC "Ukrtatnafta" and PJSC "Kremenchuk Carbon Black Plant".

– Mechanical engineering and metalworking – represented by the production of large-scale machinery, railcars, wheels, and road equipment. Major enterprises include PJSC "AvtoKrAZ", PJSC "Kremenchuk Wheel Plant", PJSC "Kryukiv Railway Car Building Plant", PJSC "Kremenchuk Foundry", and PJSC "Kremenchuk Road Machinery Plant".

– Food industry – a sector that supplies the population with high-quality dairy, meat, bakery, and confectionery products. It is represented by PJSC "Kremenchuk City Dairy Plan"t, PJSC "Kremenchuk Meat", SE "Kremenchuk Grain Products Plant", PJSC "Kremenchuk Confectionery Factory "Roshen", LLC "Kremenchuk Bread Plant", PE "Lukas», PE "Ilona", LLC "Marketopt", PE "Suvorov", among others.

– Light industry – includes enterprises producing textile goods and leather products such as PJSC "Kremenchuk Production and Trade Company "Kremtex", the Cost-Accounting Production Company "Ruta", and LLC "Kremenchuk Leather Plant".

– Construction industry – provides the production of reinforced concrete structures and other building materials essential for the infrastructural development of the city and the region, and is represented by the Reinforced Concrete Structures and Products Plant and the Quarry Management Enterprise.

Thanks to its unique combination of industrial traditions and an innovative approach, Kremenchuk remains one of the most important manufacturing centers in Ukraine. A powerful industrial base provides not only domestic needs, but also actively supplies products to the international market. The strategic location of the city and developed infrastructure make Kremenchuk attractive for investors and guarantee its further development as a powerful industrial center.

At the same time, the city's industry is a source of environmental pollution in the Kremenchuk region and contributes to the formation of environmental hazards (Shmandiy et al., 2024). The high level of concentration of industrial facilities causes the accumulation of a significant amount of household and industrial waste in the city of Kremenchuk, which is an important environmental problem. The largest amount of waste in the Poltava region is generated in the city of Kremenchuk.

It is likely that a significant portion of hazardous waste ends up in containers with household waste or in unauthorized landfills, which creates additional risks to the environment and human health. This assumption is due to the lack of a developed infrastructure in the region for the treatment of hazardous waste. Although treatment facilities are available and operational in certain regions, these capacities are not sufficient to process the waste generated throughout the country.

2.2. Current status of hazardous waste management in Kremenchuk

We conducted an analysis of existing technologies for hazardous waste management in Ukraine that could be applied in the city of Kremenchuk. The study was based on an analysis of the regulatory framework, namely, the study of domestic legislation and familiarization with international agreements ratified by Ukraine (Pro pryjednannja Ukrainy do B-azelskoi konvencii…, 1999). Changes in legislation, trends in legal regulation and its impact on the waste disposal sector are analyzed.

In accordance with the National Waste Management Strategy in Ukraine until 2030, the development of the Regional Waste Management Plan in Poltava Oblast until 2033 is underway. For the purpose of public awareness, the draft document was posted on the official website of the Poltava Oblast (Departament ekolohii ta pryrodnych resursiv…, 2024).

In 2024, regional public hearings were held on the draft regional plan, where important proposals from local government representatives were considered. But, in our opinion, in order to cover the global problems of the region, it w as necessary to involve not only representatives of local government, but also representatives of polluting enterprises and waste processing enterprises in public hearings, who were to voice all pressing problems in the field of waste management.

According to the register of the Ministry of Environment of Ukraine, 34 business entities have licenses in the field of hazardous waste management, of which only a few entities process a wide range of waste. The vast majority of enterprises process only a few types of waste (Rejestr ocinky vplyvu na dovkillja, 2025). In Poltava region, there is only one enterprise that manages waste exclusively in the form of oil/water and hydrocarbon/water mixtures and emulsions.

That is, we can conclude that a number of wastes, such as oil filters, oily waste sand and rags, lead batteries, contaminated containers, roofing felt, slate, sleepers, spent absorbents, etc. are not processed in the Poltava region. This indicates that waste generated in the process of economic activity is either stored at enterprises or transferred to other regions. We believe that for a large industrial region, the lack of waste treatment infrastructure poses an environmental threat, has a negative impact on the surrounding environment, and poses a potential threat to the health and life of the population, i.e., creates an ecological hazard. The partial lack of environmental control during wartime only exacerbates this threat.

We conducted an analysis of the activities of licensed enterprises engaged in the disposal of hazardous waste. Having analyzed the register of business entities in the field of waste management, we came to the conclusion that currently only a few enterprises located in the Odessa region manage the largest amount and range of hazardous waste in Ukraine. The considerable distance to the waste management facility is a significant obstacle to the effective organization of hazardous waste disposal. In addition, the capacity of waste processing enterprises may not be sufficient to meet the needs for the disposal of the vast amount of hazardous waste generated in Ukraine. Given this, we believe that there are problems in the field of hazardous waste management that require significant attention from the community, scientists, government representatives, and investors.

Based on data from open sources, including the registers of the Ministry of Environment of Ukraine, the draft Regional Waste Management Plan in Poltava region until 2033, and the Ecological Passport of the city of Kremenchuk, we have formed a list of waste that is subject to processing and is the most common type of waste generated in the vast majority of both large and small industrial enterprises, institutions, and organizations (Tabl. 1). The optimal list of waste is usually formed based on several criteria and standards. First of all, waste is classified according to the sources of waste generation, then it is classified according to physical state (solid, liquid, gaseous) and chemical composition (presence of organic and inorganic substances, toxicity, presence of heavy metals, etc.), the hazardous properties of waste are assessed by establishing the presence of hazardous chemicals or persistent organic pollutants.

Nomenclature of hazardous waste generated at the vast majority of enterprises

№	Waste group	Departure code	Availability of hazardous waste disposal facilities		Processing operation
			in the Poltava region	in Ukraine	
1	Waste mineral oils	13 01 09* 13 01 10* 13 01 11* 13 01 12* 13 02 04* 13 02 05* 13 02 06* 13 02 07* 13 02 08*	missing	available	R7, R9, R12, R13, D10, D13, D15
2	Waste from industrial off-gas treatment plants	10 02 07* 10 02 13* 10 03 19* 10 05 06*	missing	available	D10, D13, D15
3	Fly ash from coal-fired power plants	10 01 14*	missing	available	D10, D13, D15
4	Unsorted waste batteries	20 01 33*	missing	available	D9, D10, D13, D15
5	Waste oils/water, hydrocarbons/water in the form of mixtures and emulsions	06 05 02* 07 04 11* 12 01 06* 12 01 07* 12 01 10* 16 01 07* 16 12 23*	available	available	D9, D10, D13, D15, R9
6	Clinical and related waste	16 12 46* 18 01 10* 20 01 31*	missing	available	D10, D13, D15
7	Waste from the production, manufacture and use of artificial resins, latexes, plasticizers, adhesives/binding materials	08 01 13* 08 01 15* 08 01 17* 08 01 21* 17 08 01* 20 01 27* 08 03 12* 08 03 17* 08 04 09*	missing	available	D10, D13, D15
8	Asbestos waste (dust and fibers)	16 12 30* 17 06 05* 16 12 27* 17 06 01*	missing	available	D10, D13, D15
9	Bituminous materials	17 05 05* 17 05 07* 19 13 01*	missing	available	D10, D13, D15

The collected data indicate that there is currently an insufficient number of hazardous waste treatment facilities in the Poltava region.

The main operations for hazardous waste treatment in Ukraine include:

– D9 Physico-chemical treatment not specified elsewhere in this Annex, resulting in the formation of final compounds or mixtures which are removed by carrying out operations specified in items D1-D12 of this Annex, including evaporation, drying, calcination, etc.;

– D10 Incineration on land;

– D13 Preliminary waste treatment operations prior to disposal, including sorting, crushing, compaction, granulation, drying, shredding, conditioning, or separation;

– D15 Storage.

– Operations related to the recovery of mineral oils and oil/water mixtures may be carried out under the following recovery codes:

– R7 Recovery of components used to reduce pollution;

– R9 Oil refining or other reuse of oil products;

– R12 Preliminary operations on waste for the operations specified in items R1-R11, preliminary operations prior to recovery, including pre-treatment, including dismantling, sorting, crushing, compacting, granulating, drying, grinding, conditioning, repackaging, separating, mixing or blending prior to submission to any of the operations specified in items R1-R11;

– R13 Storage of waste prior to the operations specified in items R1-R12 (except collection operations).

2.3. Current status of non-hazardous waste management

Based on the results of the analysis of the regulatory framework, publications in scientific journals, conference materials, and interviews with specialists in the field of ecology and waste management, we found that the situation with regard to mixed household waste and non-hazardous waste is not critical. According to the register of the Ministry of Environment of Ukraine, some enterprises in the Poltava region already have permits for waste processing. After monitoring state environmental programs, we found out that measures have been developed aimed at improving existing landfills, rehabilitating unauthorized landfills, and introducing a cluster approach to waste management, which is one of the key elements of regional waste management policy. The draft Regional Waste Management Plan for Poltava Oblast until 2033 explores 3 main scenarios for the formation of optimal coverage zones (clusters) for household waste management:

Scenario 1. Division of Poltava region into 4 clusters taking into account the administrative division of Poltava region.

Scenario 2. Division of Poltava region into 5 clusters.

Scenario 3. Division of Poltava region into 6 clusters.

Based on cost assessment, comparison of alternatives, and expert recommendations, Scenario 3 was selected as the basis for development. This scenario envisions the establishment of six regional landfills in the Poltava region, based on existing landfills and dumpsites, as well as allocated land plots (in the cities of Kremenchuk and Poltava, and in the Hlobynska, Bilytska, Petrivsko-Romenska, and Pyriatynska territorial communities), along with four waste processing facilities located in the villages of Bilyky, Dmytrivka, and Tereshky, and the city of Lubny.

In Kremenchuk, the regional landfill is planned to be established on the site of the currently operating municipal landfill, which, in our view, poses environmental hazards. The landfill covers an area of approximately 28 hectares and has been in operation for over 50 years. There is no anti-filtration protection or other essential engineering safety structures in place; however, there is potential for its reconstruction and continued operation.

Although none of the existing landfills in the region currently meet environmental standards, a strategic direction for their development has already been defined. Key issues have been identified, and solutions for urgent problems in the municipal waste management sector are being developed.

We consider it appropriate to establish a sorting line or station at all r egional landfills in the Poltava region. Additionally, we propose the organization of facilities for processing bulky and renovation waste, as well as green waste treatment. The materials resulting from the shredding of plant waste will be temporarily stored in specially equipped areas until further use – either for covering waste layers within the landfill or for utilization beyond the site.

Packaging waste management (paper and cardboard packaging, glass packaging (glass bottles), ferrous metals, PET bottles, other types of plastics, wooden packaging, aluminum cans) is the most developed area in the region. There are a certain number of business entities that collect safe secondary raw material waste in the Poltava region. These are private enterprises and individual entrepreneurs (IEPs) that have a permit to process waste, as evidenced by data from the register of the Ministry of Environment of Ukraine. The system of separate collection of resource-valuable waste in the city of Kremenchuk has been implemented and is functioning.

Therefore, it can be stated that the management of mixed household waste and packaging waste in the region is carried out properly, and the prospects for the development of this industry are clearly monitored, as indicated in the draft Regional Plan.

However, through the analysis of the activities of specialized enterprises, we found out that the ways of managing hazardous waste in the Poltava region have not been defined, and the infrastructure is missing. This creates a threat of accumulation of this waste in the places of its generation. The lack of hazardous waste treatment infrastructure in the region can result in waste being released into the environment or into landfills for non-hazardous waste as part of household waste.

3. Results and Discussion

In order to obtain comprehensive information about the current state of hazardous waste disposal technologies in Ukraine and their development prospects, we analyzed data from Environmental Impact Assessment (EIA) reports available on the official website of the Ministry of Environmental Protection and Natural Resources of Ukraine. We also examined the domestic market of proposed waste management technologies by reviewing relevant online sources, scientific journal articles, and conference proceedings.

Our analysis revealed that the companies handling the largest volumes and widest range of hazardous waste–such as UTILVTORPROM LLC (Teplodar) and UKREKOPROM LLC (Odesa) – primarily utilize thermal waste treatment units (Rejestr licenzij na zdijsnennja hospodarskoi dijalnosti..., 2025). In particular, both companies use the UT-3000D thermal incinerator, which is designed for the incineration of both solid and liquid hazardous waste (Fig. 1).

This incinerator ensures environmentally safe waste destruction through high-temperature combustion. Its capacity allows for the disposal of up to 500 kg of waste per hour, or approximately 3650 tons of waste annually. The unit's design includes the following technological components:

- primary combustion chamber (main body of the incinerator);
- secondary combustion chamber (afterburner);
- waste loading hatch;
- ash removal hatch;
- air supply system (forced-draft fan);
- burners for both the primary and secondary chambers;
- control panel.

Fig.1. Thermal waste disposer UT3000D

To prevent the formation of harmful chemical compounds such as dioxins and furans, the technological process involves rapid cooling of flue gases before they are fed into the purification system. To do this, the flue gases are mixed with the required amount of air, cooled and directed to a scrubber in a special installation. The scrubber performs a dual function, namely: it neutralizes chemical compounds formed during combustion and provides mechanical cleaning of the flue gases before they are released into the atmosphere.

In general, the flue gas cleaning system in the UT3000D may include a combination of high-temperature post-combustion, catalytic cleaning, chemical neutralization, cooling, and filtration, which ensures compliance with environmental standards and reduces emissions of harmful substances into the atmosphere.

As a result of waste incineration, ash is formed, which accumulates in special containers. After filling, their contents are taken to a landfill for further safe disposal. It is worth noting that the thermal energy released during incineration has no practical use in this technological process. The main emphasis is on environmental safety and the efficiency of emission treatment, which allows reducing the level of environmental pollution.

Thus, thanks to the use of a thermal recycler, the following waste processing operations are carried out: D15, D13, D10 (Pro upravlinnja vidchodamy, 2022).

To destroy organic waste, UKREKOPROM LLC uses a t hermal waste disposer of the UT750D type, Fig. 2.

Fig.2. Incineration plant type UT750D

The thermal incinerator provides environmentally safe incineration of waste of various origins and composition. It is capable of neutralizing animal, biological, medical, food, household, veterinary and other types of waste, and uses a similar incineration technology to the UT3000D incinerator. The combustion rate is 200-250 kg/h, which ensures the utilization of more than 4 thousand tons of waste per year. The temperature regime in the combustion chamber is maintained at 1 200°C, and in the after-burning chamber at the same temperature the oxidetion process is completed. To reduce the harmful impact on the environment, the units are equipped with droplet traps that ensure effective cleaning of flue gases. Each unit has its own gas cleaning system. The capacity of the UT750D unit is usually designed for smaller waste volumes (compared to the UT3000D), but the principles of gas purification are similar. This means that although the purification stages may be similar, the UT750D may have less complex filtration systems or a smaller number of purification process stages. Also, in each specific case, additional or alternative cleaning methods may be used depending on the specifics of the waste being disposed of.

Given the current trend to minimize emissions of pollutants into the atmosphere, the incineration of hazardous waste in high-temperature furnaces is gradually being replaced by more environmentally friendly methods, such as plasma gasification, chemical neutralization, biological decomposition and stabilization. The most promising technologies are plasma decontamination and biological treatment, as they minimize the formation of secondary toxic substances. We consider it relevant and appropriate that some scientists, in particular (Vashchenko et al., 2023), are exploring the prospects for implementing plasma technologies for the processing of hazardous waste. The possibilities of using plasma technology for the disposal of hazardous medical waste are being considered, and plasma technologies for the disposal of industrial and household waste are being investigated. The scientific group of the E.O. Paton Institute of Materials Science and Welding is developing plasma technologies for the disposal and gasification of various types of waste, which may include hazardous components. However, it should be noted that plasma gasification is a relatively new and high-cost technology and requires further research and improvement for large-scale implementation (Matveev & Heletukha, 2019).

Considering the above, we believe that today it is advisable to use thermal waste treatment. The use of this technology can satisfy the waste disposal needs of the entire region. We considered the prospect of installing 2 disposers of the type UTZ000D for hazardous waste and UT750D for animal waste on the territory of one of the operating landfills in Kremenchuk. Although plasma technology provides almost complete destruction of waste, this technology has not yet been widely implemented due to the need for long-term testing and development of mechanisms for safe use. In many countries, waste incineration in

UT plants is a common and regulated method, while the implementation of plasma technology requires additional research and adaptation of the regulatory framework. In addition, plasma technology requires high energy costs, which complicates its economic efficiency. Currently, traditional UT installations are more feasible due to the economic and technical limitations of plasma technology. However, in the long term, plasma processing may become more profitable, especially if technological breakthroughs in energy efficiency occur or equipment costs decrease.

We (Titova et al., 2024) investigated the set of negative factors in the area of waste disposal sites using the example of the Kremenchuk municipal landfill for household waste, which has been in operation since 1965. In particular, the landfill contains a livestock burial ground, which is intended for the disposal of biological waste. It is currently almost completely filled (Ecological passport, 2020). The territory of the municipal landfill for household waste borders two industrial waste landfills (on the north side – LLC "Eco-Force" and on the south side - PJSC "Kremenchuk Steel Plant"). The municipal cemetery is located in the direction of the groundwater flow, Fig. 3.

Fig.3. Location of the Kremenchuk municipal municipal waste landfill. 1– landfill sludge storage LISh, 2– livestock burial ground, 3– hazardous waste landfill, 4– city cemetery, 5– quarry, 6– residential development

According to the results of environmental monitoring in the area where the above-mentioned facilities are located, periodic groundwater contamination was detected, but the concentrations of pollutants decreased significantly as the distance from the facilities increased. Due to the necessity of maintaining existing waste disposal sites and the lack of alternatives for establishing new landfills or hazardous waste management facilities, we believe that currently operating facilities are suitable for continued use, provided that certain environmental protection measures are implemented. These measures include the installation of an anti-filtration barrier and protective structures, conservation of the animal burial site, and planting of greenery, among others.

According to research on actual air pollution levels at the Kremenchuk landfill and within its sanitary protection zone, the concentrations of pollutants do not exceed permissible levels. To improve the hazardous waste management system, we consider it promising to construct a hazardous waste treatment facility on the territory of the existing hazardous waste landfill.

Based on the environmental impact assessment of UT-3000DP and UT-750D incineration units (Zvit, 2025), it was found that the actual concentrations of pollutants in the ground-level atmosphere are below the maximum permissible concentrations, indicating that no excessive negative impact on environmental components is expected from such operations.

It can be assumed that installing the above-mentioned waste incineration units at the studied landfill will have minimal environmental impact, and will reduce the risk of soil and water contamination. However, this assumption requires further analysis, as in practice the equipment may operate under conditions deviating from design specifications, and other toxic substances (e.g., dioxins, furans, heavy metals) may be generated during incineration that are not always accounted for in project calculations. Moreover, the cumulative effect of such pollutants needs careful study.

To draw a precise conclusion, it is advisable to conduct modeling of actual pollution dispersion and a comprehensive environmental risk assessment.

Given the lack of alternatives, we believe that the only viable solution for waste management in the region at present is the reconstruction of existing treatment facilities and the expansion and modernization of hazardous waste processing infrastructure.

Considering economic, environmental and social aspects, we have justified the feasibility of installing hazardous waste disposers of the UT3000DP and UT750D type on the landfill territory. The grounds are the following key arguments:

1. Reducing the volume of waste and, accordingly, reducing the need to create new landfills or expand existing ones.
2. Reducing the level of pollution that occurs as a result of the natural decomposition of waste, which is accompanied by the formation of methane, dioxins, furans and other harmful substances. Incineration in high-temperature chambers allows you to neutralize toxic substances, preventing environmental pollution.
3. Controlled process of hazardous waste disposal, which increases the safety of landfill operations.
4. Reducing the costs of transporting and storing waste, which contributes to more efficient use of resources.
5. Compliance with environmental and sanitary standards, which minimizes the risk of penalties from regulatory authorities.
6. Improving the sanitary situation in the surrounding areas: reducing unpleasant odors, air and groundwater pollution, and preventing the spread of rodents, insects, and infections.
7. Implementation of modern recycling technologies, demonstrating a responsible attitude towards the environment and society.
8. The possibility of obtaining environmental certificates, which opens up prospects for state funding and international grants.
9. Easy integration of equipment that does not require complex infrastructure and can operate on gas or diesel fuel.
10. Creating new jobs, which contributes to the development of the local economy.

Ash and slag produced by incineration of waste may contain toxic or harmful substances, especially if the waste contains hazardous or chemically active components. Therefore, such waste is often classified as secondary hazardous waste that must be disposed of. An important factor when choosing a location for waste disposal facilities is the availability of an operating waste landfill. Waste generated during the incineration process can be disposed of at the site of its generation, which eliminates the problem of removing residues from incineration and transporting them to other regions.

Of course, despite all the advantages of using waste disposers, there are certain disadvantages that should be taken into account when making a decision about their installation. These include: significant capital expenditures for site equipment, purchasing a waste disposer, laying communications; operating costs; flue gas cleaning, obtaining permits, and generation of ash and slag.

4. Conclusions

Summarizing the results of the research, we state that to ensure the implementation of measures within the framework of the reform in the field of waste management, it is necessary to create hazardous waste processing facilities. We consider it advisable to install waste incineration plants in the city of Kremenchuk on the territory of the existing hazardous waste landfill for the following reasons:

1. The city of Kremenchuk is a powerful technogenically loaded center of the Poltava region, which generates the largest amount of hazardous waste that requires disposal.
2. Availability of a land plot that meets the requirements of environmental legislation for the construction of a waste treatment facility, namely: sufficient distance to residential development, location within the city limits, availability of access roads, availability of a landfill for the disposal of residues from waste incineration.
3. Operation of a hazardous waste treatment facility (incineration plant) will reduce the amount of waste that ends up in a hazardous waste landfill.
4. The issue of animal waste disposal will be resolved, making it possible to conserve the animal burial site located in the center of the landfill, which occupies a significant area.

The installation of waste incinerators will not only significantly reduce the volume of waste, but also create a controlled system of its disposal that will meet modern environmental standards and the basic principles of reforming this sector. We believe that for the successful implementation of the project, it is necessary to involve local governments as key partners who can help create favorable conditions for the implementation of the latest environmental technologies.

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INTENSIFICATION OF THE WASTEWATER TREATMENT PROCESS IN THE PRODUCTION OF SANITARY WARE USING COAGULANTS AND FLOCCULANTS

Andrii Shkop, Sergii Kulinich, Oleksii Shestopalov, Alona Bosiuk ✉, Antonina Sakun, Nataliia Ponomarova

National Technical University «Kharkiv Polytechnic Institute», 2, Kyrpychova Str., Kharkiv, 61002, Ukraine
Alona.Bosiuk@mit.khpi.edu.ua

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Abstract. This article discusses the issue of sludge water treatment generated in the production of ceramic sanitary ware. Experimental studies were conducted on the effectiveness of physical and chemical treatment methods, in particular the use of coagulants (aluminium sulphate) and flocculants of various types (anionic, non-ionic, cationic). The optimal parameters for water treatment have been determined, which allow for the maximum removal of suspended particles and minimise the formation of sediment. It has been established that the use of aluminium sulphate in a concentration that does not lower the pH of the medium below 6.0–6.5, in combination with flocculants, ensures effective water clarification. The best result was obtained with a flocculant dosage of 250 g/t in a ratio of anionic to non-ionic 1:1. The combined use of coagulants and flocculants made it possible to reduce the residual turbidity of water to <5 mg/dm³ and accelerate the precipitation of finely dispersed particles by 1.5–2 times compared to traditional methods. An improved technological scheme for purification has been proposed, which includes coagulation, flocculation, settling and centrifugation, with the possibility of further use of purified water in the production cycle. The results obtained can be used to modernise local treatment facilities of ceramic industry enterprises and introduce closed water use systems. The proposed reagent selection method is adaptable to wastewater of similar composition and reduces the environmental impact.

Keywords: wastewater treatment, coagulation, flocculation, sedimentation rate, water reuse, environmental safety.

1. Introduction

The production of ceramic sanitary ware is accompanied by the generation of significant amounts of wastewater containing fine suspended particles, residues of clay materials, mineral salts, and organic impurities. The discharge of organic compounds, heavy metals, and chemicals used in the ceramic industry leads to substantial water pollution. Therefore, wastewater must undergo thorough treatment (Shurygin et al., 2021). The low natural sedimentation rate of suspended particles complicates the purification process and necessitates the use of reagent-based methods, particularly coagulation and flocculation (Shkop et al., 2017 b).

The basic technology for treating wastewater in the production of ceramic sanitary ware involves several main stages. First, mechanical methods are used, including coarse cleaning with screens and grates, sand traps and sedimentation tanks to remove coarse impurities. The next stage is physical and chemical treatment, during which chemical reagents are usually used to precipitate impurities in the form of sludge. However, these methods are not effective enough for removing colloidal and fine particles that

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remain in the water after settling. As a result, the treated water remains highly turbid, and the sludge formed requires complex disposal. Biological treatment is not usually used due to the specific composition of the wastewater from this production. Thus, traditional technological solutions do not provide a high degree of treatment, which limits the possibilities for reusing water in production.

Known technological schemes for wastewater treatment at ceramic industry enterprises are generally similar but differ in scale and capacity. Their main drawback lies in the considerable volume of sludge generated and the insufficient efficiency of water clarification, which limits the possibility of its reuse in the production process.

The current challenge is to explore combined treatment methods that can improve process efficiency, reduce water clarification time, minimize sludge volume, and facilitate its further disposal. This study aims to assess the effectiveness of various reagents and develop an improved wastewater treatment scheme that allows for the reuse of treated water.

Wastewater generated during the production of ceramic sanitary ware contains a large amount of fine suspended solids, which significantly complicates its treatment. Traditional methods such as sedimentation are often insufficient due to the low settling rate of particles and high residual turbidity of the water. Moreover, the resulting sludge requires additional measures for dewatering and disposal, placing an additional burden on both production processes and the environment.

An important aspect of the problem is the limited availability of water resources, which necessitates the development of technologies that enable the reuse of treated water within the production cycle. This would contribute to reducing wastewater discharge volumes, decreasing the consumption of fresh water, and enhancing the environmental safety of ceramic industry enterprises.

Therefore, there is a need to improve existing wastewater treatment schemes through the combined use of coagulants and flocculants. This approach will accelerate the sedimentation process, improve the quality of treated water, and optimize sludge management.

The increasing demands for environmental safety and the rational use of water resources make the issue of effective treatment of ceramic industry wastewater relevant. In this production, two main and one secondary wastewater streams are generated. The first arises during the preparation of slip and the shaping of products and contains many suspended clay particles, glycerin, and surfactants. The second stream is associated with the preparation of ceramic paints and contains pigments based on metal oxides. The third, secondary, stream is domestic and fecal wastewater (Yaroshenko & Shabanov, 2011). The use of traditional methods does not provide the required level of purification, which complicates the reuse of water in production and increases the negative impact on the environment.

Modern trends in water treatment are aimed at implementing combined methods of coagulation and flocculation (Onen & Gocer, 2018), which significantly improve the quality of treated water and reduce the treatment time. The study (Yaroshenko & Shabanov, 2010) analyzed the composition of wastewater from a ceramic plant, which confirmed the high variability of their physico-chemical characteristics and the need for an individual selection of treatment methods. However, the optimal parameters for reagent dosing and effective technological solutions for wastewater from sanitary ceramics production remain insufficiently studied.

This study is aimed at finding effective wastewater treatment methods that will increase the sedimentation rate of suspended particles, reduce the amount of generated sludge, and ensure the possibility of water reuse. The implementation of the obtained results will contribute to reducing the environmental burden of ceramic industry enterprises and increasing their environmental responsibility.

The physical and chemical composition of wastewater from ceramic production varies significantly depending on the technological stage and type of product. According to experimental data and literature sources (Sari Erkan, 2019; Martínez-García et al., 2012; Chong et al., 2009), typical indicators for such effluents are: suspended solids – 800–1200 mg/dm^3, COD – 250–400 mgO$_2$/dm^3, BOD$_5$ – 50–100 mgO$_2$/dm^3, surfactants – up to 15 mg/dm^3, pH – within 6.2–8.0. Heavy metal ions are also found in wastewater: Zn^{2+} – up to 1.0 mg/dm^3, Cr^{3+} – up to 0.2 mg/dm^3, Fe^{3+} – up to 2.0 mg/dm^3, Al^{3+} – up to 1.5 mg/dm^3. Specific pollutants include glycerine, clay particle residues, metal oxides, silica, calcium, magnesium and sodium salts. Such a v ariable composition significantly complicates wastewater treatment, necessitating the use of adaptive reagent methods.

The advantages of using ceramic membranes for the filtration of complex wastewater are widely covered in modern scientific research (Almecija et al., 2009; Barredo-Damas et al., 2010; Ebrahimi et al., 2015; Ebrahimi et al., 2014; Hua et al., 2007). However, contemporary studies provide almost no practical examples for the treatment of ceramic industry wastewater. In this work, the author investigates the removal of chemical oxygen demand (COD) from ceramic industry wastewater using chemical coagulation with alum and ferric chloride ($FeCl_3$) as coagulants. In addition, the research focuses on determining the capillary suction time (CST) of sludge samples, which is an important indicator of its dewatering potential (Sari Erkan, 2019).

The wastewater treatment schemes in ceramic tile and sanitary ceramics workshops described in the literature are similar, differing only in capacity. Wastewater is discharged into equalizing tanks, from where it is pumped by membrane pumps into special settling tanks, into which a coagulant (aluminum hydroxychloride) and a flocculant (polyacrylamide) are dosed. After treatment, part of the water is returned to the production cycle as technical water. The sludge retained in the settlers is dewatered using filter presses. The portion of the sludge, as well as residue on the screens (a mixture with foreign objects), which cannot be reused in production, is transported to a solid waste landfill.

The production of sanitary ceramic products has significantly contributed to the development of industrial water treatment technologies. In particular, efficient treatment and reuse of wastewater (Maura et al., 2023) helps reduce water consumption costs and minimize the negative environmental impact. However, ceramic production also generates significant volumes of wastewater containing heavy metals and other pollutants. Studies show that ceramic industry wastewater may contain up to 15 mg/L of boron and up to 2000 mg/L of suspended solids, which requires the implementation of effective treatment methods (Martínez-García et al., 2012; Chong et al., 2009). Boron is widely used in the production of sanitary ceramics to improve their mechanical strength. Overall, ceramic materials belong to the class of inorganic compounds that may contain organic impurities and non-metallic components (Khomenko et al., 2022; Budnyk et al., 2008). Furthermore, the production process results in products with varying clay content, which may be glazed or unglazed, porous or vitreous (Barros et al., 2007; Budnyk et al., 2008).

In their study (Elias et al., 2014), the authors investigate the treatment of ceramic industry wastewater using the method of rhizofiltration, applying a bioremediation system based on water hyacinth. This approach contributes to the effective removal of heavy metals and other pollutants from wastewater, enabling the minimization of their negative environmental impact and allowing for the reuse of treated water in the production process.

However, existing wastewater treatment schemes require further improvement to enhance the efficiency of pollutant removal and reduce environmental impact. In particular, the issues of optimizing the dosing of coagulants and flocculants to minimize excess sludge formation, as well as the possibilities for its further disposal or recycling, remain insufficiently studied. As noted by the author in their research (Onyshchuk, 2023), the effectiveness of flocculation and coagulation largely depends on the careful selection of reagents and technological parameters, which must be adapted to the specific type of wastewater. An unresolved issue is also the methodology for selecting different types of coagulants and flocculants using technological tests, which allow the obtained results to be used for adjusting the operation of treatment equipment.

In addition, the issue of reducing freshwater consumption in production processes through the maximum reuse of treated wastewater remains relevant. Promising research includes the implementation of additional treatment stages, particularly sorption and membrane technologies, to achieve the required quality of water returned to production.

2. Experimental part

The aim of this study is to improve the efficiency of wastewater treatment in ceramic tile and sanitary ware production by removing suspended solids through the selection of optimal doses and ratios of coagulants and flocculants.

This is necessary for the enhancement of technological treatment schemes, which will help reduce the negative environmental impact and increase water conservation within production processes.

To achieve this aim, the following objectives were set:

– to investigate physical and physicochemical methods for treating wastewater samples from ceramic tile and sanitary ware production and to determine their effectiveness;

– to assess the efficiency of various coagulants and flocculants, as well as their combinations;

– to develop a treatment technology for the removal of suspended solids from wastewater.

The study was conducted using real wastewater samples from an operating sanitary ware production facility, collected at different times and from various workshops: Sample № 1 (solid phase concentration: 23 g/l); Sample № 2 (solid phase concentration: 7.8 g/l).

The sludge waters from ceramic sanitary ware production contain solid particles of varying sizes, formed as a result of technological processes. The main parameters of the studied samples included volume, solid content, and pH value. The kinetics of particle sedimentation were examined by observing changes in water transparency over different time intervals. The study allowed for the determination of the optimal settling time required to achieve the highest degree of liquid clarification.

The research was carried out in several stages:

1. Sample preparation – wastewater samples with volumes of 5 – 20 liters collected from ceramic sanitary ware production were subjected to preliminary analysis to determine the concentration of solid residue using the evaporation method.
2. Gravitational settling – the initial samples were tested under still settling conditions for 4 to 24 hours, with changes in clarity and particle sedimentation rate recorded.
3. Centrifugation – a laboratory beaker centrifuge was used at separation factor values Fr = 990 – 2286 to evaluate the efficiency of mechanical phase separation.
4. Chemical treatment – various reagents were used for coagulation and flocculation of suspensions, including ferric chloride, aluminum oxychloride, and aluminum sulfate as coagulants, and cationic, anionic, nonionic flocculants, as well as their combinations. For each reagent, the sedimentation rate of the suspension after the addition of flocculants (V_1) and after intense mixing (V_2) was recorded according to the methodology described in more detail in publications (Shkop et al., 2017b; Shestopalov et al., 2019).

The diagram shown in Fig. 5 is a basic diagram and reflects the general sequence of treatment processes recommended for wastewater of a similar composition. Technological parameters, such as process duration, reagent dosage, sludge volume and moisture content, depend on specific production conditions and may vary. According to the methodology described in this study, the recommended coagulant consumption is 100 g/m^3, flocculant consumption is 250 g/t (in two stages: 125 (non-ionic) + 125 (anionic) g/t), and the moisture content of the sludge after centrifugation is 45 ± 5 %. The studies were conducted in triplicate, the results were averaged, and the deviations did not exceed ±5 %, which confirms their reliability.

5. pH monitoring – changes in the pH of the medium after the addition of coagulants and flocculants were recorded, as this parameter affects sediment formation and aggregation efficiency.
6. Comparison of effectiveness – the effectiveness of different reagent combinations was compared, and optimal doses and conditions were identified to achieve the highest treatment efficiency.

3. Results and Discussion

As a result of gravitational settling of Sample No. 1, the following observations were made:

– after four hours of settling, clarification was minimal; the sample remained cloudy with approximately 50 % of the particles settling out;

– after 24 hours of settling, the sample remained turbid, indicating the presence of fine suspended particles (primarily clay particles such as kaolin clays).

To study the kinetics of gravitational sedimentation, a 500 ml sample of wastewater was placed in a transparent laboratory measuring flask (cylinder) with a diameter of 50 mm to observe the process of clarification and sediment formation. The kinetics of sediment growth in the sample during the settling process are shown in the graph in Fig. 1.

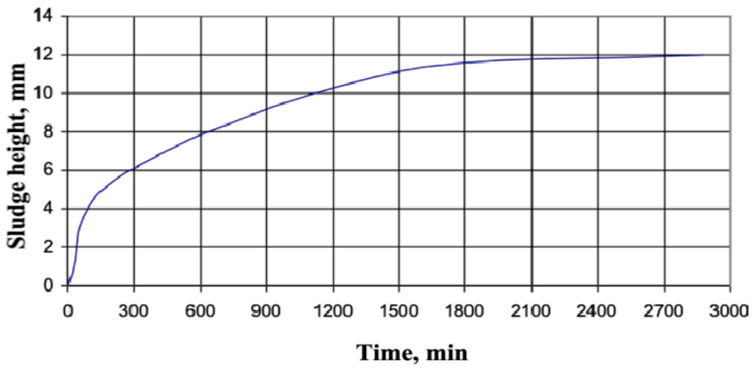

Fig.1. Sedimentation kinetics during the settling process

An analysis of the sedimentation kinetics indicates that the wastewater sample contains finely dispersed particles forming a stable dispersion system, for which gravitational settling is largely ineffective (only coarse particles settle, while the majority remain suspended). However, preliminary settling allows for the removal of approximately 40–60 % of the solid phase (depending on the settling time) without the use of chemical reagents.

Centrifugation of the initial sample without chemical enhancement was performed using a laboratory beaker centrifuge at separation factors of Fr = 990, Fr = 1500, and Fr = 1940 (Tabl. 1).

Table 1

Results of Centrifugation of Sample №1 in the laboratory Centrifuge

Separation Factor, Fr	Volume/Weight of Initial Sample	Weight of clarified sample, g	Note
990	250 ml /256.4 g	247.1	The sample is turbid, after 17 hours of settling, sediment is visible at the bottom.
1500	250 ml /257.1 g	247.15	
1940	250 ml /255.95 g	247.1	

Fig. 2 shows the appearance of clarified water after centrifugation in a laboratory beaker centrifuge at separation factors of Fr = 990, Fr = 1500, and Fr = 1940.

An analysis of the results indicates that centrifugation does not yield fully transparent water but does partially reduce the concentration of suspended particles. Complete clarification and the production of clear water can only be achieved through the use of chemical coagulants and flocculants, which destabilize the dispersion system formed by fine solid-phase fractions.

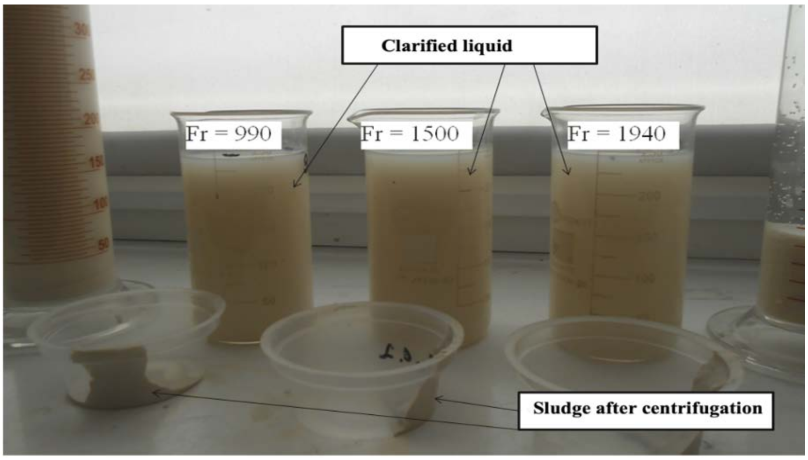

Fig.2. Appearance of clarified water after centrifugation

At the next stage, chemical treatment of the sample was carried out using various reagents.

1. When the initial 250 mL sample was treated with 0.5 mL of 10 % ferric chloride, clear clarified water with slight whiteness was obtained. The sedimentation rate V_1 at 50 % of the sample volume was 0.6 mm/s. After centrifugation in a beaker centrifuge at Fr = 990, clear clarified water and a yellowish precipitate were obtained.

2. When the initial 250 mL sample was treated with 0.1 mL of aluminum oxychloride, clear clarified water with slight whiteness was obtained. The sedimentation rate V_1 at 50 % of the sample volume was 0.3 mm/s. After centrifugation in a beaker centrifuge at Fr = 990, clear clarified water was obtained.

3. When the 250 mL sample was treated with flocculants (50 % cationic + 50 % anionic) at a 0.05 % concentration (180 g/t), white clarified water was obtained. The sedimentation rate was V_1 = 6.1 mm/s and V_2 = 2.9 mm/s. After centrifugation in a beaker centrifuge at Fr = 990, white but non-transparent clarified water was obtained.

4. When the 250 ml sample was treated with 0.6 ml of 10% aluminum sulfate, whitish clarified water was obtained (see Fig. 3a). The sedimentation rate V_1

at 50 % of the sample volume was 0.36 mm/s. After centrifugation in a beaker centrifuge at Fr = 990, clear clarified water with a small amount of white sludge was obtained.

5. When the 250 mL sample was treated with a nonionic flocculant at a 0.05 % concentration (180 g/t), white clarified water was obtained. The sedimentation rate was V_1 = 5.4 mm/s and V_2 = 2.8 mm/s.

6. When the 250 mL sample was treated with 0.5 ml of 10 % aluminum sulfate followed by the addition of a nonionic flocculant at a dosage of 90 g/t, clear clarified water was obtained (Fig. 3 b). The sedimentation rate was V_1 = 6.7 mm/s and V_2 = 5.2 mm/s. After centrifugation in a beaker centrifuge at Fr = 990, clear clarified water and sludge with a moisture content of 51 % were obtained.

a *b*

Fig.3. Appearance of samples after treatment:
a – with aluminum sulfate; b – with aluminum sulfate followed by enhancement with a nonionic flocculant

An analysis of the clarification results for Sample No. 1 indicates that the best performance for this type of wastewater was achieved using aluminum sulfate and a nonionic flocculant. The introduction of these reagents resulted in clear water. The highest efficiency was demonstrated by the combination of this coagulant with the nonionic flocculant, as their joint action led to the formation of large, fast-settling aggregates (V_1 = 6.7 mm/s), which were minimally affected by mixing (V_2 = 5.2 mm/s).

As a result of gravitational settling of Sample No. 2, the following was observed:

– no clarification was observed after 12 hours; the sample remained whitish and turbid, with a sediment layer at the bottom of the measuring cylinder approximately 0.5 to 1 mm thick;

– after 24 hours of settling, the sample remained whitish and turbid, indicating the presence of fine suspended particles, with the sediment layer increasing to about 1.5 to 2 mm.

– During centrifugation of the sample in a laboratory beaker centrifuge without chemical enhancement at separation factors of Fr = 990 and Fr = 1500, no significant differences were observed in the degree of clarification or the amount of solid sludge obtained; in both cases, the sludge volume was minimal (Tabl. 2).

Table 2

Results of Centrifugation of Sample № 2

№	Separation factor value , g	Exposure time, s	Suspension separation results			
			Volume, ml	Volume of liquid, ml	Volume of sludge, ml	Description of clarified liquid and sludge
1	900…990 (800…990)	26	250	248/248.65	~1	White, turbid clarified liquid; a small amount of sludge present; sludge is moist.
2	1500…1580	36	250	250/247	~1	Whitish, turbid clarified liquid; a small amount of sludge present; sludge is moist.

When treating Sample № 2 (500 ml) with 1 ml of 10 % aluminum oxychloride, followed by the addition of a combination of nonionic flocculant (250 g/t) and anionic flocculant (250 g/t), clear clarified water was obtained. The sedimentation rate was V_1 = 9.5 mm/s and V_2 = 2.9 mm/s. After compaction, the sludge volume amounted to 1/10 (50 ml) of the sample volume, corresponding to a concentration of 78 g/l.

However, this total flocculant dosage of 500 g/t is not optimal, which prompted further chemical testing of Sample № 2 with various reagents, yielding the following results.

Stage 1. The dosage of the coagulant solution (aluminum sulfate, which had shown high effectiveness in previous tests on Sample № 1) and the amount of flocculants remained constant, while the types and combinations of flocculants were varied.

When the 250 ml sample was treated with 0.5 mL of 10 % aluminum sulfate, the formation of small aggregates (flocs) was observed. Then, a flocculant with a 0.05 % concentration was added at a dosage of 257 g/t, and the sedimentation rate of the flocs was measured, as well as their residual sedimentation rate after 40 seconds of mechanical stirring with a laboratory mixer. The results of the study are presented in Tabl. 3.

Table 3

Results of selecting the type and combination of flocculants

Type of flocculant added after coagulant	Sedimentation rate of flocs after formation (V_1), mm/s	Sedimentation rate of flocs after intense mixing (V_2), mm/s	Characteristics of clarified liquid
Anionic flocculant	11.67	3.8	Fine suspension
Cationic flocculant	4.2	1.46	Fine suspension
Nonionic flocculant	18.17	5.58	Clarified white suspension
Flocculant mixture (50 % nonionic + 50 % cationic)	5.21	2.05	Clarified white suspension
Flocculant mixture (50 % nonionic + 50 % anionic)	13.75	9.82	Clear water

An analysis of Tabl. 3 indicates that the nonionic flocculant demonstrated higher overall effectiveness. However, the most mechanically stable flocs were formed when using a combination of nonionic and anionic flocculants. This may indicate the presence in the water of either solid particles with varying charges or the formation of secondary structures when combining flocculants – where one flocculant adsorbs more effectively onto particle surfaces, and the other forms bridges and promotes floc growth. These results are consistent with previous studies; for example, in coal sludge treatment, the highest efficiency was achieved using a combination of nonionic and anionic flocculants (Shkop et al., 2017 a), while for foundry dust sludge, a combination of anionic and cationic flocculants proved most effective (Bosiuk et al., 2024).

Stage 2. The optimal amount of coagulant and its effect on the flocculation process were investigated. Increasing the coagulant dosage in wastewater may be economically disadvantageous and negatively affect flocculation.

At this stage, the dosage and types of flocculants were kept constant, while the coagulant dosage was varied and changes in the pH of the medium were recorded.

When treating Sample №3 (250 ml; initial pH = 8.39) with 10 % aluminum sulfate in volumes ranging from 0.5 to 3 ml, the pH of the sample changed from 6.98 to 4.87. After the formation of small aggregates (flocs) over ~10 minutes, flocculants (50 % nonionic + 50 % anionic) at a 0.05 % concentration and dosage of 257 g/t were added. The sample was then mixed, and sedimentation rates were measured as in the previous experiments. The results are presented in Fig. 4.

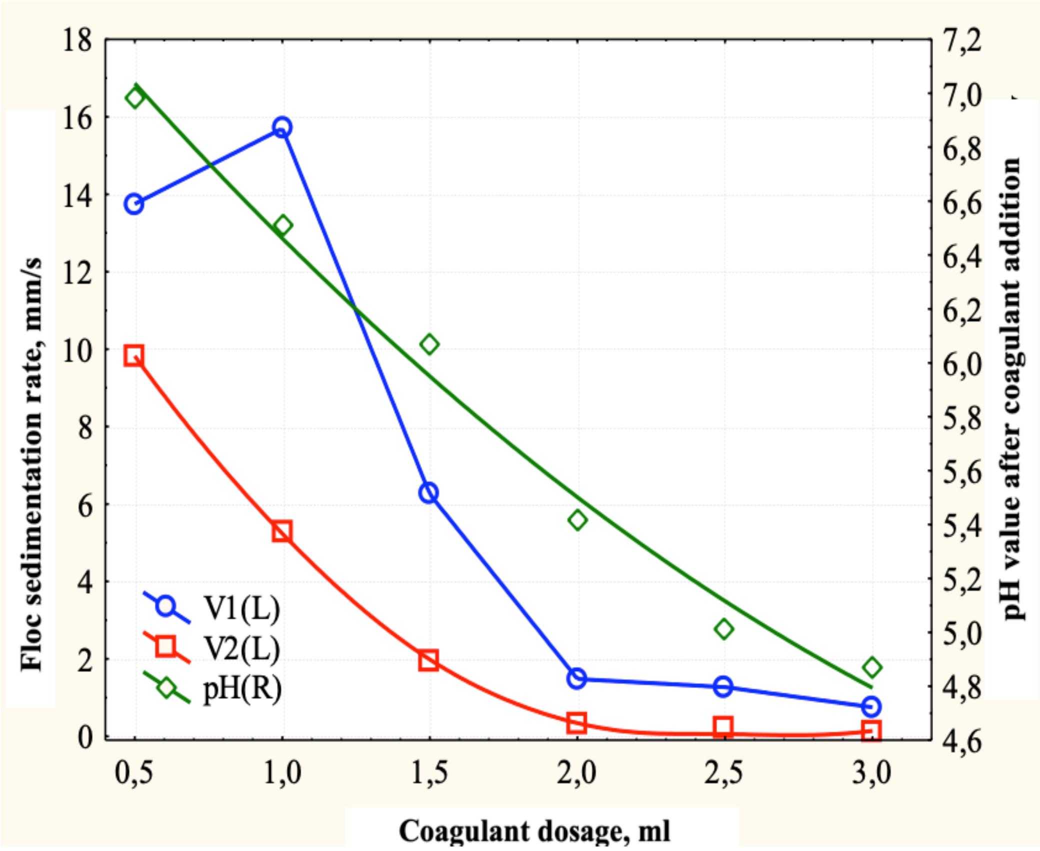

Fig.4. Dependence of floc sedimentation rates on coagulant dosage and pH changes of the medium

An analysis of the results shown in Fig. 4 indicates that increasing the coagulant dosage while maintaining a constant flocculant rate leads to a reduction in both the size and strength of the flocs. This may be attributed to changes in the pH of the medium due to the accumulation of sulfate ions in the liquid.

Changes in ceramic sanitary ware production technology, particularly in the composition of raw materials or the parameters of individual operations, can significantly affect the chemical composition of wastewater and, accordingly, the effectiveness of coagulants and flocculants. Therefore, it is advisable to use an adaptive approach that involves regular analysis of the composition of wastewater and selection of optimal reagents based on the results of laboratory tests.

Thus, the analysis of the conducted research allows for the following general conclusions:

In most samples, clarification of the liquid phase occurred slowly, indicating high suspension stability. After 24 hours of sedimentation, many turbid suspended clay particles (kaolin) remained in the samples, confirming the need for additional treatment. Centrifugation without chemical reagents also failed to produce clear water but did allow for the rapid separation of coarse particles. The use of a laboratory centrifuge at different separation factors did not significantly improve the removal of fine particles of dispersed clay.

For maximum removal of suspended solids in less concentrated samples (C = 7 .8–16 g/L), it is advisable to use coagulants in combination with flocculants. Among the coagulants, aluminum sulfate showed the highest efficiency in promoting aggregation and destabilizing the dispersed suspension. The use of aluminum sulfate combined with various flocculants led to complete clarification of the liquid, free of suspended particles. The most effective combinations included 50 % nonionic and 50 % anionic flocculants. It was found that the coagulant dosage should not be excessive and should not reduce the pH of the medium below 6.5.

Therefore, to achieve the best water clarification results, it is advisable to apply a combined use of coagulants and flocculants, while also maintaining an optimal pH level in the medium.

Based on the summarized findings above, the following treatment scheme can be proposed for sanitary ware manufacturing enterprises (Fig. 5).

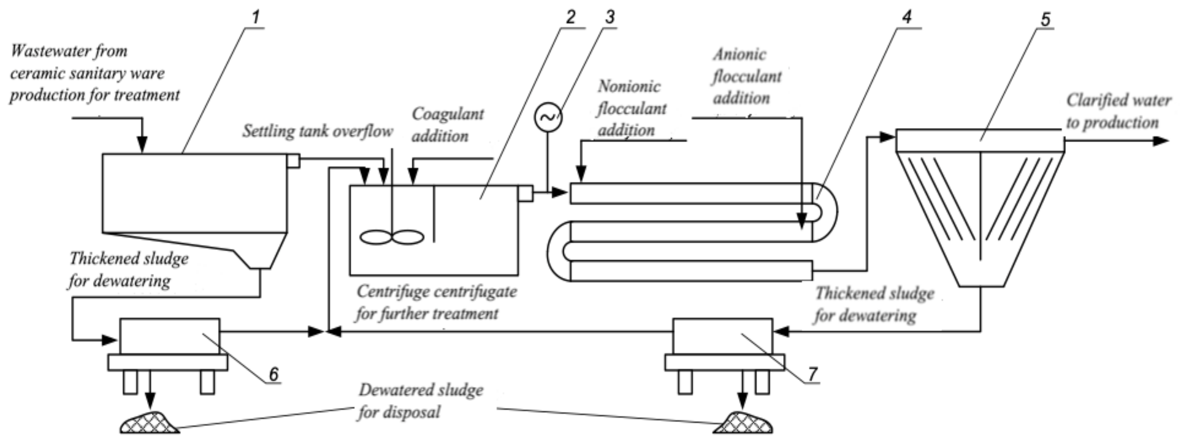

Fig. 5. Proposed wastewater treatment scheme for sanitary ware production:1 – settling tank; 2 – tank with stirrer and floc formation chamber; 3 – pH sensor; 4 – tubular flocculator; 5 – lamella (inclined plate) settler; 6, 7 – centrifuges

Wastewater from different sections of sanitary ware production is directed to a settling tank, where large sand-sized particles (>80 μm) settle out and are sent for dewatering in centrifuge 6. The overflow from the settling tank, containing fine-dispersed particles, flows into tank 2, which serves as both a storage and floc formation chamber, where it is mixed with a coagulant. The coagulant destabilizes the dispersed suspension and is then directed to the flocculator 4, where nonionic flocculant is first added, followed by anionic flocculant. Prior to the flocculator, the pH of the medium is monitored using a pH sensor 3.

The formed flocs settle in the lamella settler 5, and the clarified water is returned to the production process for technological use. Sludge from settler 5 is dewatered in centrifuge 7. Centrifugates from centrifuges 6 and 7 may contain residual particles and are therefore returned to tank 2 for further treatment. The sludge from the centrifuges is returned to production for disposal.

Thus, the proposed scheme enables the removal of suspended solids from wastewater with minimal reagent consumption, allowing both the solid phase and treated water to be reused in production. The doses, types, and order of addition of coagulants and flocculants should be determined and selected based on laboratory tests, the methodology and examples of which are described in this article.

4. Conclusions

The study analyzed the effectiveness of various physical and physicochemical methods for treating sludge waters from ceramic sanitary ware production. The obtained results allowed for the identification of optimal technological solutions for each stage of water treatment, aimed at improving efficiency and minimizing environmental impact.

To achieve maximum removal of suspended solids, it is recommended to use aluminum sulfate as a coagulant at a concentration that does not reduce the pH of the medium below 6.0 – 6.5, in combination with flocculants. As flocculants, a 1:1 ratio of nonionic and anionic flocculants is recommended at a dosage of 250 g/t.

These results and the proposed methodology can be applied to the treatment of wastewater with similar composition; however, for each specific production type, the selection of reagent types and concentrations should be determined through technological testing following the methodology described in this article.

Based on the summarized results, a technological wastewater treatment scheme has been proposed that enables the removal of both coarse and fine dispersed particles using a minimal amount of reagents.

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RESEARCH ON THE EFFECT OF HUMIC SUBSTANCES-BASED PREPARATIONS IN PROMOTING SOIL BIODEGRADATION PROCESSES

Oleh Kibarov✉, Ganna Trokhymenko, Vladyslav Nedoroda

Admiral Makarov National University of Shipbuilding,
9, Heroiv Ukrayiny Ave., Mykolaiv, 54025, Ukraine
kibarovoleg9@gmail.com

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Abstract. The paper presents an analysis of the market of fertilizers and organic additives that promote the biodegradation of herbicide residues in the soil and ensure stable growth and development of agricultural crops. The work also presents studies of the action of biostimulants based on humic substances in promoting the activation of plant defense mechanisms when combating stress in conditions unfavorable for growth. To study the effect of such biofertilizers on the growth and development of cereal crops under stressful conditions of exposure to glyphosate, the phyto-indicator *Sorghum bicolor subsp. Drummondii* was used, as well as all known types of fertilizers based on humic substances. These include liquid organic experimental fertilizers based on humic acids with an increased composition of fulvic acids, as well as the more popular potassium humate and inoculants based on them, which include strains of bacteria of the genus *Bacillus* and ascomycete fungi *Trichoderma.* The main research methods are experiment, comparison, and analysis.

Keywords: bioremediation, growth stimulants, herbicides, fulvic acids, humic acids.

1. Introduction

The increased usage of herbicides for agricultural weed control has led to an annual global herbicide consumption of about one million tons. The extensive usage of herbicides has sparked worries about how their residues may affect soil ecology and human health. Herbicides harm the soil microbiome and associated ecosystem functioning in addition to inflaming the human small and large intestines. The future of sustainable agriculture and the welfare of society depend on thorough research into how pesticide residues alter soil microorganisms and functions. Soil ecosystems are multifaceted and multifunctional by nature. Climate regulation, primary productivity, carbon sequestration, nutrient supply and cycling, soil biodiversity maintenance, water purification and regulation, and more are all functions of soil. Long-term environmental and human issues including pesticide use, pollution buildup, climate change, and intensified agricultural land use are all exacerbated by these functions (Alister et al., 2020).

Humic compounds, protein hydrolysates, seaweed extracts, and microbes are examples of biostimulants that have demonstrated the ability to enhance plant growth, boost crop output and quality, and bioremediate soils. However, trying to understand the underlying mechanisms of commercially available biostimulants is difficult due to their heterogeneous composition and multimolecular structure. Recent molecular research has started to identify the pathways that particular products stimulate at the cellular and gene levels, however the majority of studies have concentrated on the broad impacts of biostimulants on crops. Improved crop protection and soil bioremediation methods could result from a better understanding of molecular impacts.

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The sorption and desorption of pesticides are the primary variables influencing their fate in the environment. Improper sorption-desorption mechanisms can lead to decreased microbial activity and increased pesticide volatilization or leaching. To combat these issues, fulvic acid—an organic molecular chain with carboxyl and phenolic functional groups—is employed as a sorption-desorption agent. Numerous polar or ionic pesticides react favorably with fulvic acid. For instance, the nitrogen of the imidacloprid molecule can establish robust hydrogen bonds with the phenolic groups of fulvic acid. Fulvic acid can also create a potent sorption mechanism with carbamates (carbaryl and carbofuran), phenoxyacetic acids, and imidacloprid (Zhang et al., 2012). These strong interactions allow fulvic acid to protect and buffer pesticide molecules, increase their solubility, and reduce the required dosage of pesticide by 20–30 % (Ćwieląg-Piasecka et al., 2018).

Plant nutrition management can be enhanced using fulvic acid as a biostimulant to improve nutrient availability and uptake.

While chemical fertilizers increase productivity, they also contribute to environmental pollution and climate change. Organic biostimulants, such as fulvic acid, serve as non-toxic chelating and water-binding agents that improve nutrient uptake and plant productivity. Fulvic acids easily chelate essential nutrients (Zn, Fe, Mg, Ca) and transfer them to plants. These acids naturally occur in lignite, soil, and peat, and form a complex mixture with phenolate and carboxylic groups through organic matter decomposition. Humic acids, which have lower molecular weights and higher oxygen content than fulvic acids, are abundant in these mixtures (Canellas et al., 2015).

Fulvic and humic substances are promising in enhancing plant resistance to abiotic stress. Studies show that applying seaweed extract and humic acid to pre-treat certain grasses improved leaf hydration under drought, increased root and shoot growth, and boosted antioxidant activity. Treating bell pepper (Capsicum annuum) with humic acid under salinity reduced Na uptake and increased N, S, Cu, Fe, Mg, Ca, Mn, and K in roots and shoots, indicating protection under moderate salinity stress (Çimrin & Türkmen, 2010). Similarly, applying humic acids to beans (Phaseolus vulgaris) under high salinity increased proline accumulation and reduced membrane leakage, indicating improved stress adaptation (Aydin et al., 2012).

Fulvic acid also acts as a pollutant remover when mixed with pesticides. When droplet pesticides land on soil, fulvic acid can emulsify and disperse them, altering water surface tension and enabling ion exchange reactions. As a colloid with large surface area, it binds pesticides strongly, reducing their harmful effects on soil microbes and crops. Under certain conditions, fulvic acid can even degrade pesticide residues, further protecting the ecosystem.

The term “humates” refers to sodium or potassium salts of humic acids, forming the chemical basis of humus. Humus maintains soil biochemical equilibrium and fertility. Fertilizers made from soft brown coal or peat are rich in humic substances and fulvic acids, vital for soil health. For example, preparation of potassium humates involves grinding coal, mixing with KOH, and separating the solid phase. This concentrated humic fertilizer is rich in humic and fulvic acids and trace elements. Using potassium humate on soil improves water retention, boosts beneficial microbes, and enhances nutrient availability. It chelates essential minerals, improving plant growth and soil structure. Studies show that potassium humate significantly enhances soil composition by binding particles, improving drainage, and reducing compaction. Its organic matter content supports diverse soil microorganisms, accelerating nutrient cycling and improving fertility (El-Beltagi et al., 2023). Humate application also lowers soil Salinity and retains moisture, reducing the need for irrigation.

Best practices for potassium humate involve using it as a soil enhancer during planting (mixing with topsoil) and as a foliar spray to improve nutrient uptake. It should be sprayed in the early morning or late evening with water to prevent evaporation.

To further enhance humic biostimulants, they are often combined with soil microbes. Common beneficial strains include Bacillus and Trichoderma. Although the exact plant-microbe interactions under stress are not fully understood, many microbes can act as biostimulants in challenging environments. Genera such as Pseudomonas, Rhizobium, Bacillus, Azotobacter, Azospirillum, and Bradyrhizobium contain strains adapted to saline, alkaline, acidic, or arid soils. These microbes modify their cell walls and accumulate solutes (e.g., exopolysaccharides, lipopolysaccharides) to survive stress, forming protective biofilms on roots and retaining water. Inoculating soil with plant growth–promoting rhizobacteria (PGPR) can enhance plant stress tolerance by improving hydration and nutrient uptake (Selvakumar & Joshi, 2009).

For example, Rhizobium strains can produce exopolysaccharides that help maintain root-zone hydration under drought or salinity (Abd El-Ghany et al., 2020).

Field studies show that inoculating crops with nitrogen-fixing or salt-tolerant bacteria improves stress resistance. Inoculation of maize with Azotobacter strains under salt stress increased availability of P and N and helped the plant exclude Na. For wheat under salt stress, saline-tolerant Azotobacter improved grain yield and nitrogen content (Kaushal, 2015). When two strains of Rhizobium leguminosarum (one salt-tolerant, one sensitive) were inoculated into pea and faba bean, plants with the tolerant strain fared better under salt stress (Ihsan and Hussein, 2005). Inoculating chickpeas and faba beans with Azospirillum brasilense enhanced root colonization, nodulation, and salt tolerance. Another bacterium, Azotobacter chroococcum, showed salt tolerance; inoculating crops with it on saline soils increased yields of peas, potatoes, rice, wheat, and cotton, as well as root and shoot growth (Hamaoui et al., 2001). These findings highlight that selecting the right biostimulant–based on composition, soil type, and stress factors–is crucial for enhancing plant stress resilience.

2. Materials and Methods

The experiment analyzed the effect of humic substance–based biostimulants on the growth of *Sorghum bicolor subsp. Drummondii* (Sudan grass) and their interaction with glyphosate herbicides. The treatments included the following fertilizers and inoculants:

- BioFulvo – a liquid organic fertilizer containing 150–200 g/L fulvic acids, 10 g/L humic acids, and Bacillus amyloliquefaciens ssp. plantarum. It is produced from processed organic waste (bran, grain waste, straw, etc.) and is rich in low-molecular fulvic acids. It also contains Bacillus strain 531 (a heavy-metal–resistant biofertilizer).
- Stubble Destroyer – a biological inoculant with live cells and spores of Bacillus subtilis and Bacillus licheniformis (≥1.0×10^9 CFU/cm³), spores of Trichoderma viride and T. lignorum, and their metabolites. Contains ≥100 g/L humic substances.
- Potassium Humate – a concentrated organo-mineral humic fertilizer with 70 g/L humic acids, 34 g/L fulvic acids (total 104 g/L humic substances), and macro- and micronutrients (N, K, B, Co, Cu, P, Zn, Fe, Mn, Mo). It is used for seed treatment, foliar feeding, and root feeding to stimulate rapid growth.

The herbicides used were:

1. «Urahan Forte» – 500 g/L glyphosate.
2. «Federal» – 480 g/L glyphosate (isopropylamine salt) + 60 g/L dicamba.

At the first stage, all soil samples were treated with the fertilizers at the following dilutions:

- «BioFulvo» at 1:500, 1:100, 1:10
- Stubble Destroyer at 1:500, 1:100, 1:10
- Potassium Humate at 1:500 and 1:300

Several control soil samples received no fertilizer. After two weeks, all soil samples were sown with *S. bicolor subsp. drummondii* seeds and watered every three days. This established the baseline growth under the different biostimulant treatments.

One week after sowing, above-ground parts of the plants were treated with the herbicides. A week later (day 14 after sowing), plants were again treated with the fertilizers. Thus, the experimental scheme involved alternating fertilization and herbicide stress to assess how pre-treatment with humic biostimulants affected plant recovery and growth.

Throughout the experiment, plant growth was measured by sprout height at specified intervals (days 8, 14, 18 after sowing). Mortality rates were also recorded under combined herbicide and biostimulant treatments. Control (water-only) samples were used for comparison.

3. Results and Discussion

Potassium humate treatments (especially 1/500 dilution) increased early growth by about 20 % compared to control, indicating a significant stimulation of sprouting. In contrast, the microbial inoculant (Stubble Destroyer) at high concentrations (e.g. 1/10) appeared to inhibit growth by 25–50 %. This adverse effect might be due to the instability or over-concentration of microbial spores causing stress to seedlings.

The BioFulvo treatment (rich in fulvic acids) increased average height by about 5 % over control, reflecting its biostimulant role.

On the 8th day after sowing, plant growth measurements yielded the results summarized in Tabl. 1.

Table 1

Phytoindicator growth on the 8th day after sowing (in cm)

Drugs	Control/ Water	«BioFulvo» Drug	Stubble destroyer	Potassium humate
Concentrations		1/500	1/500	1/500
	3	5	3	7.7
	5	12.5	6	9.5
	5.1	9	5	9.1
	3	1.5	5.5	3.8
	4.5	4.5	6.5	4
	6	5	10	4.9
	6.2	5.3	1.5	7
	9.5	6.3	2.5	4.2
	10.5	9.5	4.1	10
Concentrations		1/100	1/100	1/300
		3	7	4.5
		3	5.5	5
		4.5	7	6
		7.5	3.3	8
		8.5	4.5	6.5
		10	4	8.5
		3	6.8	6
		1.5	3.9	5.5
		2	10.4	10
Concentrations		1/10	1/10	1/300
		8	2	3.5
		6.7	2	4.2
		9	6.3	4
		6.5	1.5	1
		6.5	4.2	5.1
		4	7.1	5.3
		7.9	-	6.3
		7.5	3	10
		8.3	3.4	12.2

The better performance of potassium humate may be attributed to its additional nutrients (K and trace elements) that strengthen the root system and stress resistance. The general results of the progression of sprout growth on the 8th day is shown in Fig.1.

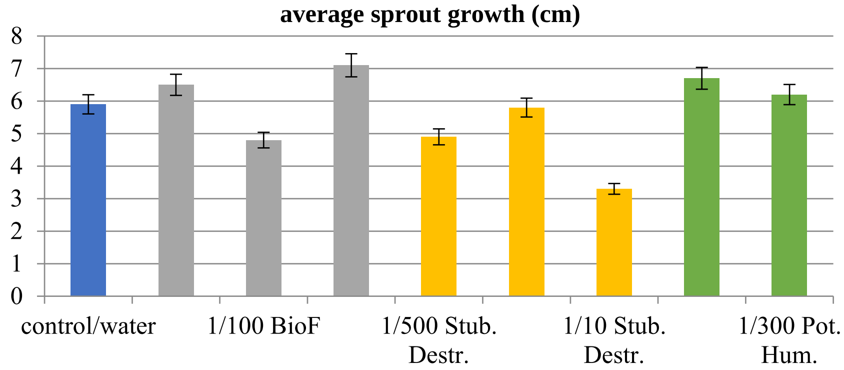

Fig.1. Phytoindicator growth on the 8th day after sowing (cm)

A week after sowing, the above samples were treated with herbicides. The results of the growth of the phyto-indicator a w eek after herbicide treatment shown in Tabl. 2.

Table 2

Phytoindicator growth on the 14th day after sowing (cm)

Drugs	Control/ Water	«BioFulvo» Drug	Stubble destroyer	Potassium humate
Concentrations		1/500	1/500	1/500
	6.8	9.5	8	9.2
	9	13.5	12	11.3
	9.3	15	9.5	13
With «Urahan F.»	4.5	3.2	7	4.5
	6	3	8.2	4.5
	7	7.8	11.2	8.9
With «Federal»	9	–	–	7
	11.3	–	–	5.5
	12	–	–	13.5
Concentrations		1/100	1/100	1/300
		5.3	12	10
		9.2	13	12
		12.5	12.5	12
With «Urahan F.»		9.2	3	6.5
		9.5	4.8	6
		12	4	9.5
With «Federal»		–	6.8	–
		–	–	–
		–	11	6
Concentrations		1/10	1/10	1/300
		14.5	5.1	13.1
		8.7	6	11.5
		14	8.7	13.7
With «Urahan F.»		7	3.5	6.5
		6.8	5	5
		7	7.1	5
With «Federal»		8	–	7.5
		9	–	11.5
		11	–	13

After one week of herbicide stress, growth was generally suppressed. In the most extreme case (herbicide + inoculant 1/10), plant growth was nearly halted. The highest growth at this stage was in control (no herbicide) and in treatments with BioFulvo (1/10) and potassium humate, which suggests some protective effect. Fig. 2 illustrates the relative heights under herbicide treatment.

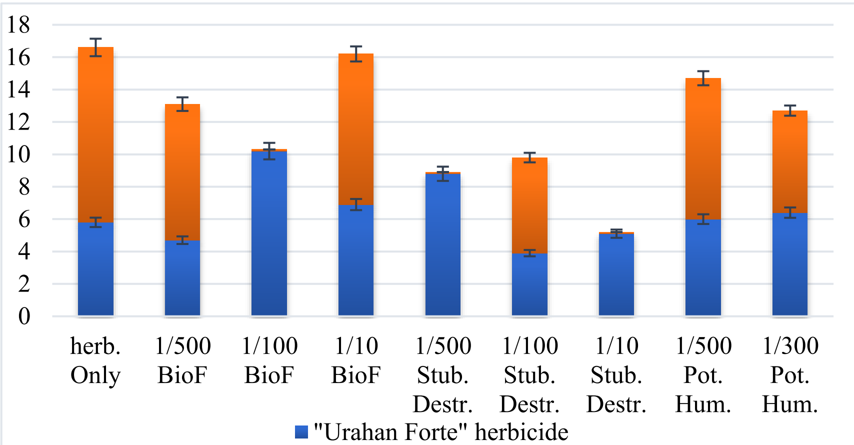

Fig.2. Growth ratio of herbicide-treated plants (cm)

One week later (day 18), plants received a second round of fertilizers. By day 18, potassium humate treatments showed the greatest recovery, with the highest average growth among all samples (Tabl. 3). BioFulvo also improved growth but to a lesser extent. The combined use of potassium humate likely helped plants adapt to the adverse conditions.

Table 3

Phytoindicator growth on the 18th day after sowing (cm)

Drugs	Control/ Water	«BioFulvo» Drug	Stubble destroyer	Potassium humate
Concentrations		1/500	1/500	1/500
	9.2	13.1	10.5	14
	9.5	16.5	12	15.2
	12.2	18	10.5	15.3
With «Urahan F.»	–	–	–	–
	–	–	–	–
	–	–	–	8.9
With «Federal»	–	–	–	–
	–	–	–	–
	–	–	–	–
Concentrations		1/100	1/100	1/300
		10	15.2	12.2
		10.2	14.5	12.9
		12.5	16	16.1
With «Urahan F.»		–	–	7.2
		–	4.8	–
		–	–	–
With «Federal»		–	–	–
		–	–	–
		–	–	–
Concentrations		1/10	1/10	1/300
		14.5	6.1	13.5
		14	6	12.5
		14	8.7	18
With «Urahan F.»		–	3.5	7.2
		–	5	6.9
		7	–	5
With «Federal»		–	–	–
		–	–	–
		–	–	–

By day 18, the highest single-sprout heights in controls were observed with: (1) Potassium humate 1/500 – 22.5 cm; (2) BioFulvo 1/500 – 19.5 cm; (3) BioFulvo 1/100 – 19.0 cm. Mortality rates under herbicide + biostimulant treatments were: Federal herbicide – 100 % mortality; Urahan Forte – 73 % mortality; with potassium humate 1/300 – 33 % mortality, 1/500 – 66 %; with BioFulvo 1/100 – 66 %, 1/10 – 66 %; with Stubble destroyer 1/100 – 66 %, 1/10 – 33%; all others – 100 %.

These results show that humic-based biostimulants promoted activation of plant defense mechanisms under stress. The potassium humate treatments, rich in K and trace elements, provided the strongest protection, likely by strengthening root systems and triggering stress-resistance pathways. The fulvic-rich BioFulvo also benefited early vegetative growth via its high biological activity and ability to increase membrane permeability for nutrients and metabolites. The mixed bacterial/fungal inoculant (Stubble Destroyer) did not consistently improve growth; indeed, some Trichoderma strains appeared to reduce growth when overdosed, indicating that such biostimulants require careful dosage and context-specific use.

4. Conclusions

Applying biostimulants based on humic substances to crops may improve their ability to withstand environmental stressors. The present study identified specific treatment combinations that significantly enhanced Sorghum growth under glyphosate stress. A deeper understanding of the mechanisms by which these biologic stimulants act—alone or in combination with microbes—will be needed to optimize their use. Our findings suggest that selecting the right type and concentration of humic-based fertilizer is crucial. In this experiment, a fulvic/humic fertilizer (BioFulvo) enhanced early growth, and potassium humate provided better protection against herbicide stress due to its nutrient content. The bacterial/fungal inoculant showed mixed results, highlighting that such treatments must be tailored to the crop, soil, and purpose.

In summary, humic substance–based preparations significantly influenced plant growth and stress adaptation. Fulvic acid–rich fertilizers improved cell permeability and growth in early stages, while potassium humate (with K and minerals) better stimulated protective functions and stress resistance. The presence of microbial inoculants (e.g. Trichoderma, Bacillus) can enhance effects but requires careful selection and dosage. These results underscore the promise of humic biostimulants in bioremediation and sustainable agriculture, provided their use is optimized based on environmental conditions and crop needs.

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OPTIMIZATION OF SUBSTRATE COMPOSITION BASED ON FOOD AND ORGANIC WASTE COMPOST

Oksana Shkvirko[1]✉, Myroslav Malovanyy[1], Ivan Tymchuk[1], Volodymyr Zhuk[1], Myroslava Bilokur[2], Lubomyr Tymchyshyn[2], Ruslan Boyko[1], Mariia Korbut[3], Bohdan Romanovych[1], Galyna Krusir[4]

[1]Lviv Polytechnic National University,
12, S. Bandera Str., Lviv, 79013, Ukraine
[2]Lviv communal enterprise "Green City",
1, Rynok Sq., Lviv, 79008, Ukraine
[3]Zhytomyr Polytechnic State University
103, Chudnivska Str., Zhytomyr, 10005, Ukraine
[4]Institute for Ecopreneurship, School of Life Sciences, University of Applied Sciences und Arts Northwestern Switzerland, Hofackerstrasse,
30, Muttenz, 4132, Switzerland
oksana.m.shkvirko@lpnu.ua

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Abstract. The research investigated the influence of compost-based substrates on plant growth and development over 25 days. The study utilized compost from the Lviv municipal enterprise “Green City”, which consisted of garden and park waste (leaves, branches, and mowed grass), as well as food waste from city residents and organic food waste from manufacturing enterprises. The composting process was conducted in a designated area under controlled conditions. A mixture of compost, peat, soil, sand, and clay, mixed in various ratios, was used to prepare the substrate. The bioindication method was used to evaluate how the substrates influenced the dynamics of plant growth. The experimental results were used to determine the average germination rate of ryegrass in the test samples, along with the average values of key plant parameters, including stem height, root length, and plant weight. It found that, after the experiment ended, the highest germination rate was in option 1 – 95.8 %, and the lowest in option 4 – 85.8 %. The highest average values of the main parameters of ryegrass were in options 1, 2, 3, and 4, and the lowest in the control sample and option 5.

Keywords: compost, substrate, bioindication, plant parameters, ryegrass.

1. Introduction

Modern agriculture and horticulture are actively seeking effective and environmentally safe methods to increase yields and improve product quality. A practical approach is to use sorbents (Ptashnyk et al., 2020; Soloviy et al., 2020; Malyovanyy et al., 2013) to enhance soil structure and encapsulated fertilizers (Vakal et al., 2020, Nahursky et al., 2022, Shkvirko et al., 2024, Grechanik et al., 2022) for the sustained release of plant nutrients. One of the key aspects in this context is the use of quality substrates that can influence plant growth and development. Recently,

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organic substrates based on c ompost have gained increasing popularity due to their environmental friendliness, high nutrient content, and ability to enhance the physicochemical properties of the soil (Shu et al., 2022).

Compost, when used as a substrate base, provides a rich supply of macro- and microelements, enhances soil structure, boosts its moisture retention ability, and supports the growth of beneficial microorganisms (Adugna, 2016; Cozzolino et al., 2016). However, different types of compost-based substrates can have different compositions and properties, which directly affects the effectiveness of their use in growing plants (Khater, 2015). Additionally, studies show that combining compost with other organic or inorganic components, such as peat, vermicompost, biochar, or mineral additives, can significantly alter its effects on plants (Bernal et al., 2017).

In the context of global climate change and increasing food needs, a crucial task is to enhance the resilience of agroecosystems and mitigate the anthropogenic pressure on soil cover. Therefore, the use of organic substrates, particularly compost-based ones, contributes not only to the conservation of natural resources but also to the reduction of synthetic fertilizer use, which in turn minimizes their negative environmental impact (Hargreaves et al., 2008). Additionally, composting organic waste helps alleviate the challenges of agricultural and household waste disposal, thereby contributing to a circular economy and sustainable agricultural development (Ayilara et al., 2020).

Studies have shown that the use of different compost-based substrates affects seed germination rates, plant biomass, root system development, and overall crop productivity (Hargreaves et al., 2008). However, the question of the optimal composition of substrates for specific plant species remains open, which necessitates a comparative analysis of different types of compost substrates. Furthermore, the effect of the substrate on plant development can depend largely on environmental conditions such as temperature, humidity, and soil type. Therefore, it is essential to determine which substrate characteristics—such as structure, organic matter content, water retention capacity, and microbiological activity—are most important for the growth of different plant species, as well as which combinations of components work best in various climate zones (Bedada et al., 2014).

Another key factor is the environmental advantages associated with the use of compost-based substrates. Because conventional fertilization methods frequently lead to negative effects like nitrate contamination of groundwater and soil degradation, using compost substrates offers a dual benefit: enhancing plant growth while also helping to preserve natural resources and reduce the environmental impact of agriculture (Ayilara et al., 2020, Grechanik et al., 2023).

The purpose of this study is to analyze and compare the effects of various compost-based substrates on plant growth and development.

This study will enable us to understand better the mechanisms by which different types of compost substrates influence plant growth and development. The findings can be used in industrial agriculture, organic farming, and horticulture to develop optimal crop cultivation technologies. Specifically, they can enhance the efficient use of organic waste, which is essential for promoting sustainable agricultural development and reducing environmental harm.

2. Materials and Methods

The studies were conducted using compost obtained from the Lviv Composting Station, along with dark gray podzolized soil, peat, sand, and clay.

The composting process was implemented at the composting site of the Lviv municipal enterprise “Green City” (Fig. 1).

Fig. 1. General view of the composting site of the Lviv municipal enterprise “Green City”

The technological scheme of composting provides for the presence of the following zones:

- composting zone (maturation in clamp), which is equipped with a hard improved coating and a sewage network for collecting surface rainwater and meltwater;

- branch crushing and screening area,
- input raw material storage areas,
- automotive parking lot;
- finished product storage area.

All organic and garden waste arriving at the composting station weighed on scales. Organic waste from the population is immediately loaded into containers for disinfection, where it remains for 48 hours. The branches are chopped in a woodchipper. After that, the organic waste is mixed with shredded wood, leaves, and grass. The resulting mixture is placed in clamps for maturation. The resulting mixture is placed in clamps for maturation. Every 3–5 days, the piles are mixed and aerated to prevent rotting. The composting process typically lasts between 3 a nd 5 months. This process occurs with the release of heat, so the temperature in the clamps can reach 70 °C. After 3 months, the mature, stabilized product is sieved through a sieve.

List of types of raw materials processed at the composting department:

- garden and park waste (leaves, branches, mowed grass);
- food organic waste from city residents;
- food organic waste from manufacturing enterprises.

All raw materials must meet the requirements specified in cooperation agreements.

During acceptance, company personnel verify compliance.

Requirements that raw materials must meet: the separately collected food waste must not contain plastic garbage bags, Tetra Pak, vinegar, oil, juice, milk, cheese, yogurt, butter, meat, fish products, or finished products that have been subjected to significant heat treatment as a result of frying.

To obtain substrates, the listed components were mixed in the following ratio:

- Control option: soil.
- Option 1: clay – 20 %, soil – 20 %, compost – 20 %, sand – 20 %, peat – 20 %.
- Option 2: clay – 20 %, soil – 20 %, compost – 30 %, sand – 20 %, peat – 10 %.
- Option 3: clay – 20 %, soil – 20 %, compost – 40 %, sand – 10 %, peat – 10 %.
- Option 4: clay – 0 %, soil – 30 %, compost – 40 %, sand – 30 %, peat – 0 %.
- Option 5: clay – 0 %, soil – 0 %, compost – 40 %, sand – 40 %, peat – 20 %.

To determine the effect of the substrate on plant growth and development, we used the bioindication method (DSTU, 2004; DSTU, 2002). To achieve this, 10 ryegrass seeds (*Lolium perenne*) were planted in 100 mL containers filled with the substrates mentioned above. During the experiment, observations were made of the time of sprout emergence, the number of sprouts per day, and overall germination. At the end of the experiment, root length and mass, as well as stem height and mass, were measured. To minimize statistical errors in data processing, experiments were conducted in six replicates.

3. Results and Discussion

To determine which substrate is best suited for growing plants using the bioindication method, the average germination rate of ryegrass was calculated, as shown in Tabl. 1.

Table 1

Average ryegrass germination rate in the study samples, %

Variant	Days						
	4	*6*	*8*	*10*	*15*	*20*	*25*
Control	34.2	77.5	89.2	89.2	89.2	89.2	89.2
Option 1	80.8	95.8	95.8	95.8	95.8	95.8	95.8
Option 2	60.8	85.0	89.2	89.2	90.0	90.8	90.8
Option 3	72.5	82.5	84.2	87.5	90.8	90.8	90.8
Option 4	59.2	79.2	80.8	85.8	85.8	85.8	85.8
Option 5	58.3	75.8	80.8	86.7	86.7	86.7	86.7

As can be seen from this table, the first ryegrass sprouts appeared in all samples on the 4th day, with the best germination rate of 80.8 % observed in option 1 and the lowest in the control sample – 34.2 %. However, when examining the other samples, as in the case of option 1, the average germination rates on the fourth day also exceeded those of the control sample (soil). Thus, option 2 exceeded the control by 77.8 %, option 3 by 111.9 %, and options 4 and 5 by 73.1 % and 70.5 %, respectively. On the sixth day, the average germination rate continued to be higher in the compost-containing samples, with option 1 showing the highest rate at 95.8 %, compared to 77.5 % in the control sample. Beginning on the 10th day of the experiment, the average germination rate in the control sample, as well as in options 1, 3, and 5, stabilized and remained unchanged through the end of the study. As for options 2 and 3, here, the average indicator continued to change for another 10 days. At the end of the experiment (day 25), the average germination rate in options 1, 2, and 3 exceeded the control (soil) by 7.4 %

and 1.8 %, respectively, and in options 4 and 5 this rate was already lower than the control by 3.8 % and 2.8 %, respectively.

Fig. 2 shows the general appearance of plants in the study samples on t he 25th day of the experiment.

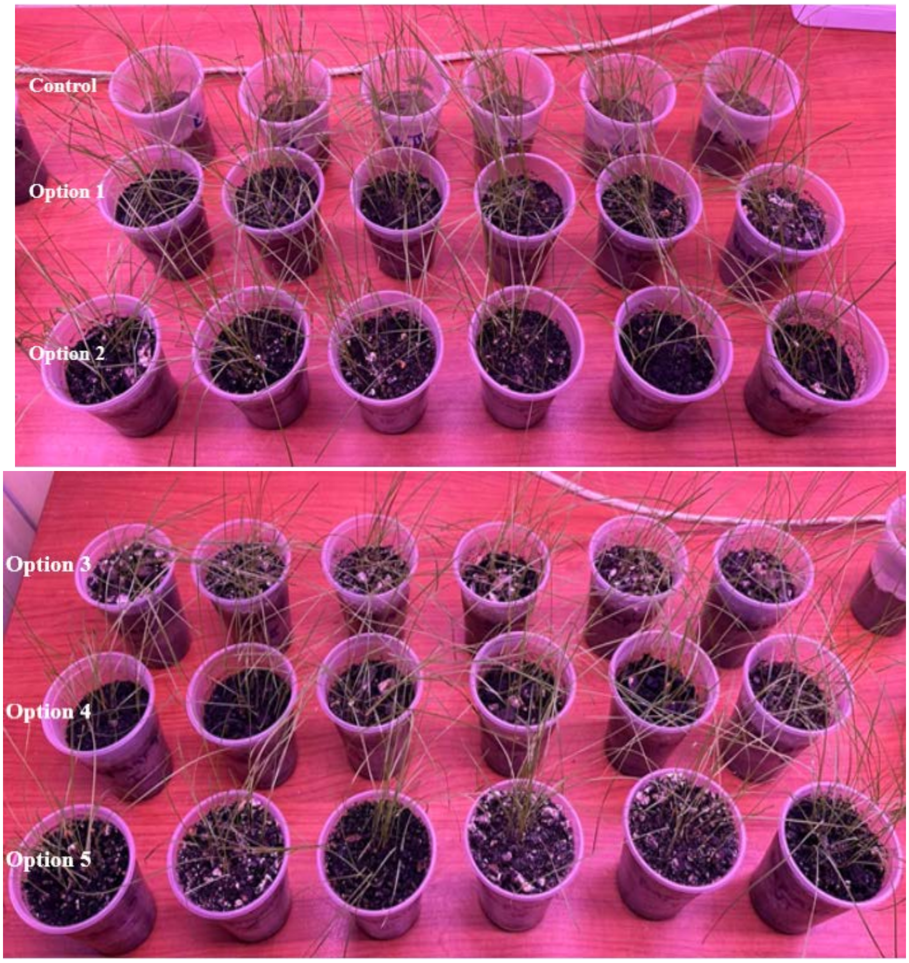

Fig.2. General appearance of ryegrass plants in the study samples on the 25[th] day

From this figure, it can be seen that, unlike the control sample, all samples containing compost had larger stems in the ryegrass plants, indicating an increased content of nutrients necessary for plant growth and development.

To determine the effect of compost-based substrates on the growth and development of ryegrass plants at the end of the experiment, Tabl. 2 presents the main plant measurement parameters (stem height, root length, plant weight).

Table 2

Average measurements of the main parameters of ryegrass development in experimental samples

Variant	Average stem height, cm	Average root length, cm	Average stem weight, g	Average root weight, g	Average plant weight, g
Control	13.54	1.64	0.014	0.006	0.02
Option 1	14.89	4.11	0.016	0.008	0.024
Option 2	14.33	5.06	0.013	0.005	0.018
Option 3	14.34	2.35	0.018	0.007	0.025
Option 4	14.58	3.46	0.019	0.008	0.027
Option 5	13.48	3.54	0.012	0.005	0.017

Based on the data in Table 2, graphs were created to illustrate the changes in the average values of the main ryegrass parameters across the experimental samples (Fig. 3, 4). The parameters of ryegrass growth in the control sample (soil) were taken as 100 %.

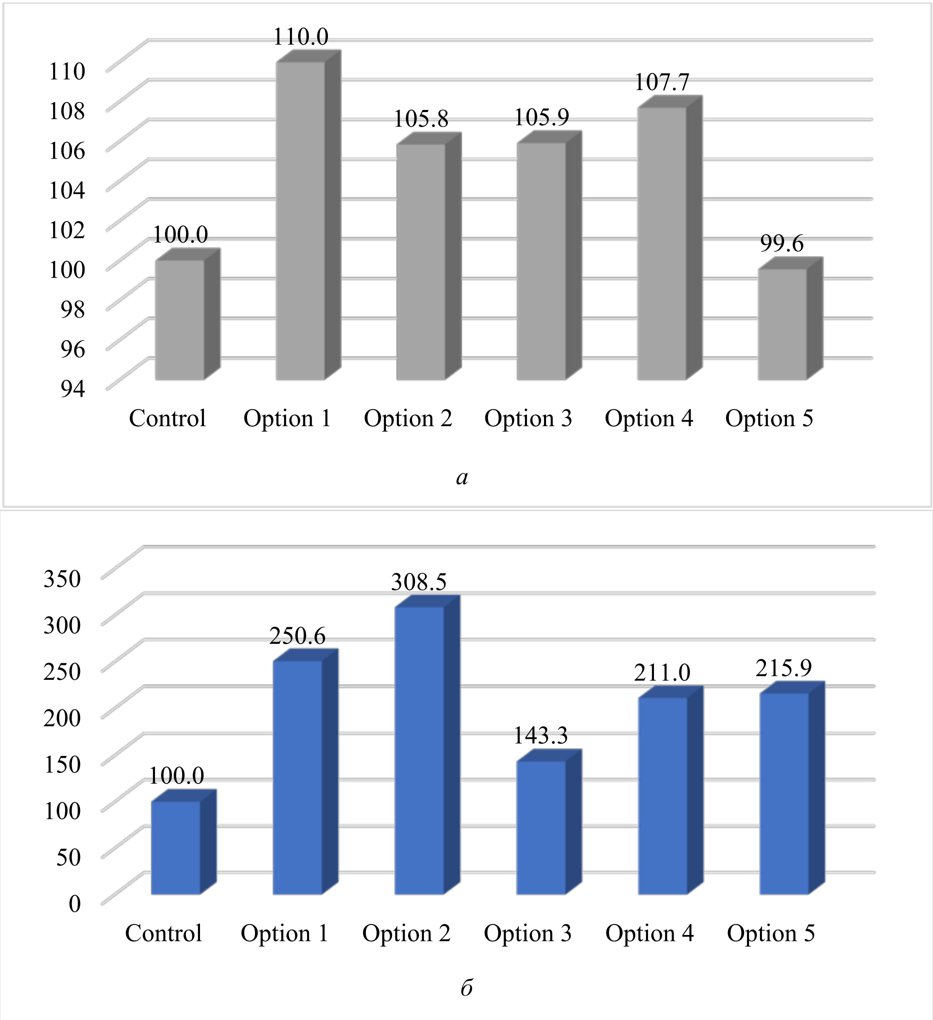

Fig.3. Change in ryegrass growth indicators in experimental samples: a – stem; b – root

The results indicate that the highest average stem heights of ryegrass were observed in options 1, 2, 3, and 4, surpassing the control by 10 %, 5.8 %, 5.9 %, and 7.7 %, respectively. In contrast, option 5 showed an average stem height that was 0.44 % lower than the control.

Regarding the roots (Fig. 3(b)), the average values show considerably greater variation compared to the control sample. The most substantial increase is seen in option 2, where the root index surpasses the control by 208.5 %. In options 1, 4, and 5, the increases are 150.6 %, 111 %, and 115.9 %, respectively. Even in option 3, although the increase is smaller, the value still exceeds the control by 43.3 %. As observed, in the four compost-containing substrates (options 1, 2, 4, and 5), the average root length was more than double that of the control, which can be attributed to the abundance of essential nutrients that support plant growth and development.

Figure 4 displays the results of variation in the mass of key ryegrass parameters.

The average stem mass (Fig. 4(a)) in options 1, 3, and 4 surpassed the control by 14.3 %, 28.6 %, and 18.8 %, respectively. In contrast, options 2 and 5 showed lower values, falling short of the control by 7.1 % and 14.3 %, respectively.

As in the previous case, the average root mass (Fig. 4(b)) exceeded the control sample in options 1, 3, and 4. Meanwhile, the highest values were recorded in options 1 and 4, each showing a 33.3 % increase compared to the control, while option 3 demonstrated a 16.7 % improvement. As for options 2 and 5, here, the average root mass was already 16.7 % less than the control in both cases.

Analyzing the average mass of ryegrass plants (Fig. 4(c)) reveals that, like the previous two parameters, the highest values were observed in options 1, 3, and 4 exceeding the control by 20 %, 25 %, and 3 5 %, respectively, while options 2 and 5 showed lower values, falling below the control by 10 % and 15 %, respectively.

Thus, in all three cases, the best impact on plant development was in options 1, 3, and 4.

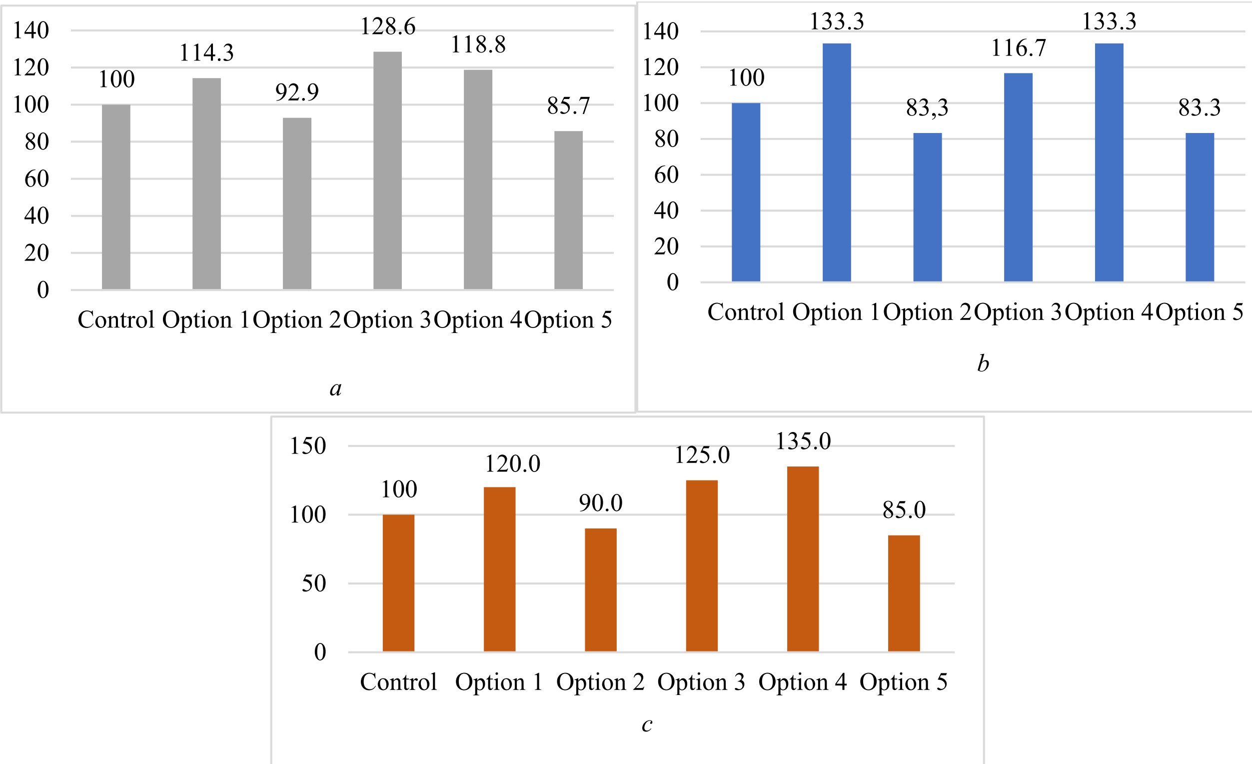

Fig.4. Variation in the mass of key ryegrass parameters across the experimental samples:
a – average mass of the stem; b – average mass of the root;
c – average mass of the plant

4. Conclusions

Hence, the study's findings demonstrate that substrates composed of compost and additional components have a positive influence on plant growth and development. Thus, the highest average germination rate was in option 1 – 95.8 %, and the average indicators of the main plant parameters exceeded the control by 10 % when determining stem height, by 150.8 % – root length, by 14.3 % – stem mass, by 33.3 % – root mass, by 20 % – plant mass. In addition, high rates were also in option 3 and the lowest in option 5.

Therefore, compost-based substrates can serve as a full or partial substitute for peat, commonly used to support plant growth, without compromising crop yields. Compost substrates supply plants with essential macro- and microelements and also harbor beneficial microorganisms that support healthy root system development. Moreover, these findings can help optimize cultivation techniques for both agricultural and ornamental crops, contributing to the development of guidelines for the efficient application of organic fertilizers in crop production.

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ENVIRONMENTAL PROBLEMS

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QUALITY ASSESSMENT OF DRINKING WATER FROM DIFFERENT WATER SUPPLY SOURCES IN VYNNYKY (LVIV REGION)

Ulyana Khromyak[1]✉, Pavlo Bosak[1], Oksana Telak[2]

[1]Lviv State University of Life Safety,
35, Kleparivska Str., Lviv, 79007, Ukraine
[2]Fire University,
52/54, Słowackiego Str., Warsawa, 01-629, Poland
ulanajukovska@gmail.com

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Abstract. A thorough evaluation of drinking water quality was performed for several sources in Vynnyky, Lviv region, including springs on B. Khmelnytsky and M. Kypriyan Streets, a well located at 17 K. Hrynevycheva Street, and tap water from the centralized supply system at 14 V. Sukhomlynskyi Street. The parameters analyzed encompassed total hardness, pH level, overall mineral content, as well as concentrations of chlorides, sulfates, iron, ammonium, nitrates, nitrites, and electrical conductivity The analysis revealed that water from the well at 17 K. Hrynevycheva Street had the most parameters exceeding acceptable limits. Notably elevated levels of total hardness, nitrates, and overall mineralization were identified, rendering this source inappropriate for drinking without prior purification The water sample from the spring on B. Khmelnytsky Street showed an elevated iron concentration, which negatively affects the sensory qualities of the water – such as its taste and appearance – and could potentially endanger human health if consumed over an extended period. Water obtained from natural sources exhibited elevated electrical conductivity and total dissolved solids, surpassing the thresholds established by European water quality regulations. In two of the samples – specifically, the spring on M. Kipriyan Street and the well – the nitrate levels were found to be 3 to 5 times higher than the allowable values outlined in Sanitary and Epidemiological Norms 2.2.4-171-10 for drinking water. Although tap water showed the smallest deviations among the tested sources, it still failed to comply with the standards of Council Directive 98/83/EC due to excessive mineral content and high electrical conductivity.

Keywords: drinking water, natural sources, well, centralized water supply, physical and chemical parameters.

1. Introduction

The quality of potable water plays a crucial role in maintaining public health and supporting the stability of ecosystems. In the context of the growing anthropogenic impact on the environment, increasing urbanization, and the usage of natural resources for economic and recreational purposes, the issue of systematic monitoring of water sources is becoming particularly relevant. Specifically, local water sources used without centralized treatment may be subject to contamination with nitrogen compounds, metals, and excess mineral components, which creates potential risks to human health (Klimchyk, 2019).

The issue of drinking water quality in Western Ukraine is addressed through a comprehensive assessment of physical, chemical, sanitary, hygienic, and

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microbiological indicators. In particular, in the Sambir territorial community, where the main source of water supply is wells (the study focused on wells located in the settlements of Chernikiv, Ralivka, and Novy Kalyniv, in the village of Kruzhiky), significant excesses of ammonium ion concentrations were detected – in some samples up to 4.1 mg/dm^3 while maximum permissible level is 0.5 mg/dm^3. Nitrate levels (11.3 – 18 mg/dm^3) remained within the norm (≤50 mg/dm^3), but their presence in water is a sign of potential fertilizer contamination. Increased water mineralization was also detected – up to 980 mg/dm^3, which is close to the limit value, and the total hardness ranged from 5.9 to 8.2 mmol/dm^3, exceeding the hygienic standard in some samples. The amount of phosphates and nitrites ranged from 0.073 mg/dm^3 to 0.082 mg/dm^3, respectively, indicating a systemic violation of drinking water quality in the region, which poses a risk to the health of the population, especially vulnerable groups (Bryndzia et al., 2025).

Similar negative trends were observed in a long-term study of changes in water quality in private wells in the village of Bryukhovychi (Lviv region) for the period 2011 – 2023. A significant increase in mineralization has been detected: while at the beginning of the observations the water was classified as fresh (<500 mg/dm^3), by 2023 the indicators approached or exceeded 1000 mg/dm^3, indicating a transition to a weakly mineralized type. Water hardness has also increased significantly, which may be the result of both natural and man-made factors. Ammonium, nitrates, and nitrites content has increased at most water sampling points, with many indicators exceeding the standards. The overall water quality for the period 2011 – 2023 has significantly deteriorated, making such water undesirable for regular consumption without additional purification (Kalmyk et al., 2024).

In a study (Stepova et al., 2019) of natural springs in Lviv, located in the Vysokyi Zamok and Pohulyanka parks, in Vynnyky, and green space near Lviv State University of Life Safety, it was found that all analyzed samples significantly exceeded the limit concentrations of calcium and magnesium, which determine the hardness of water at a level of more than 10 mmol/dm^3. The content of nitrates, nitrites, sulfates, ammonium, and lead in these samples also exceeds the relevant hygiene standards.

A study of the Lviv municipal system of water supply for 2009 – 2015 was analyzed, which showed the following results: 5.3-6.4 % of samples were not in compliance with sanitary standards, and 2.1-5.5 % were not in compliance with microbiological standards. In most cases, the problems are related to the high level of equipment wear (over 65-70 %), the lack of effective disinfection systems (often only chlorination is used), and the lack of sanitation protection zones around water intakes. In 50 % of rural water supply systems, sanitary protection projects have not been implemented at all. This creates conditions for the recontamination of already purified water during its transportation, and thus reduces its sanitary safety even in a centralized system (Krupa & Lototska-Dudyk, 2016).

The sources analyzed demonstrate a systematic degradation of potable water quality in the region of Western Ukraine. In decentralized systems (wells, springs), significant exceedances of permissible concentrations of ammonium, heavy metals (lead), nitrates, and increased hardness have been detected, making such water unfit for consumption without additional treatment. A gradual increase in mineralization and salt supersaturation has also been recorded in sources previously considered as safe. Although centralized water supply is of better quality, it is also vulnerable due to the technical deterioration of networks, inefficient purification technologies, and low levels of sanitary control. The data obtained indicate a critical need to upgrade water treatment systems, introduce modern disinfection methods, and create an effective monitoring system of water quality (Lotochka et al., 2019).

The town of Vynnyky, located 6 km east of Lviv, was selected for the study of drinking water quality. It is part of the Lviv city community and has an area of 6.67 km^2 with a population of about 20,000 people. The city is distinguished by its recreational resources, in particular Vynnyky Lake, a reservoir with running water. The Emily Resort sports and recreation complex and the Football Academy are located near the lake. The Marunka River, a left tributary of the Bilka River, which is part of the Western Bug River basin, also flows through the city. Its length is 14 km, and the basin area is 65 km^2 (Khromiak & Vorobets, 2025).

The objective of the study is to analyze the physical and chemical indicators of drinking water quality from various water sources in the city of Vynnyky, Lviv region.

2. Experimental part

The samples were taken from water sources in Vynnyky, located on B. Khmelnytsky Street (near the Emily Resort recreation complex) and M. Kipriyan

Street, to investigate their chemical content. The distance between them is 2.8 km. Also, for comparison, water samples were taken from a w ell on K. Hrynevychova Street, 17, and tap water (V. Sukhomlynsky Street, 14). Water samples were taken in February 2025.

The analysis of water samples war conducted at the research laboratory of environmental safety at Lviv State University of Life Safety. The following indicators were analyzed: total hardness, pH, total salt content, concentration of chlorides, sulfates, iron, ammonium, nitrates, nitrites, and electrical conductivity.

The methods used for determination of these indicators are standard and comply with the current requirements for water quality analysis. The study was based on the requirements of DSTU EN 1420-1:2004, DSTU ISO 7887:2003, DSTU 4077-2001, DSTU ISO 15923-1:2018, and DSTU ISO 6059:2003 (DSTU EN 1420-1:2004, 2004; DSTU ISO 6059:2003, 2003; DSTU ISO 7887:2003, 2003; DSTU ISO 1 5923-1:2018, 2018; DSTU 4077-2001, 2001).

At the sampling site, an analysis of organoleptic indicators was carried out, including smell and the general appearance of the sample (characteristic color, turbidity, sediment), and transparency.

3. Results and Discussion

Total water hardness (Fig. 1) is one of the key physical and chemical parameters that determines the calcium and magnesium content in water, which, in high concentrations, not only change its organoleptic properties, but can also have an adverse effect on human health and the functioning of household appliances.

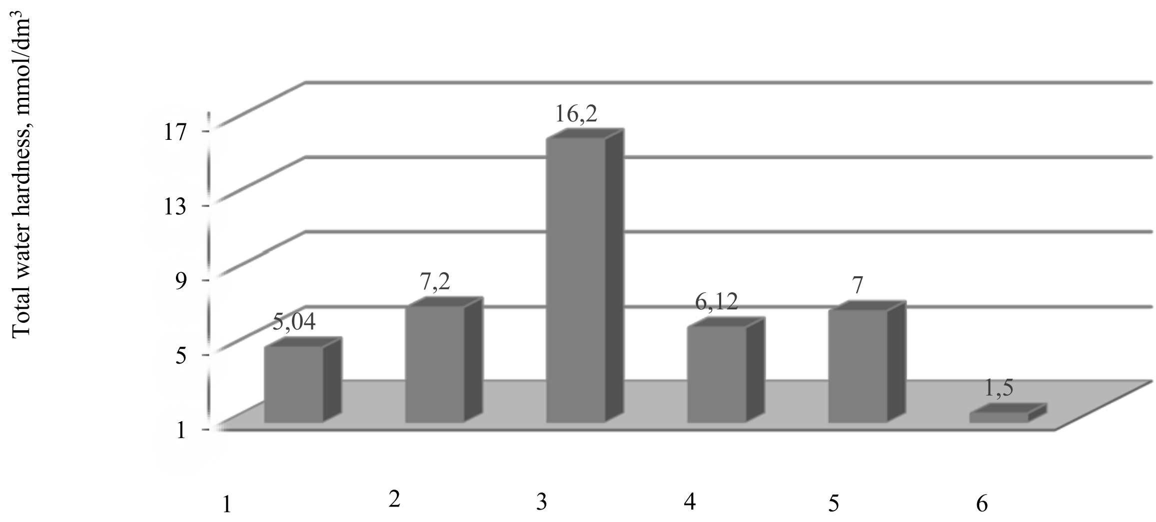

Fig. 1. Total water hardness: 1 – spring on M. Kipriyan Street; 2 – spring on B. Khmelnytsky Street; 3 – well on K. Grynevychova Street, 17; 4 – tap water on Sukhomlynskoho Street 14; 5 – drinking water requirements according to DSanPiN 2.2.4-171-10; 6 – drinking water requirements according to Directive 98/83/EC

According to the results in Fig. 1, it was found that the highest level of total hardness was recorded in the sample from the well on K. Grynevycha, 17 (16.2 mmol/dm^3), which exceeds the hygienic standards established by DSanPiN 2.2.4-171-10 (7.0 mmol/dm^3) twice (DSanPiN 2.2.4-171-10, 2010) and the requirements of Directive 98/83/EC more than thrice (Directive 98/83/EC of the Council, 1998). This indicates excessive water hardness, which requires pre-treatment of water before consumption.

Water from the spring on B. Khmelnytsky Street is also characterized by increased hardness (7.3 mmol/dm^3). In samples from the spring on M. Kipriyan Street (4.5 mmol/dm^3) and tap water (3.9 mmol/dm^3), the total hardness does not exceed the limits, which indicates their conditional suitability for consumption in terms of this indicator.

An important indicator affecting the quality of drinking water is the hydrogen index (pH) (Fig. 2).

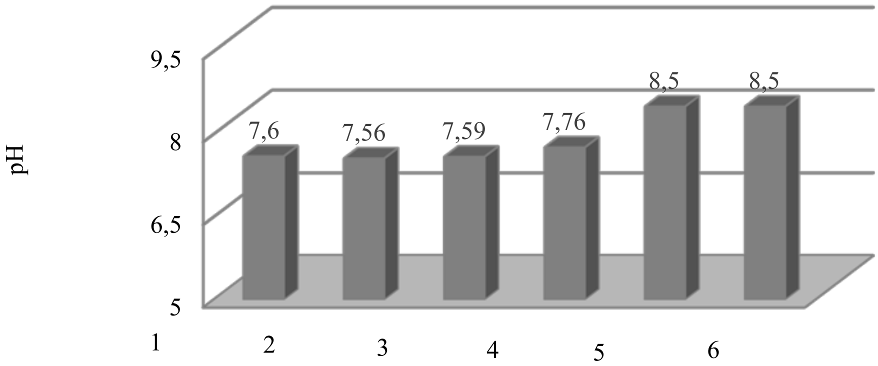

Fig.2. Hydrogen index (pH): 1 – spring on M. Kipriyan Street; 2 – spring on B. Khmelnitsky Street; 3 – well on K. Grynevychova Street, 17; 4 – tap water on Sukhomlynskoho Street, 14; 5 – requirements for drinking water according to DSanPiN 2.2.4-171-10; 6 – requirements for drinking water according to Directive 98/83/EC

In all s amples, the hydrogen index is within normal limits. The optimal pH of drinking water ranges from 6.5 to 8.5. It should be noted that a low pH in water creates an acidic medium in the body, which leads to thickening of the blood, saliva, and lymph, hindering the enrichment of cells with oxygen and the removal of toxins, and leading to the blood clots formation and parasites promoting. All people with cancer have acidification of the organism (low pH) (Bardov et al., 2020).

It should be noted that the total salt content (mineralization) is an important indicator of drinking water quality, characterizing the total concentration of dissolved inorganic substances – primarily Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, SO_4^{2-}, and CO_3^{2-}. Excessive mineralization can have a n egative impact on human health, in particular, increased stress on the cardiovascular system, disruption of the water-salt balance, and kidney function (Bardov et al., 2020). Figure 3 shows a comparative assessment of the salt content in water from various sources in the city of Vynnyky, including natural springs, wells, and the water supply system, and regulatory limits according to Ukrainian and European standards (DSanPiN 2.2.4-171-10, 2010; Directive 98/83/EC of the Council, 1998).

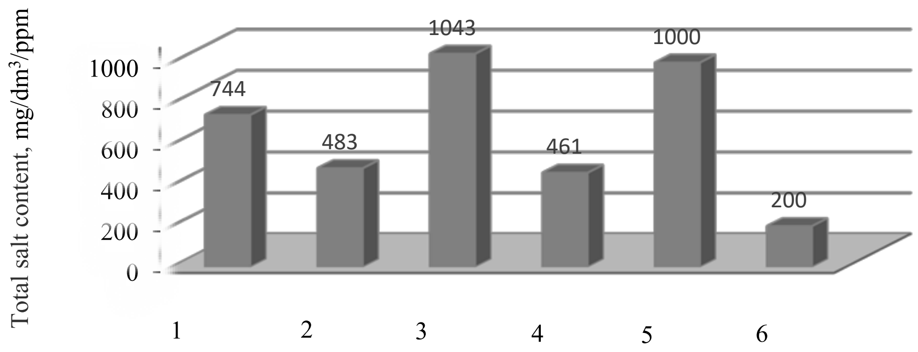

Fig.3. Total salt content: 1 – spring on M. Kipriyan Street; 2 – spring on B. Khmelnitsky Street; 3 – well on K. Grynevychova Street, 17; 4 – tap water on Sukhomlynskoho Street, 14; 5 – requirements for drinking water according to DSanPiN 2.2.4-171-10; 6 – requirements for drinking water according to Directive 98/83/EC

According to DSanPiN 2.2.4-171-10, which are approved in Ukraine, there is practically no excess of normal limits in these samples (in sample 3 there is an insignificant increase in salt content). If these values are compared with the requirements for drinking water according to Council Directive 98/83/EC of November 3, 1998, all samples exceed the standards.

Chlorides and sulfates are important inorganic components of drinking water. Their excessive content in the drinking water can negatively affect its organoleptic properties, cause corrosion of pipelines, and disrupt human organ functions. The sources of these compounds can be both natural geological formations and anthropogenic factors, in particular domestic and industrial wastewater and the use of mineral fertilizers. Therefore, determining the content of Cl^- and SO_4^{2-} is a n ecessary stage in the comprehensive analysis of drinking water quality. The ions content was measured in selected water samples.

No elevated content of Cl^- and SO_4^{2-} were detected in any of the test samples analyzed. This indicates the absence of Cl^- and SO_4^{2-} contamination, which is a positive marker, since an excess of these ions can cause a bitter taste, have a negative impact on human health, and cause pipeline corrosion.

Iron is one of the quality indicators of drinking water. High iron content can change the color, smell, and taste of water, cause sediment, and, with long-term consumption, lead to iron accumulation in the body, which negatively affects the liver, pancreas, and cardiovascular system (Bardov et al., 2020). Fig. 4 shows the iron content in water from different sources in the city of Vynnyky.

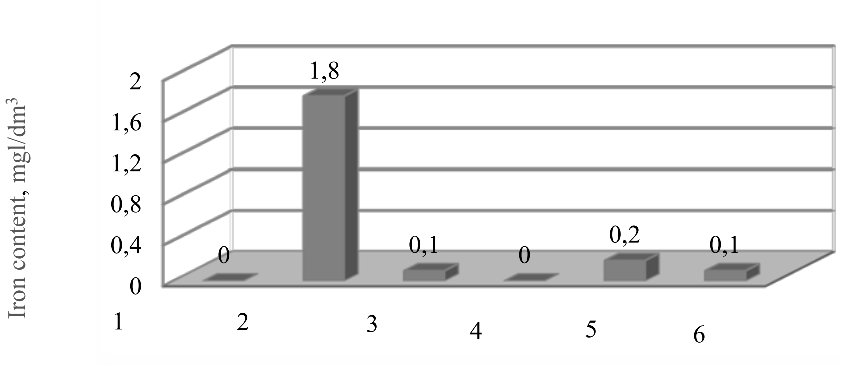

Fig.4. Iron content: 1 – spring on M. Kipriyan Street; 2 – spring on B. Khmelnitsky Street; 3 – well on K. Grynevychova Street, 17; 4 – tap water on Sukhomlynskoho Street, 14; 5 – requirements for drinking water according to DSanPiN 2.2.4-171-10; 6 – requirements for drinking water according to Directive 98/83/EC

A significant excess of iron content was found in sample 2 (source on B. Khmelnytsky Street). Water from this source had a characteristic rusty color and a metallic taste. No excessive iron content was found in rest water samples studied.

The ammonium content in water was also examined (Fig. 5). Excessive ammonium concentration in water may indicate the organic residues or domestic sewage. These indicators are controlled in accordance with national and European water quality standards.

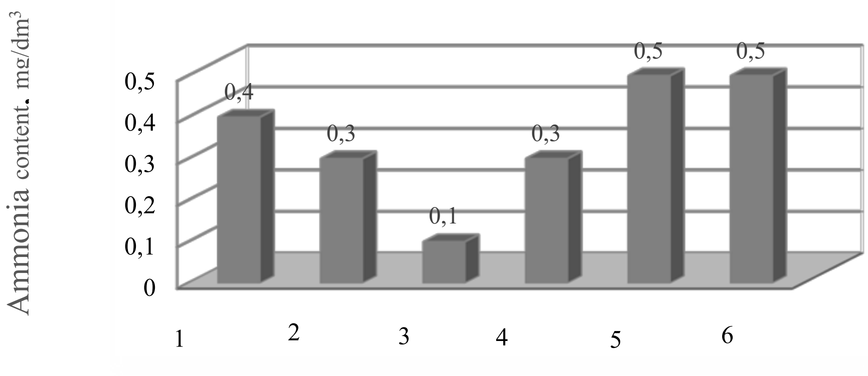

Fig.5. Ammonia content: 1 – spring on M. Kipriyan Street; 2 – spring on B. Khmelnitsky Street; 3 – well on K. Grynevychova Street, 17; 4 – tap water on Sukhomlynskoho Street, 14; 5 – requirements for drinking water according to DSanPiN 2.2.4-171-10; 6 – requirements for drinking water according to Directive 98/83/EC

It has been established that the ammonium content in the samples doesn't exceed the limits.

NO_3^- are among the most common chemical pollutants of natural and drinking water, which enter water sources mainly through agrochemicals, wastewater, and the decomposition of organic matter. The excessive content of nitrates in drinking water poses a great threat to human health, especially for children, as it can lead to methemoglobinemia. Monitoring nitrate content is a key part of water quality monitoring. Fig. 6 shows the nitrate content in water samples collected in the city of Vynnyky.

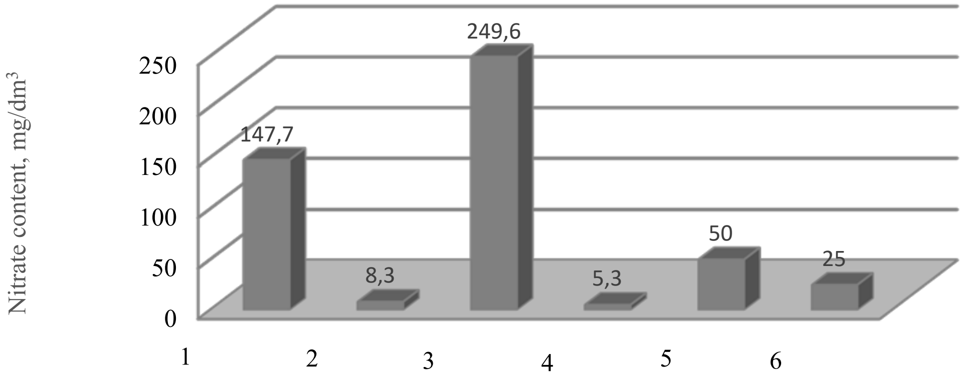

Fig.6. Nitrate content: 1 – spring on M. Kipriyan Street; 2 – spring on B. Khmelnitsky street; 3 – well on K. Grynevychova Street, 17; 4 – tap water on Sukhomlynskoho Street, 14; 5 – requirements for drinking water according to DSanPiN 2.2.4-171-10; 6 – requirements for drinking water according to Directive 98/83/EC

The highest concentration of nitrates was found in water from a well on K. Grynevychova Street, 17, and from a spring on M. Kipriyan Street, exceeding permissible standards. Water from a spring on B. Khmelnytsky Street and tap water meet sanitary standards. The results indicate the need for purification and constant monitoring of sources with elevated nitrate levels.

Nitrates become toxic because they are partially converted into more toxic nitrites in the digestive organs, causing tissue respiration disorders. Nitrates form cancer-causing substances in the body. When water containing nitrates is consumed, there is a lack of oxygen for the respiratory organs, resulting in suffocation. It's especially dangerous for small children and infants. Nitrates are imperceptible in color, smell, and taste; on the contrary, the more nitrates there are, the more “tasty” the water feels (Bardov et al., 2020).

The studies conducted did not reveal any nitrites in the samples.

Electrical conductivity in drinking water is not regulated, but this indicator is important for protecting the water supply system. High electrical conductivity can cause corrosion. All tested samples have increased electrical conductivity.

4. Conclusions

Water from natural springs in Vynnyky, Lviv region, on B. Khmelnytsky Street and M. Kypriyan Street, and from the well (K. Hrynevych Street, 17) and tap water (V. Sukhomlynsky Street, 14) were examined. Research revealed that the water is unsuitable for consumption. It was found out that all samples contained excessive levels of various indicators.

The greatest deviations were observed in the water sample from the well (K. Hrynevychova Street, 17) where significant exceedances of the following indicators were recorded: total hardness of 16.2 mmol/dm^3, which significantly exceeds the permissible standards, the concentration of NO_3^- exceeded the sanitary permissible level by 5 times, and the total salt content (1043 mg/dm^3) exceeded the European standard (up to 200 mg/dm^3). The water from the spring on B. Khmelnytsky Street has excessive iron content, which impairs the organoleptic properties of the water and poses a potential risk to human health with prolonged consumption. All samples showed increased electrical conductivity, indicating an excessive content of dissolved impurities. At the same time, the pH, NH_4^+, Cl^-, SO_4^{2-}, and NO_2^- values remained within the established standards. The investigation highlights the importance of pre-treatment of water before consumption, along with the implementation of continuous monitoring of water resources in the town of Vynnyky to ensure safe water supply and prevent environmental and medical-biological risks.

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ENVIRONMENTAL PROBLEMS

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IMPACT OF MILITARY OPERATIONS ON THE NATURE RESERVE FUND OF UKRAINE

Olena Uvaieva[1]✉, Larysa Shevchuk[2], Olena Herasymchuk[2], Liudmyla Vasilieva[2]

[1]Polissia National University,
7, Staryy Blv., Zhytomyr, 10002, Ukraine
[2]Zhytomyr Polytechnic State University,
103, Chudnivska Str., Zhytomyr, 10005, Ukraine
bio-2016@ukr.net

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Abstract. The war in Ukraine has caused extensive destruction to the Nature Reserve Fund (NRF), resulting in land degradation, water pollution, biodiversity loss, and disruption of ecosystem functions. Over 1.2 million hectares of protected areas (≈30 % of the NRF) have been impacted. The estimated environmental damage exceeds 2 trillion UAH (~55 billion USD), with restoration costs projected at 1.5–2 billion USD.Key consequences include the loss of 70–80 % of steppe ecosystems, soil contamination with heavy metals (5–10 times above safe levels), 30–50 % reductions in rare fungi and plant populations, and a 25–40 % decline in key bird species. Water pollution has critically degraded rivers such as the Siverskyi Donets and Dniester, and the Black Sea, causing mass die-offs of aquatic organisms. The study also highlights the role of wildfires in NRF degradation, with satellite data revealing increased thermal anomalies and large-scale fires, particularly in the Askania-Nova Biosphere Reserve. Vegetation recovery remains incomplete due to severe ecosystem disturbance. An integrated methodology–combining descriptive analysis, GIS, ecological monitoring, and remote sensing–was employed to assess environmental damage. The findings underline the urgent need for comprehensive recovery measures, including demining, soil remediation, water restoration, and biodiversity conservation. International cooperation (EU, UNEP, World Bank, WWF) and reparations are key mechanisms to support Ukraine's post-war ecological recovery.

Keywords: Nature Reserve Fund (NRF), war impact, wildfires, soil pollution, biodiversity loss, ecosystem restoration.

1. Introduction

The Nature Reserve Fund (NRF) of Ukraine is a national asset and an integral part of the global natural and cultural heritage. In this study, the NRF refers to the state-managed network of protected areas in Ukraine established under national conservation legislation. It includes nature reserves, biosphere reserves, national nature parks, and other officially designated protected territories. These areas encompass ecosystems and landscapes vital for the preservation of Ukraine's rare biodiversity and natural heritage, while also supporting sustainable environmental development and maintaining ecological balance. As such, the NRF constitutes a core component of the national ecological network (On the Nature Reserve Fund, 2018).

War is among the most destructive drivers of environmental catastrophes, often resulting in long-term ecological consequences. During the ongoing conflict in Ukraine, protected areas have suffered extensive damage (Hartmane et al., 2024). Since the onset of armed aggression by the russian federation in 2014, numerous nature reserves, national parks, and other protected sites have been impacted by military activity, pollution, and disrupted natural processes.

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According to the Ministry of Environmental Protection and Natural Resources of Ukraine, approximately 30 % of protected areas have been affected, encompassing over 900 individual sites (Pereira et al., 2022; Udovenko et al., 2023). This poses a major threat to biodiversity and ecological stability, as these areas are critical for conserving rare species of flora and fauna and delivering key ecosystem services, including water purification, carbon sequestration, and climate regulation (Mammadov et al., 2024).

The impact of war on Ukraine's NRF includes the destruction of ecosystems, water and soil contamination (Biyashev et al., 2024; Shebanina et al., 2024), and exposure to hazardous chemicals, ammunition, and landmines that hinder natural restoration (Drobitko & Alakbarov, 2023; Subiros et al., 2024). Critical ecological disruptions include interrupted animal migration routes, declining populations of rare species, and shifts in plant communities caused by environmental contamination (Rawtani et al., 2022; Tsaryk & Kuzyk, 2022; Kvach et al., 2025). The military conflict has also significantly degraded aquatic ecosystems, with rivers and lakes polluted by oil, heavy metals, and chemical residues from military equipment and munitions (Slessarev et al., 2024), while simultaneously undermining ecological tourism and conservation efforts (Kucher et al., 2023).

Of particular concern is the intensification of wildfires across protected areas, caused by c ombat activity, shelling, airstrikes, and the inability to respond due to landmines or occupation. These pyrogenic impacts have destroyed habitats and disrupted vegetation cycles, severely limiting ecosystem resilience and recovery (Filho et al., 2024; Gatti et al., 2025).

One of the most pressing challenges is assessing the environmental damage to protected areas, given the long-term consequences for biodiversity and ecosystem functionality (Zwarich & Pylipets, 2024). It is critical to identify contamination levels and develop damage assessment methodologies that support effective postwar ecosystem restoration and conservation planning (Gatti et al., 2025). Restoration strategies must adopt an integrated approach that combines ecological, social, and economic dimensions while leveraging international conservation mechanisms for biodiversity and ecosystem service recovery (Skliar & Skliar, 2024).

Ukraine's protected areas play a vital ecological role not only at the national level but also as part of global natural systems. Their destruction or degradation carries broader implications for biodiversity and ecological security in Europe and globally. Therefore, it is essential to implement both national recovery initiatives and internationally aligned conservation strategies focused on sustainable ecosystem development (Verzillo, 2025). The protection of Ukraine's NRF during wartime requires the development and implementation of new natural resource management approaches to safeguard the country's environmental heritage for the future.

The *objective* of this study is to provide a comprehensive analysis of the destructive impact of warfare on land, water resources, and biodiversity within Ukraine's NRF, assess pyrogenic dynamics and environmental damage, and outline restoration pathways for protected areas with international support.

2. Materials and Methods

2.1. Area of Study

Fig. 1 illustrates the impact of the war on Ukraine's NRF, highlighting the affected forests, steppes, and other protected areas. The most damaged regions include the eastern, southern, and northern parts of Ukraine, where military operations have led to significant environmental degradation. The war zone overlaps with critical natural reserves, particularly in Donetsk, Luhansk, Kherson, Zaporizhzhia, and Crimea, posing a severe threat to biodiversity and ecosystem stability.

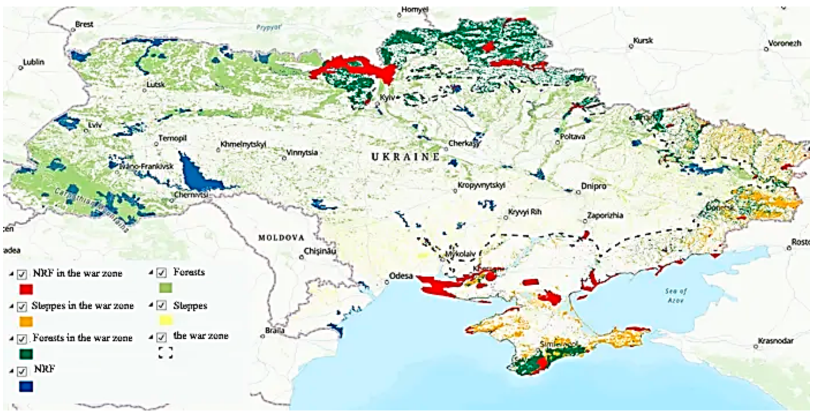

Fig.1. Damage to natural and protected areas of Ukraine due to the military invasion of the russian federation (Ministry of Environmental Protection and Natural Resources of Ukraine, 2023).

2.2. Methods

An integrated methodological approach was applied, combining descriptive analysis, spatial (GIS) analytics, ecological monitoring, and remote sensing techniques to assess the environmental consequences of warfare on NRF territories.

1. Remote Sensing and GIS Analysis. Satellite monitoring data were used to evaluate the pyrogenic dynamics of protected areas. Thermal anomalies were identified using NASA FIRMS data, based on MODIS and VIIRS sensors with spatial resolutions of 375–1000 meters. To determine the extent of burned areas, multispectral Sentinel-2 imagery with 10-meter resolution was utilized. Damage visualization was performed using the Short-Wave Infrared Reflectance (SWIR) index. Post-fire vegetation recovery was analyzed using the Normalized Difference Vegetation Index (NDVI), calculated from red and near-infrared reflectance bands.

2. Spatial Analysis of Ecosystem Degradation. Pre-war and post-war conditions of natural territories were compared using Sentinel-2 imagery in the QGIS environment. Indicators assessed included forest cover loss, wetland degradation, habitat fragmentation, landscape structure changes, and the identification of the most severely affected areas.

3. Descriptive and Archival Analysis. Archival environmental data regarding NRF conditions before and after the full-scale invasion were systematized. Sources included official reports from the Ministry of Environmental Protection of Ukraine, the State Environmental Inspectorate, scientific publications, and open-source data (media, satellite services).

4. Ecological Monitoring. Field and remote-sensing observations were conducted to assess biodiversity changes and the condition of soils and water. Baseline ecological indicators were established to characterize the impact of warfare on rare and endangered species, soil fertility, and hydrological stability.

This integrated approach enables an in-depth investigation of the scale of ecological destruction, the spatial dynamics of fire-related processes, and the ecosystem restoration potential within Ukraine's protected areas.

Area and number of NRF located in hazardous zones and temporarily occupied territories (Rybalova et al., 2023)

Type of NRF	Total Area of NRF, ha	Number of NRF	NRF in Hazardous Zones		NRF in Occupied Territories	
			Area, ha	Number	Area, ha	Number
Nature Reserve	92578	9	14197	5	51775	6
Biosphere Reserve	369527	3	334217	3	-	-
National Nature Park	406855	17	270098	15	14005	3
Regional Landscape Park	224359	16	125972	15	84	1
Nature Sanctuary	524241	797	328537	739	112599	61
Protected Tract	22832	103	18625	101	553	2
Natural Monument	9319	392	7045	350	2263	42
Botanical Garden	1135	4	55	2	1080	2
Dendrological Park	406	6	404	6	-	-
Zoological Park	49	3	45	3	-	-
Park-Monument of Landscape Art	1890	76	1232	62	387	14
Total	1653191	1426	1100427	1301	182746	131

3. Results and Discussion

3.1. Adverse Impact of War on the Land Resources of Ukraine's NRF

Military operations in Ukraine have led to significant degradation of land resources within NRF, manifesting in mechanical soil destruction, contamination with toxic substances, and the loss of natural vegetation cover (Smirnova et al., 2024). According to the Ministry of Environmental Protection and Natural Resources of Ukraine, approximately 1.2 million hectares of protected land have been affected by military actions, accounting for more than 30 % of the total NRF area. The most heavily damaged regions include Kharkiv, Donetsk, Luhansk, Kherson, and Zaporizhzhia oblasts, where hostilities have been most intense (Dudnieva, 2024).

In total, 17 national parks, 9 nature reserves, and 3 biosphere reserves have come under the influence of active hostilities or occupation. Among them are UNESCO-recognized sites such as the Black Sea Biosphere Reserve, located in Kherson and Mykolaiv oblasts, and the Askania-Nova Biosphere Reserve. Up to 14 % of the Chornobyl Radiation and Ecological Biosphere Reserve was affected by fire caused by military activities, and up to 94 % of the territory was under occupation, leading to severe soil degradation (Filho et al ., 2024)One of the most severe consequences of the war has been the destruction of steppe ecosystems in southern and eastern Ukraine. In Meotyda National Nature Park (Donetsk Oblast), over 80 % of the territory was devastated by artillery shelling and military equipment. Explosions and fires destroyed vast areas of rare flora, including Ukrainian feather grass (*Stipa ucrainica* P. Smirn., 1951) and Schrenk's tulip (*Tulipa schrenkii* Regel, 1873) (Kvach et al., 2025). The destruction of steppe soils has also led to the disappearance of habitats for species such as the spotted ground squirrel (*Spermophilus suslicus* (Güldenstädt, 1770)) and the Caspian whipsnake (*Dolichophis caspius* (Gmelin, 1789)), both listed in the Red Book of Ukraine.

Mechanical soil disruption has caused widespread erosion, which has significantly accelerated due to military operations. According to ecological assessments, in regions like the Luhansk Nature Reserve, water erosion has increased 3–4 times, resulting in the loss of topsoil and impeding natural soil regeneration (Kucher et al., 2023). Heavy machinery traversing protected areas has compacted the soil, negatively affecting its structure and aeration. As a result, vegetation recovery has been considerably slowed or rendered impossible without human intervention.

Another ecological concern is chemical contamination of soils due to munitions explosions, military equipment residues, and fuel spills. In Zaporizhzhia National Nature Park, levels of heavy metals such as lead, cadmium, and mercury have been found to exceed pre-war levels by 5–10 times (Gatti et al., 2025). Toxic contamination leads to mutations and the death of microorganisms that play a key role in maintaining soil fertility. This directly impacts plant health and poses a threat to wildlife that comes into contact with contaminated soil and water (Slessarev et al., 2024).

In addition to chemical contamination, landmines have become a serious environmental threat across protected territories. According to the State Environmental Inspectorate of Ukraine, approximately 30 % of natural areas in conflict zones are contaminated with explosive ordnance, making them inaccessible and unfit for natural regeneration. For example, in the Chornobyl Biosphere Reserve, around 2,000 mines and munitions have been identified, endangering species such as the Przewalski's horse (*Equus przewalskii* (Poliakov, 1881)) and the white-tailed eagle (*Haliaeetus albicilla* (Linnaeus, 1758)) (Halyna et al., 2024). In the Yelanets Steppe Nature Reserve, located in Mykolaiv Oblast, large areas have been mined, preventing conservation measures and biodiversity monitoring efforts.

3.2. Analysis of Pyrogenic Dynamics within Ukraine's Nature Reserve Fund

The full-scale invasion of Ukraine by the russian federation has significantly intensified wildfire impact on the country's NRF. Areas that previously experienced minimal anthropogenic disturbance have become zones of active conflict, which has severely limited the implementation of fire prevention measures. Since early 2022, the number of thermal anomalies across Ukraine has dramatically increased, particularly within national parks and biosphere reserves.

Satellite data from FIRMS (MODIS and VIIRS) confirmed numerous instances of thermal anomalies indicative of wildfire activity. Compared to the pre-war period (January–February 2022), a marked increase in thermal hotspots was observed in March–April 2022, especially in areas of ongoing combat. This trend persisted into 2023–2025, albeit with some reduction in intensity in later years (Fig. 2).

a *b* *c*

Fig.2. Thermal anomalies in Ukraine for the periods: a – 24.01–24.02.2022, b – 24.02–24.03.2022, c – 01–30.04.2025

The Askania-Nova Biosphere Reserve exemplifies the large-scale pyrogenic impact. In 2023 alone, at least seven major wildfires were recorded within the reserve, destroying over 5,300 hectares of steppe ecosystems. Sentinel-2 satellite imagery using the SWIR spectral index clearly delineated burn zones and enabled detection of changes in phytocenotic structures (Fig. 3).

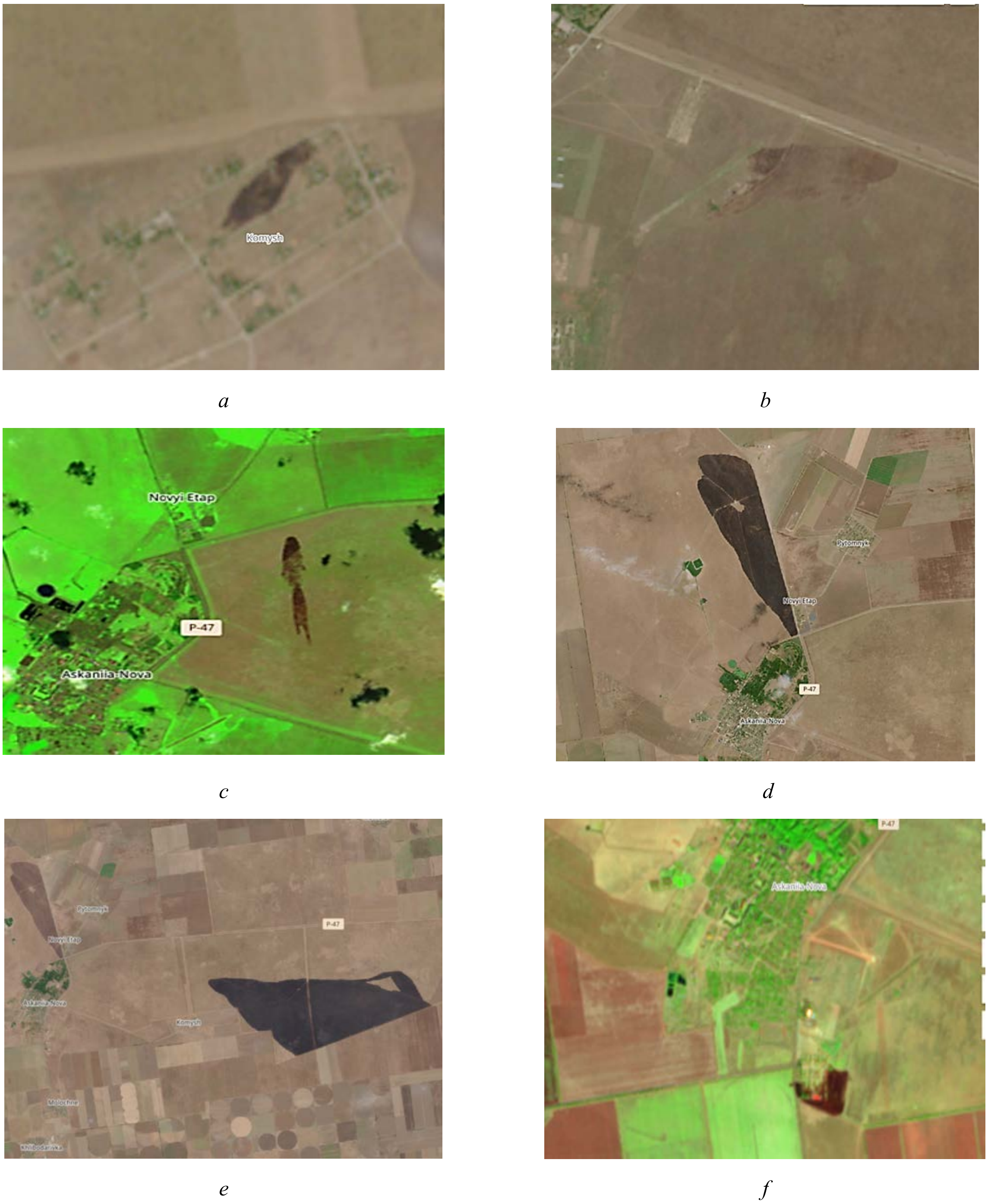

Fig.3. Pyrogenic events in the Askania-Nova Reserve during:
a – 30.07.2022, b – 29.08.2022, c – 27.03.2023, d – 24.08.2023, e – 08.09.2023, f – 28.09.2023

The post-fire ecosystem recovery in Askania-Nova was evaluated using the Normalized Difference Vegetation Index (NDVI). NDVI dynamics indicated gradual, yet incomplete, vegetation regeneration in 2024 following peak fire events in August–September 2023. Vegetation indicators in summer 2024 remained below pre-war levels, highlighting the lasting impact of wildfires (Fig. 4).

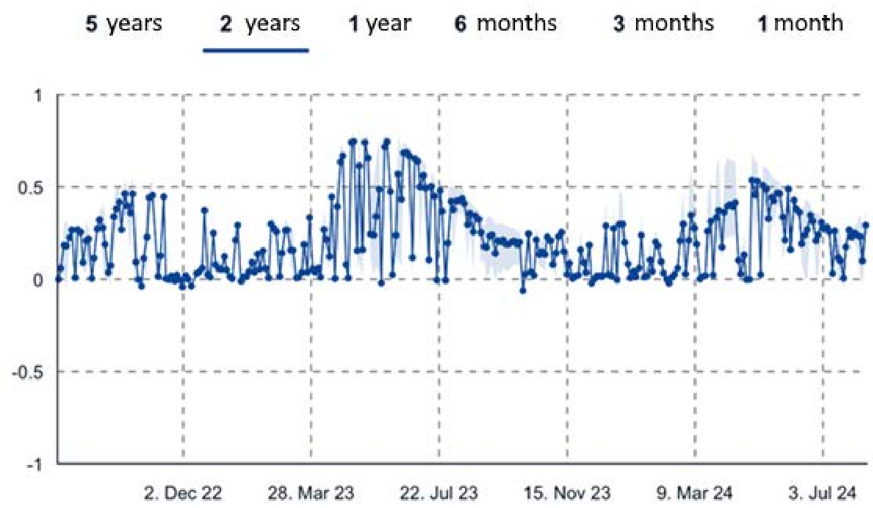

Fig.4. NDVI trends in the area of highest pyrogenic impact within Askania-Nova Reserve

Overall, pyrogenic dynamics within Ukraine's NRF during wartime are marked by high spatial variability and closely correlate with front-line proximity and combat intensity. The most affected reserves are located in occupied zones or near active hostilities. These findings are critical for assessing the loss of Ukraine's natural heritage and for designing strategies for ecological rehabilitation of impacted areas.

3.3. Pollution of Water Resources in Ukraine's Nature Reserve Fund During the War

The war in Ukraine has caused extensive pollution of water resources, significantly affecting ecosystems within NRF. Explosions, shelling, the destruction of hydraulic structures, and the leakage of fuels and toxic substances have led to severe deterioration in the quality of water in rivers, lakes, reservoirs, and estuaries. According to the Ministry of Environmental Protection and Natural Resources of Ukraine, approximately 20 % of aquatic ecosystems in protected areas have undergone critical changes due to military actions.

One of the most heavily affected water bodies is the Kakhovka Reservoir, which lost more than 70 % of its water volume after the dam was destroyed. This led to the mass death of riverine flora and fauna, a decline in groundwater levels, and the degradation of coastal ecosystems (Kvach et al., 2025). As a result, large areas, including the "Velykyi Luh" and "Nyzhno-dniprovskyi" National Nature Parks, lost their wetlands, which had served as vital habitats for numerous bird, amphibian, and fish species. Notably, populations of sterlet (*Acipenser ruthenus* Linnaeus, 1758), wood frog (*Rana sylvatica* LeConte, 1825), and squacco heron (*Ardeola ralloides* (Scopoli, 1769)) suffered significant declines, as these species are highly dependent on such ecosystems (Gatti et al., 2025).

Beyond the physical loss of water bodies, the Siverskyi Donets River–an essential source of freshwater for eastern Ukraine–was heavily polluted. Military activity caused the release of heavy metals (lead, cadmium, mercury) and petroleum products into the river, increasing pollutant concentrations 5–7 times above pre-war levels (Kucher et al., 2023). Similar outcomes were observed in the Dniester Estuary, where polluted runoff entered the waters following infrastructure destruction in the south. These contaminations led to mass deaths of mollusks, crustaceans, and fish, such as the Black Sea sprat (*Clupeonella cultriventris* (Nordmann, 1840)) and zander (*Sander lucioperca* (Linnaeus, 1758)) (Slessarev et al., 2024).

The Black Sea ecosystem has also been severely impacted by the war, as large amounts of fuel, explosives, and toxic waste from sunken military equipment have entered its waters. Water analyses conducted near the coasts of Odesa and Mykolaiv oblasts revealed elevated concentrations of polycyclic aromatic hydrocarbons and heavy metals (Halyna & Seredyuk, 2024). These contaminants pose serious risks to marine biodiversity, including populations of the long-snouted seahorse (*Hippocampus guttulatus* Cuvier, 1829), common dolphin (*Delphinus delphis* Linnaeus, 1758), and the turbot (*Scophthalmus maeoticus* (Pallas, 1814)), which are highly sensitive to pollution.

Another critical issue is the pollution of groundwater due to infrastructure destruction and the leakage of hazardous chemicals. According to the State Environmental Inspectorate of Ukraine, 60 % of groundwater samples collected in conflict zones exceeded safe levels for ammonium, nitrates, and heavy metals. The situation is particularly critical in Zaporizhzhia and Kharkiv oblasts, where industrial waste has entered river systems. In the "Homilshanski Lisy" National Nature Park, located along the Siverskyi Donets River, there has been a sharp decline in fish and aquatic invertebrate populations, indicating severe chemical contamination (Dudnieva, 2024).

3.4. Damage to Biodiversity in Ukraine's Nature Reserve Fund During the War

The war in Ukraine has caused catastrophic losses in biodiversity, manifesting in the destruction of natural habitats, mass mortality of rare and endangered species, disruption of animal migration routes, and contamination of ecosystems with toxic substances. Ecosystem destruction and soil contamination have led to significant changes in the mycobiota of protected areas. In forests affected by combat, the number of fungi, which play a cr ucial role in sustaining soil ecosystems, has drastically declined. In particular, in the Homilshanski Lisy and Rivne Nature Reserves, populations of the dotted bolete (*Boletus luridiformis* (Rostk.) Sacc., 1888) and the rare pine bolete (*Boletus pinophilus* Pilát & Dermek, 1973) have decreased. These fungi are essential components of mycorrhizal relationships in coniferous forests (Kvach et al., 2025). Due to heavy metal contamination from military equipment, toxins accumulate in fungal fruiting bodies, posing health risks to wildlife and humans consuming wild mushrooms.

Explosions, fires, the movement of military vehicles, and soil contamination have caused the disappearance of numerous rare plant species. In the Black Sea Biosphere Reserve, large-scale fires resulted in the loss of over 60 % of steppe vegetation, critically impacting populations of Dnipro feather grass (*Stipa borysthenica* Klokov ex Prokudin, 1980) and Buhian pink (*Dianthus hypanicus* Andrz., 1821) (Kucher et al., 2023). These plants are endemic to the Black Sea region, and their natural recovery may take decades.

Another critically affected species is the Dnipro ragwort (*Senecio borysthenicus* (Andrz.) Andrz. ex Czerep., 1995), which grows in floodplain meadows and on sandy dunes of the Nyzhnodniprovskyi National Nature Park. Military operations in these areas have destroyed approximately 50 % of this species' populations, significantly increasing the risk of its extinction in Ukraine (Slessarev et al., 2024).

The war has led to a massive decline in bird populations, particularly those inhabiting steppes, wetlands, and forests. Rare species such as the booted eagle (*Hieraaetus pennatus* (Gmelin, 1788)) and the griffon vulture (*Gyps fulvus* (Hablizl, 1783)) have been severely affected by the destruction of reserves in the Meotyda and Karadag regions. Shelling and fires in these areas have resulted in the disappearance of up to 40 % of breeding populations (Gatti et al., 2025).

The population of the black stork (*Ciconia nigra* (Linnaeus, 1758)), which nests in forest ecosystems of central and western Ukraine, has also suffered greatly. Frequent explosions and deforestation for military needs have complicated nesting conditions, leading to a 25 % reduction in population size compared to pre-war levels (Dudnieva, 2024).

War-induced damage to aquatic ecosystems has also threatened species such as the common tern (*Sterna hirundo* Linnaeus, 1758) and squacco heron (*Ardeola ralloides* (Scopoli, 1769)), which depend on the wetlands of the Dniester Estuary and the Kakhovka Reservoir. Due to contamination from heavy metals and petroleum products, about 35 % of nesting colonies of these species have been lost, putting their regional survival at risk (Halyna et al., 2024).

Recent work by Filho et al. (2024) confirms that over 30 % of avian nesting habitats in the Chornobyl Biosphere Reserve have been affected by wildfires and military occupation, threatening endangered species such as the white-tailed eagle (*Haliaeetus albicilla* (Linnaeus, 1758)) and the red-footed falcon (*Falco vespertinus* Linnaeus, 1766).

3.5. Assessment Challenges and Environmental Damage to Ukraine's NRF

The full-scale war has caused enormous environmental losses in Ukraine, particularly in its NRF. According to the Ministry of Environmental Protection and Natural Resources of Ukraine, total environmental damages from military operations already exceed 2 trillion UAH (about 55 billion USD), a s ubstantial share of which stems from degraded ecosystems within protected areas. Restoration of forests and steppe ecosystems alone is estimated to require at least 1.5 billion USD, while mitigating water pollution may cost an additional 500 million USD (Kvach et al., 2025).

One of the main challenges in assessing damage is the lack of access to all affected areas due to ongoing hostilities and extensive landmines. Preliminary estimates suggest that approximately 30 % of NRF territory in eastern and southern Ukraine is inaccessible for ecological monitoring (Dudnieva, 2024). Another challenge lies in methodology−standard damage assessment methods require long-term monitoring, including soil, water, and air analysis, as well as tracking changes in plant and animal populations (Halyna et al., 2024).

3.6. Financing Mechanisms for the Restoration of Protected Areas

Securing funding for the restoration of Ukraine’s ecosystems will be a k ey post-war priority. Potential mechanisms for financing include:

Government Funds and International Financial Aid. Ukraine should establish a n ational "Protected Areas Restoration Fund," co-financed by international donors and governed transparently. Current national recovery programs are already being designed with support from the EU and the U.S. For instance, the EU's Green Recovery Program may offer up to €500 million in grants for the restoration of protected areas. The World Bank has also expressed readiness to support the rehabilitation of ecologically sensitive zones and fund post-war environmental recovery initiatives (Slessarev et al., 2024).

Reparation Mechanisms. Ukraine has legal grounds to seek compensation from the russian federation for ecological damage through international courts, including the International Court of Justice and the European Court of Human Rights. One potential source of funding could be frozen Russian assets, which may be redirected toward ecological rehabilitation of protected areas (Kucher et al., 2023).

Support from International Environmental Organizations. The World Wide Fund for Nature (WWF) is actively involved in conservation efforts in Ukraine and can assist in funding restoration of degraded ecosystems. The United Nations Environment Programme (UNEP) has special funds designated for war-related environmental damage and can become a strategic partner in demining reserves and rehabilitating soils (Gatti et al., 2025).

3.7. The Role of International Organizations in NRF Recovery

International organizations are vital not only for financial aid, but also for providing scientific monitoring and effective recovery strategies. Among the key partners for Ukraine are:

Green Climate Fund (GCF) – capable of financing long-term projects for protected area restoration and climate adaptation.

Global Environment Facility (GEF) – supports programs on biodiversity, forest conservation, and remediation of contaminated sites.

European Environment Agency (EEA) – provides technical assistance in developing environmental policy and standards suitable for Ukraine.

World Resources Institute (WRI) – specializes in ecological mapping and ecosystem service assessment.

Some researchers (Filho et al., 2024) propose the development of a "Marshall Plan for Environmental Recovery", which would consolidate international support and deliver a coordinated approach for cleaning and restoring Ukraine’s protected areas.

4. Conclusions

The war that has been ongoing in Ukraine since 2014 has triggered an unprecedented ecological crisis, profoundly affecting the country’s Nature Reserve Fund. Over 1.2 million hectares of protected areas have been damaged, which constitutes more than 30 % of all protected areas, including biosphere reserves, national nature parks, and regional landscape parks. The most heavily impacted areas are in eastern and southern Ukraine, notably the Black Sea Biosphere Reserve, Meotyda, Askania-Nova, and the Luhansk and Rivne Nature Reserves.

A combination of descriptive analysis, geoinformation modeling (based on Sentinel-2 satellite imagery in QGIS), remote sensing, and ecological monitoring enabled the assessment of spatial dynamics of ecosystem destruction. Notable consequences include forest cover reduction, soil degradation, water pollution, and loss of up to 50 % of populations of certain plant, fungal, and animal species. The destruction or disappearance of habitats for species such as *Stipa borysthenica*, *Ciconia nigra*, and *Boletus pinophilus* poses a direct threat to regional biodiversity.

A particularly critical issue is the intensification of pyrogenic processes, which have affected large areas of protected territories. Satellite imagery revealed more than 5,000 hectares of burned ecosystems in the Askania-Nova Biosphere Reserve alone, indicating a p rofound transformation of natural landscapes.

Despite the severe damage, accurate assessment remains difficult due to several factors: limited access to occupied areas, landmines, the destruction of monitoring infrastructure, and a lack of pre-war baseline data for parts of the NRF. Total environmental damage is currently estimated at over 2 trillion UAH (≈55 billion USD), with restoration costs projected at 1.5–2 billion USD.

The recovery of Ukraine's NRF requires a systematic and long-term approach. Priority actions should include demining, soil remediation, reintroduction of rare species, restoration of wetlands, and the reconstruction of environmental monitoring infrastructure. Funding can be secured through: reparations; targeted funds from international partners (UNEP, GEF, WWF, Green Climate Fund, EU Green Recovery); Ukraine's national environmental fund; and public-private partnerships (PPP).

Ukraine has a unique opportunity not only to restore its damaged ecosystems but also to integrate modern European practices in the management of protected areas, contributing to the conservation of Europe's landscape and biotic diversity as a whole.

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ASSESSMENT OF HEAVY METAL POLLUTION LEVELS IN SOILS OF SPECIFIC AREAS OF THE ODESA INDUSTRIAL-URBAN AGGLOMERATION

Tamerlan Safranov[1]✉, Olena Nikipelova[2], Dmytro Shelinhovskyi[1]

[1]*Odesa I.I. Mechnikov National University,*
2, V. Zmiienka Str., Odesa, 65082, Ukraine
[2]*Engineering and Technological Institute "Biotechnics" of the National Academy of Agrarian Sciences of Ukraine,*
26, *Maiatska doroha Str., Khlibodarske village, Odesa oblast, 67667, Ukraine*
safranov@ukr.net

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Abstract. Unlike the more dynamic air basin and surface waters, where active self-purification processes occur, soil virtually lacks this capacity. The cleansing processes in soil are very slow, only through leaching, plant uptake, and water erosion, which poses an environmental hazard in urbanized areas over long periods. In the process of intensive urbanization, the soil cover has been influenced by many anthropogenic factors, resulting in changes to its physical and chemical properties and an increase in heavy metal concentrations. An analysis of previous research results shows that the most contaminated soils with specific heavy metals are found in industrial zones and areas adjacent to high-traffic roads. In contrast to these technogenically stressed areas, attention is drawn to park and square zones, where elevated background concentrations of lead and zinc have been recorded, whereas copper content in all areas was identified to be below background levels. However, the range of calculated geoaccumulation index values for these heavy metals corresponds to a low-to-moderate level of soil contamination which varies according to the distance from sources of technogenic pollution. According experimental results by biosensor bioluminescent analysis of soils from certain parks and squares of the Odesa agglomeration, no significant inhibition of luminescence levels of microbial cells-the basis of the sensor elements-was observed. This indicates the absence of substances which have toxic effect to soil microorganisms.

Keywords: heavy metals, soil cover, urbanized area, pollution.

1. Introduction

In the context of intensive anthropogenic contamination of the natural components of the environment in urbanized areas, particularly the soil cover, the assessment of soil contamination levels by various pollutants, including heavy metals, becomes especially relevant. It is known that HM is a conventional term for a group of chemical elements classified based on atomic mass, toxicity, density, and other criteria. In studies devoted to environmental pollution, HM typically refer to chemical elements with a mass exceeding 50 atomic units or a density greater than 8 g/cm^3 (*Cr,* V*, Fe, Mn, Co, Cu, Ni, Zn, Mo, Sb, Cd, Hg, Sn, Pb, Bi,* etc.). A key factor in identifying these elements as heavy metals is their extremely toxicity to biological organisms at low concentrations, as well as their ability to bioaccumulate and biomagnify. Virtually all HM that fall under this definition (*Pb, Hg, Cd*, and *Bi*, whose biological roles remain unclear)

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actively participate in biological processes and are components of many enzymes (Filon, 2020). HMs are not only toxicants but also natural soil micronutrients, the content of which depends on the physicochemical properties of parent rocks and the specific nature of soil formation processes. Some HM, such as *Cu* and *Zn*, are essential micronutrients for soil fertility when present in optimal concentrations. Depending on their sources and properties, HMs in the soil are divided into those associated with parent rocks and those entering into the soil through anthropogenic activity. This leads to the destabilization of the soil's physicochemical properties, a decrease of number and diversity of soil organisms, and contamination with various pollutants, including HM. The background content of HM in the soil corresponds to their natural concentrations in soils of different soil-climatic zones, without significant anthropogenic impact.

Contamination with HM contributes to a reduction in soil porosity and negatively affects the circulation of air, water, and nutrients. The danger of HM pollution in soils also lies in the fact that it leads to deterioration in the quality of the rest of natural environmental components.

Determining the forms in which HM exist is a labor-intensive and analytically complex task, as they can be present in a wide variety of mineral and non-mineral compounds. The dominant methods for determining HM nowadays include atomic absorption spectrometry, mass spectrometry, and electrochemical techniques. The sensitivity of these methods and whether they detect total or mobile forms of the metals should be taken into account.

In urbanized areas, natural environmental components are affected by different anthropogenic factors which have led to the huge loss of their capacity for self-purification. Unlike the more dynamic air and surface water systems, which have active self-purification processes, the soil cover lacks such capabilities. Soils in urban areas are cleansed of HM very slowly, primarily through leaching, plant uptake, water erosion, and deflation. In polluted urban soils, organic matter content decreases, the natural *pH* balance of the topsoil is disrupted, and the cation exchange capacity declines, reducing the soil's buffering ability. Typically, in soils of technogenically polluted areas, the content of mobile forms of zinc, cobalt, nickel, copper, and lead (including water-soluble, easily exchangeable ions, and those soluble in mildly acidic environments) is higher compared to background levels and soils in recreational zones. Due to the heterogeneous composition of soils, even within a single land plot, their physicochemical properties can vary, therefore having an impact on HM concentrations.

The distribution and toxicity level of HM in soils depend on both natural local conditions and the particular element. For instance, *Hg*, *Pb*, and *Cd* tend to pile up in the upper layers of soil but their restricted ability of migration within the soil profile and their emissions beyond the soil are insignificant.

Monitoring soil conditions is extremely important, especially given the growing anthropogenic pressures each year. In the context of intensive urbanization, it is practically impossible to eliminate anthropogenic contributions to soil contamination. However, considering the ecological risks posed by the pollution of urban soils by heavy metal, assessing their content and distribution patterns remains a highly relevant issue. their content and distribution patterns remains a highly relevant issue.

The objective of this study is to evaluate heavy metal contamination level in the soils of specific areas within the Odesa industrial-urban agglomeration.

2. Materials and Methods

The work is based on published information from foreign and domestic authors, including our own research materials. The geoaccumulation index (*Igeo*), pollution index, concentration coefficient, potential ecological risk index (Muller, 1969; Tomlinson et al., 1980; Kabata-Penddias, 2011; Kowalska et al., 2018; Shuangmei et al., 2020), and other indicators are commonly used to assess the level of soil contamination. The geoaccumulation index (*Igeo*) was applied in the given study, which serves as a geochemical criterion for identifying heavy metal contamination.

$$Igeo = \log_2(C_i/1.5\ GB), \qquad (1)$$

where C_i is the content of heavy metals in the top humus horizon; *GB* is the background content of heavy metals for soils of the steppe zone of Ukraine (Fateev et al., 2003); *the coefficient 1.5* is used to detect minor anthropogenic impact. Depending on the geoaccumulation index value, the following categories are distinguished (Muller, 1969):

1) clean soils (< 0);
2) soils with low to moderate contamination (0-1);
3) soils with moderate contamination (1-2);

4) soils with moderate to high contamination (2-3);
5) soils with high contamination (3-4);
6) soils with very high contamination (4-5).

Additionally, samples of soil were collected in several parks around Odesa. The sampling conditions were the same. Samples were collected in the morning, before noon, almost at the same time. The samples were dry. Soil samples in Peremohy Park and Shevchenko Park were collected in accordance with the requirements of DSTU 4287:2004. Sampling was performed using an auger. The most common sampling method is the «envelope» method, which was used during the study. The dimensions of the «envelope» were as follows: width – 100 m, length – 300 m. The sampling depth was 0–25 cm (within the arable layer). The collected samples were represented by southern chernozem, low in humus, heavy loam on loess. From five point samples for each park, composite samples were formed (Peremohy Park – 3 composite samples, Shevchenko Park – 2 composite samples).

The study of the content of pollutants (in particular HMs) in soils (2 samples) using the water extraction method was conducted in the «Water Monitoring Laboratory of the Southern Region of Separate Unit of the Basin Water Resources Management of the Rivers of the Black Sea Region and Lower Danube Black Sea Center for Water Resources and Soils».

Of particular interest are the empirical data from biosensor bioluminescent analysis of soils (3 samples) from specific sites within the Odesa industrial-urban agglomeration, which was carried out at the «F.D. Ovcharenko Institute of Biocolloid Chemistry of the National Academy of Sciences of Ukraine» (Rapid determination of the level of integral pollution and heavy metal…, 2012).

Analysis is based on recording changes in the intensity of bioluminescence of bacterial strains – components of the sensor element – under the influence of toxic substances present in the aqueous extract of the soil sample being analyzed, compared to a control, using a *Hidex bioluminometer* (Finland). A natural sod-podzolic soil (Pushcha-Vodytsia, Ukraine) served as the reference sample (control) for the content of hazardous substances.

When analyzing soil samples, considering the nature of their sensitivity to the content of heavy metals (HM), the following biosensor elements were used:

1) *BE1* – a biosensor element based on the *Vibrio fischeri* strain (natural luminescence);
2) *BE2* – a biosensor element based on the *Vibrio harveyi* strain (natural luminescence);
3) *BE3* – a biosensor element based on the *Photobacterium phosphoreum* strain (natural luminescence).

The bioluminescent test employed sensor elements manufactured in accordance with TU 21.2-05402714-005:2014 with Amendment No. 1 «Sensor elements for rapid biosensor analysis of the condition of agricultural soils by indicators of heavy metal contamination».

The microbial strains *Vibrio fischeri (Aliivibrio fischeri)* F1, *Vibrio harveyi* Ms1, *Photobacterium phosphoreum* B 7071, used for the development of sensor elements, are deposited in the depository of the State Scientific Control Institute of Biotechnology and Strains of Microorganisms (SSCIBSM), Kyiv (Ukraine).

The strains are characterized by the ability to quench natural luminescence if a specific HM is involved. Bioluminescent bacteria contain the enzyme luciferase, which effectively converts the energy of chemical bonds of essential metabolites into a light signal at a level suitable for measurements. The ecotoxicity parameter, E is determined by formula (2) and reflects the level of integral pollution of the object, specifically HM, and is expressed as the ratio of the intensity of bacterial bioluminescence upon contact with the test sample (*Ip)* to the intensity of bacterial bioluminescence upon contact with the reference (control) sample (reference soils/water) (*Ie)*:

$$E = \frac{I_p}{I_e}. \quad (2)$$

Risk ranges depending on the value of the environmental toxicity parameter (E) are as follows: *low* – from 0.6–0.9 to 1.1–1.5; *medium* – from 0.4–0.6 to 1.5–1.7; *high* – from 0.2–0.4 to 1.7–2.0.

3. Results and Discussion

The territory of the Odesa industrial-urban agglomeration is characterized by quite diverse soil-geochemical conditions (Khokhryakova & Kulidzhanov, 2018). During the process of intensive urbanization, the soil cover has been affected by numerous anthropogenic factors, as a result of which its physicochemical properties were changed leading to an increase in concentrations of hazardous substances, particularly HMs.

Analysis of previously conducted studies (Domuschy, 2023) shows that the most polluted soils are those of the industrial zone (0.5 – 1.7 mg/kg), where the content of mobile forms of cadmium (Cd) exceeds the maximum permissible concentrations (MPC) on 70 % of the territory. Among the most contaminated are the soils of Chornomorskoho Kozatstva Street – 10.5 mg/kg and the Luzanivka district – 150 mg/kg.

Among the motor transport highways, the most polluted are Balkivska, Serednifontanska, and Kanatna streets, where HM concentrations reach about 1 mg/kg. Within residential and recreational zones, the most polluted areas are Shevchenko Avenue, Dyukivskyi Garden, and Mykhailivskyi Park (0.92 mg/kg), where exceedances of normative HM values are approximately 4 % (Domuschy, 2023).

It is worth noting that the content of mobile forms of lead (Pb) in urban soils of various functional zones ranges from 1.5 to 202 mg/kg. Within areas of intensive transport influence, 80 % of the studied territory has *Pb* concentrations exceeding the MPC. It is deemed that the distance to motor highways determines the level of lead pollution in the soil cover of parks and squares (Domuschy, 2023).

Mobile forms of zinc's (*Zn*), like lead, in the urban soil cover varies over a very wide range: from 1.45 mg/kg to 240.0 mg/kg. Regarding the mobile forms of zinc's content, 50 % of the city's territory exceeds the standards. The industrial zone (over 8 mg/kg) and areas adjacent to highways (over 3 mg/kg) are the most contaminated by this metal (Domuschy, 2023).

Cobalt (*Co*) concentrations in the ground layer of Odesa also range broadly from 0.12 mg/kg to 22.15 mg/kg. The most polluted areas are Luzanivka (over 22.15 mg/kg), which exceeds the background content more than 50 times, and Balkivska Street (10 mg/kg) (Domuschy, 2023), i.e., technogenically stressed sites.

The highest pollution with copper (*Cu*) compounds is found on Liustdorfska Road – 17 mg/kg; Balkivska Street – 14 mg/kg; and Admiralsky Avenue – 9 mg/kg, exceeding MPC values by 3–5 times (Domuschy, 2023).

In the background of the technogenically stressed parts of the city, park and square areas hold a special place. According to (Khokhryakova & Mykhailiuk, 2021), in these zones, excess of the maximum permissible concentrations are observed only for copper. The zinc content exceeds the MPC values by 6 times, and the lead content – by 8 times.

MPC of mobile forms of heavy metals in soils, which serve as regulatory values for assessing the level of contamination, approved by the Resolution of the Cabinet of Ministers of Ukraine dated December 15, 2021, No. 1325 (On approval of standards...,2021).

According to (Khokhryakova & Mykhailiuk, 2021), concerning the heavy metals' content in the soils of certain parks and squares of the Odesa industrial-urban agglomeration, the geoaccumulation index was calculated (Tabl. 1). The calculation data for the main functional zones of the urbanized territory (Domuschy, 2023) are presented in Tabl. 2.

Table 1

Heavy metal content and geoaccumulation index (*Igeo*) values in soils from selected parks and squares of the Odesa industrial-urban agglomeration

Sample No	***The content of heavy metal, mg/kg of soil*** / *Igeo value*			Soil pollution level according to the *Igeo* value
	Pb*/ Igeo*	***Zn****/ Igeo*	***Cu****/ Igeo*	
1	4.54/−2.10	241.60/1.38	0.18/−7.81	clean (***Pb, Zn***), average ***(Zn)***
2	6.89/−1.50	13.22/−2.81	0.92/−5.46	clean (***Pb, Zn***, ***Cu***)
3	6.14/−1.67	15.02/−2.63	1.07/−5.24	clean (***Pb, Zn***, ***Cu***)
4	50.27/1.37	37.90/−1.30	1.32/−4.94	average ***(Pb)***, clean (***Zn***, ***Cu***)
5	37.79/0.95	18.38/−2.34	0.93/−5.44	weak-average ***(Pb)***, clean (***Zn***, ***Cu***)
6	2.66/−2.87	0.89/−6.71	1.36/−4.90	clean (***Pb, Zn***, ***Cu***)
7	4.53/−2.11	35.58/−1.39	0.49/−6.37	clean (***Pb, Zn***, ***Cu***)
8	9.74/−1.00	87.54/−0.09	1.33/−4.93	clean (***Pb, Zn***, ***Cu***)
9	48.32/1.31	25.10/−1.89	1.37/−4.89	average ***(Pb)***, clean (***Zn***, ***Cu***)
10	38.90/1.00	38.29/−1.28	1.58/−4.68	weak-average ***(Pb)***, clean (***Zn***, ***Cu***)
MPS	***6.0***	***23.0***	***3.0***	Maximum permissible concentrations, *mg/kg of soil*

1 – slopes near the Chkalov Sanatorium; 2 – square near the Odesa Regional Council (under the trees); 3 – square near the Odesa Regional Council (grass, lawn); 4 – «Dyukivsky Garden» (Rozkydailivska, 69); 5 – «Dyukivsky Garden» park; 6 – memorial of the 411th coastal battery;7 – «Aeroportivsky» park; 8 – Peremohy Park; 9 – Gorky Park; 10 – Shevchenko Park.

Table 2

Content of heavy metals and values of the geoaccumulation index (*Igeo*)

The name of the functional zone	***The content and MPS of heavy metal, mg/kg of soil*** / *Igeo value*			Soil pollution level according to the *Igeo* value
	Pb, 6.0/ *Igeo*	***Zn, 23.0/*** *Igeo*	***Cu, 3.0/*** *Igeo*	
Automotive	20.16/0.05	24.60/−1.92	11.02/−1.88	weak to moderate ***(Pb)***, clean (***Zn***, ***Cu***)
Recreational	18.19/−0.10	23.07/−2.01	8.02/−2.34	clean (***Pb, Zn***, ***Cu***)
Industrial	61.16/1.65	82.66/−0.17	12.58/−1.69	weak to moderate ***(Pb)***, clean (***Zn***, ***Cu***)
Residential	20.50/0.07	58.00/−0.68	1.16/−5.13	weak to moderate ***(Pb)***, clean (***Zn***, ***Cu***)
MPS	***6.0***	***23.0***	***3.0***	Maximum permissible concentrations, *mg/kg of soil*

Table 3

Presents data on the content of heavy metals in the soils of individual parks and squares of the Odesa industrial-urban agglomeration based on the results of our own research

Sampling location	Soil sample weight	Units of measurement	***Cu***	***Cd***	***Zn***	***Ni***	***Pb***	***Hg***
Shevchenko Park	40 g	mg/dm³	0.020	0.001	−	−	0.020	−
		mg/kg	0.100	0.005	−	−	0.100	−
Peremohy Park	40 g	mg/dm³	0.015	0.004	−	−	0.012	−
		mg/kg	0.075	0.002	−	−	0.060	−

The differences in the results of HM analysis in soils from specific parks in Odesa, obtained by atomic absorption spectrophotometry (Tabls. 1, 2) – DSTU 4770.2:2007, DSTU 4770.3:2007, DSTU 4770.6:2007, DSTU 4770.7:2007, DSTU 4770.9:2007 (DSTU 4770.2:2007, DSTU 4770.3:2007, DSTU 4770.6:2007, DSTU 4770.7:2007, DSTU 4770.9:2007, 2009) and water extraction (Tabl. 3), are caused by the different principles of these methods. The atomic absorption spectrophotometry method involves thedissolution of a soil sample using acids and thus determines the content of mobile forms of HMs. One of the simplest and most commonly used approaches for assessing the mobile (water-soluble) forms of soil's heavy metals is the water extraction method. It is widely used in environmental monitoring because it enables the evaluation of the level of ecological hazard of soil contamination and the bio-accessibility of metals to plants, microorganisms, and humans. However, it should be mentioned that this method does not provide complete insights into total contamination, although it is valuable for ecotoxicological assessment and environmental risk evaluation. This method determines only the fraction of heavy metals that is mobile and potentially available for plant uptake (water-soluble, mobile forms).

According to the results of the ecological toxicity assessment of soil samples from certain parks in Odesa using an experimental biosensor bioluminescent analysis (Tabl. 4), they were classified as having a low level of ecological toxicity.

Table 4

Assessment of the ecotoxicity level of soil samples from selected parks in Odesa based on experimental biosensor bioluminescent analysis

Sample No	Sampling location	*CE1*	*CE2*	*CE3*	Environmental toxicity level
1	Shevchenko Park	1.24	1.34	1.27	low
2	Peremohy Park (point 1)	1.52	1.33	1.42	low
3	Peremohy Park (point 2)	1.40	1.45	1.47	low

4. Conclusions

1. High content of heavy metals in soils have been recorded in industrial areas and along highways with intense vehicle traffic.

2. Against the background of these technogenically stressed parts of the urbanized territory, park zones and squares occupy an important place. However, even in these areas, concentrations of certain heavy metals exceed the maximum allowable limits, except for copper content. Nevertheless, soils ranging from slightly to moderately polluted, as well as pure soils, have been found in the industrial zones and highway areas. For soils within certain parks and squares of the Odesa industrial-urban agglomeration adjacent to technogenically stressed zones, soils from slightly to moderately polluted have also been recorded, while other areas contain clean soils.

3. Based on the results of biosensor bioluminescent analysis of samples of soil taken from park zones of Odesa (Ukraine), it can be pointed out that no significant inhibition of the luminescence level of microbial cells – the basic sensing elements – was detected, indicating the absence of substances toxic to soil microorganisms. A slight stimulation of microbial cell luminescence – the basic sensing elements – was observed, which may be related to the increased content of organic components in the soil samples. Soil samples analized and collected from the park zones of Odesa (Ukraine) were assigned a low level of ecological toxicity; the contamination level by individual HM is low, corresponding to their pollution level pursuant to the geoaccumulation index values.

4. Heavy metals in soils undergo transformation; this process is complex and depends on a number of factors, primarily on the nature of the metal, the soil composition, and the state of the environment. Of particular interest is the identification of the transformation algorithm and its potential impact on the ecological condition of the soil.

5. It is advisable to continue studies on the level of HMs contamination of certain areas of the Odesa industrial-urban agglomeration using various methods to identify patterns of their spatial and temporal variability.

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ENVIRONMENTAL PROBLEMS

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MODIFICATION OF SOIL SUBGRADE WITH RECYCLED CONCRETE FINES FOR REDUCED ENVIRONMENTAL IMPACT

Nataliia Topylko✉, **Yurii Novytskyi**, **Yura Turba**

Department of Highways and Bridges,
Lviv Polytechnic National University,
12, S. Bandery Str ., Lviv, 79013, Ukraine
nataliia.i.topylkoi@lpnu.ua

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Abstract. Ukraine's transition towards an energy-efficient economy, in the context of integration into the European area, represents a complex yet highly significant challenge. The post-war recovery of the country requires comprehensive modernisation of infrastructure in line with the principles of sustainable development and the standards of the European Union. Particular attention is drawn to the road construction sector, one of the most resource-intensive branches of the construction industry. Its development must be fully aligned with the goals of the European Green Deal, which encompass the reduction of greenhouse gas emissions related to the extraction and processing of natural resources, the implementation of circular economy principles, the promotion of economic growth through the increased use of anthropogenic waste as an alternative to primary raw materials, the mitigation of environmental impact, and the active deployment of environmentally driven technologies (Natsionalna ekonomichna stratehiia, 2021). As a result of the full-scale war in Ukraine, substantial volumes of mineral waste have accumulated from destroyed buildings and infrastructure, posing a serious challenge to the national resource management system. The efficient recycling of concrete debris is a key condition for reducing the environmental burden on the natural environment. This article presents research findings on the stabilisation of clayey soil using mineral fines derived from processed waste concrete, with the aim of improving the physico-mechanical properties of the subgrade in road construction.

Keywords: circular economy, sustainable development, soil modification, concrete fines, modified Proctor test, shear strength.

1. Introduction

As a consequence of the widespread destruction of buildings and infrastructure in Ukraine, the amount of mineral waste has considerably increased, with reinforced concrete debris being the most prevalent form. The challenge of managing this waste stream has become particularly urgent in the context of restoring transport infrastructure. One of the promising strategies involves reusing concrete debris in the form of finely ground particulate material (concrete fines), which is produced during the mechanical crushing and sorting of demolition waste using specialised equipment.

In 2018, the United States reported the production of nearly 600 million tonnes of building and demolition-related waste. On a global scale, the annual volume of such waste exceeds 3 billion tonnes, constituting approximately 30–40 % of total waste generated worldwide (Kaptan et al., 2024). Within the European Union, the amount reached around 38.4 million tonnes in 2020, while China exceeded 1.5

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billion tonnes (Bonifazi et al. , 2025). This vast magnitude, along with the accelerating trend — from 50 million tonnes in 1980 to 600 million tonnes by 2018 in the US — highlights the pressing challenges associated with waste handling and disposal.

In Ukraine, comprehensive nationwide statistics remain limited; however, an upward tendency in building and demolition-related waste has been repeatedly noted in municipal and institutional reports, especially in connection with post-war reconstruction efforts. Tracking the quantity of such materials is essential for advancing sustainable development and for designing coherent national strategies on waste regulation and management.

Recycled concrete fines have emerged as a promising material for improving soil properties. Research indicates that such fines can stimulate hydration processes, reduce swelling potential, and enhance strength characteristics. In particular, the use of fine fractions for modifying structurally unstable soils has proven effective: they function as a mineral filler, diminishing deformability and contributing to increased mechanical strength.

The use of recycled concrete fines as a mineral modifier for improving soil properties in road earthworks supports circular resource strategies and promotes environmentally oriented construction practices. However, despite their considerable potential, there is currently a lack of systematic data on the effects of concrete fines on the physico-mechanical properties of clayey soils, particularly loams (Mark et al., 2016).

In this context, the aim of the present study is to evaluate the effectiveness of recycled concrete fines as a mineral additive for the modification of loam characterised by high plasticity and susceptibility to deformation. The research methodology includes a detailed evaluation of the particle size distribution and mineralogical characteristics of the recycled concrete fines, as well as the results of laboratory testing of the modified soil.

2. Theoretical part

The extensive destruction of civil and industrial infrastructure in Ukraine, resulting from the full-scale military aggression by the rf, has caused the generation of vast amounts of construction-related waste. A significant portion of this debris comprises reinforced concrete elements (Antoniuk & Kostiuk, 2024; UNDP Ukraine, 2023). To address this situation, the international initiative S3RoU – Safe, Sustainable and Swift Reconstruction of Ukraine – has launched the development of mobile technologies for sorting, crushing, and reusing construction debris, with the goal of ensuring its environmentally safe processing (S3RoU Project description, 2024).

One of the potentially valuable outputs of concrete recycling is concrete fines — the finest fraction formed as a result of mechanical disintegration of concrete, which may include particles of cement paste, quartz, and granite-origin minerals, along with residual hydrated compounds (Fan et al., 2016). Although recycled aggregates have received considerable attention, concrete fines still represent a relatively underutilised material in civil engineering applications.

Owing to their fine particle size, potential residual hydraulic reactivity, and the occasional presence of calcite or carbonation-derived phases, recycled concrete fines may demonstrate characteristics of a mineral activator or modifying agent (Pasquier et al., 2018). These properties create opportunities for their application in improving the structure of clayey soils − especially under conditions of accelerated road infrastructure renewal. The present study focuses on a laboratory-based investigation into the potential of such fines as a stabilising component for roadbed materials, contributing to the implementation of circular economy principles during post-war reconstruction efforts.

Structurally unstable soils are characterised by volume changes resulting from moisture fluctuations, often necessitating reinforcement or improvement measures to address deformation caused by swelling and contraction. Owing to their high plasticity, such soils contribute to premature damage of road pavements during wetting and drying cycles. Moisture variations lead to a reduction in the density and strength of the soil subgrade, which in turn causes shear deformations, depressions, and cracking in the upper layers of the pavement structure. These defects significantly reduce the load-bearing capacity of the soil and increase maintenance and reconstruction costs.

To mitigate common failures related to the deterioration of strength characteristics in moisture-sensitive plastic soils, a variety of stabilisation techniques have been adopted. Among them, cement is frequently applied alongside other binders, including ground granulated blast furnace slag (GGBS), lime, fly ash, silica fume, and various industrial by-products (Novytskyi et al., 2023; Leon et al., 2023 a). The synergistic effect of these mixtures has demonstrated greater efficiency in enhancing soil strength compared to the use of natural aggregates alone.

An alternative approach involves the use of fine fractions of construction and demolition concrete waste generated during the crushing of structural debris (Ujile & Abbey, 2022). Due to the residual content of chemically active phases within the cementitious matrix, these materials can improve the structure and strength of clayey soils while reducing plasticity and swelling potential. Depending on their mineralogical composition, recycled concrete fines may partially replace cement−especially when activated−thereby contributing to a lo wer carbon footprint in construction. Previous studies indicate that the use of such activated materials can achieve strength levels comparable to those obtained with natural aggregates or cement, while ensuring environmentally sustainable reuse of waste.

Research confirms that fine-grained components derived from construction and demolition residues can markedly influence the mechanical behaviour of soils (Singh et al., 2017). Particles under 1.18 mm in size — especially those finer than 0.425 mm − demonstrate a high capacity to occupy voids in clayey matrices, thus promoting improved packing density and structural uniformity after compaction. This leads to lower moisture sensitivity and enhances both shear and compressive strength characteristics.

According to the USCS and ASTM D2487 classification systems, the particle size range for fines is defined as 0.475–0.075 mm. Particles smaller than 0.425 mm demonstrate the greatest technical potential, as they can not only improve compaction but also participate in pozzolanic reactions, provided that the mineralogical composition is suitable. Fines of this size contribute to: enhanced compaction and reduced void ratio; more uniform mixing of clayey soils with cement and other mineral additives; and the formation of a dense microscale environment around soil grains

In addition, screened recycled concrete fines are the most common fractions in concrete waste streams, particularly as a r esult of rapid urbanisation. These fractions are often compared to natural sands or limestone-based powders for their function in concrete or soil stabilisation systems. As a result, fine fractions of concrete waste can be used as an alternative mineral binder (if potentially hydraulically active phases are present) for soil stabilisation or as a partial replacement for cement in construction mortars, reducing the need for primary raw materials.

The hydraulic reactivity of recycled concrete fines is not guaranteed − it is determined by the phase composition rather than particle size or oxide content. Some dust fractions may be predominantly inert (e.g., quartz-based), in which case alternative stabilization strategies become more appropriate, such as mechanical, combined, or alkali activation methods. Recycled concrete fines typically contain a wide range of oxides, including silica (SiO_2), calcium (CaO), aluminum (Al_2O_3), iron (Fe_2O_3), among others. Their actual impact on soil stabilisation largely depends on their mineralogical and phase composition, which governs the material's reactivity (Kerni et al., 2015). In certain samples, a noticeable presence of active phases (e.g., residual Portlantide or unhydrated cement clinker minerals) has been observed, which may participate in hydration or pozzolanic reactions. In such cases, fractions <150 μm have the potential to partially replace conventional binders. However, not all fines exhibit chemical activity. For instance, those dominated by quartz, or other magmatic rock minerals usually display low reactivity, where the primary effect lies in densification and improvement of the soil's grain structure.

In fractions containing carbonates (e.g. calcite), reactivity can be formed under conditions of subsequent alkaline or thermal activation. This suggests the possibility of applying such materials in combination with chemical activators (e.g., lime, sodium hydroxide, ash), particularly for modifying clayey soils (Zhao et al., 2019). Thus, the effectiveness of recycled concrete fines as a stabilising agent is not universal and requires prior chemical and mineralogical assessment. In the absence of hydraulic reactivity, using such fines as an inert filler is considered effective, as it contributes to improved compaction, reduced porosity, and modified capillary behaviour within the soil matrix. Research evidence indicates that mineral fines obtained from construction waste can facilitate better packing of plastic soils by occupying pore spaces. As a r esult, the compacted mixture exhibits higher density, greater mechanical integrity, and increased stiffness. Additionally, these fines help minimise subgrade deformations and enhance the structural stability of the base layer against uneven settlement. Therefore, the use of recycled concrete fines dominated by crystalline, highly stable minerals is consistent with the approach of National Standard of Ukraine 8801:2018 (DSTU 8801:2018, 2018): such materials are employed as a granulometric additive–modifier to improve the grain-size structure of plastic soils; where required, stabilisation with traditional binders may be applied as a subsequent step (Bridgemohan et al., 2023).

In general, the effectiveness of recycled concrete fines as a stabiliser is largely determined by the combination of particle size distribution and mineralogical structure. Careful fractional preparation and, if necessary, additional activation (alkaline, thermal) allow such materials to be used to improve the mechanical properties of clayey plastic soils.

3. Materials and Methods

Materials. A clayey soil was selected for the study. To evaluate its physical properties, a particle size distribution analysis was conducted following the ISO standard 17892-4:2023 (ISO 17892-4:2023, 2023), and the Atterberg limits were determined following ISO 17892-12:2018 (ISO 17892-10:2018, 2018). The results of these tests are presented in Tabls 1 and 2, respectively.

Table 1

Physical parameters of the investigated soil

Atterberg limits			particle density ρ_s (g/cm^3)
LL (%)	PL (%)	PI (%)	
38	21	17	2.72

Table 2

Particle size distribution of the study soil

Name of parameter	Sieve analysis								Sedimentation analysis	
Size of sieve holes, mm	2	1	0.5	0.25	0.1	0.08	0.071	0.063	0.063– 0.002	<0.002
Fraction content, A %	–	–	–	–	3.52	16.63	2.92	7.57	47.14	22.22
Total content of particles	sand								silt	clay
	30.64								47.14	22.22

The soil's classification based on particle size distribution was determined using the Feret classification triangle (Fig. 1), as adopted in international standards. According to its granulometric composition, the soil was classified as a loam.

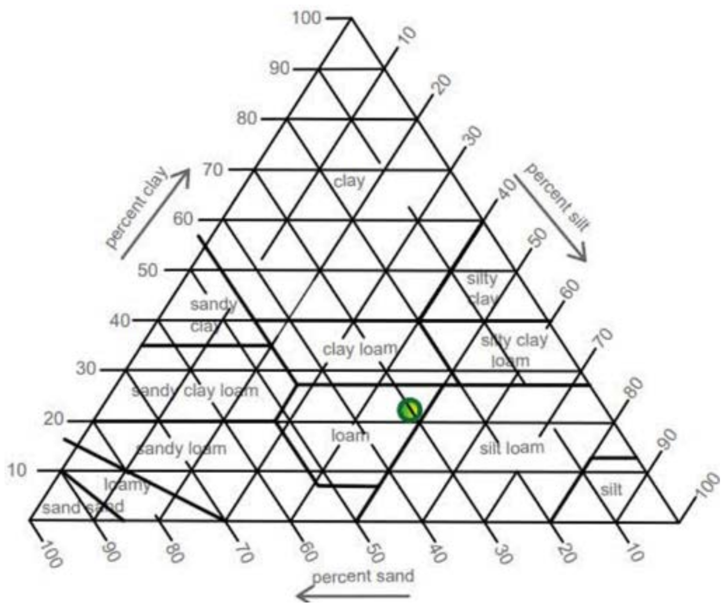


Fig.1. Soil type identified through grain size analysis

The qualitative phase composition of the loam (Figs. 2 and 3) was determined using X-ray diffraction (XRD) analysis. The diffractometer operated under the following conditions: current (I) = 12 mA, voltage (U) = 30 kV, and scanning speed = 2°/min. The method sensitivity was up to 1 %. The quantitative analysis of mineral composition was performed using Profex software, which utilises the JCPDS database to match calculated phase patterns with the experimental X-ray diffraction data as accurately as possible.

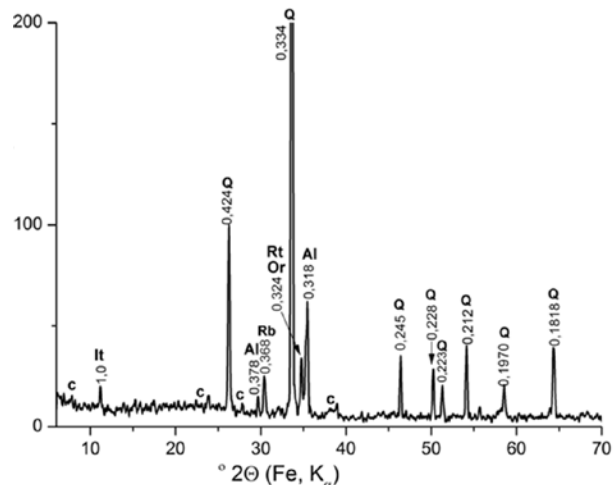


Fig.2. XRD pattern of sandy-silty loam fraction:

Q – Quartz; It –Illite;
Al – Albite; Or – Orthoclase;
Rt – rutile; Rb – RbHSO4

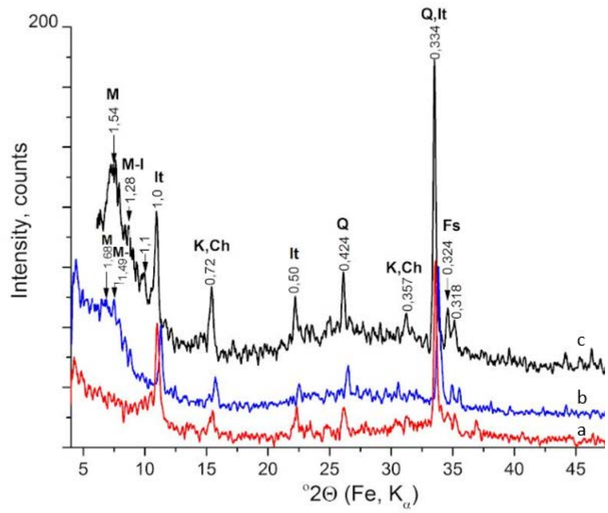


Fig.3. XRD pattern of clay loam fraction
(a − air−dry, b − saturated with ethylene glycol,
c − heated at 500^{0}C) M – Montmorillonite, M–I – Mixed-Illite–Montmorillonite, It – Illite, K – Kaolinite,
Ch – Chlorite, Q – Quartz, Fs Feldspars

Table 3

Distribution of particle sizes in recycled concrete fines

Sieve analysis												
Size of sieve holes, mm	10	5	2.5	1.6	0.63	0.5	0.315	0.14	0.08	0.071	0.063	<0.063 (Silt)
Fraction content, A %	-	0.05	0.69	0,05	0.95	0.19	2.66	50.47	29.80	1.12	4,04	9,99
Total content of particles < Ai, %	100,1	99.96	99.27	99.22	98.27	98.08	95.42	44.95	15.15	14,03	9,99	-

Recycled concrete fines are the finest mineral fraction generated during the industrial crushing and dry screening of concrete rubble from demolished buildings at specialized construction-and-demolition waste recycling plants (Circular Concrete (S3RoU)). Analysis of texture by particle size was also performed for the recycled concrete fines (Tabl. 3), and the corresponding granulometric curve was plotted (Fig. 4). The concrete fines predominantly consist of fine particles, with over 50 % passing through the 0.14 mm sieve, corresponding to ultra-fine sand, and nearly 10 % classified as silt, indicating a relatively high content of fine dust fractions.

The uniformity coefficient (U = 3.05) suggests a narrow particle size range, which is typical for poorly graded mineral materials (U < 4). The curvature coefficient (Cc ≈ 1.0) indicates an approximately symmetric distribution of grain sizes centred around the average diameter − a trait often observed in crushed mineral residues with consistent fractional composition.

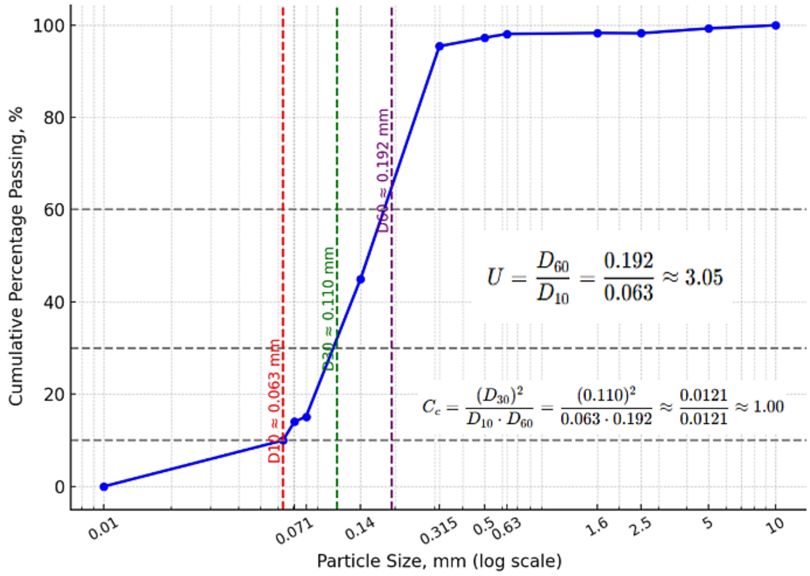


Fig.4. Grain size distribution diagram
of concrete fines indicating D10, D30, and D60 values

Fig. 5 illustrates the phase composition, which plays a key role in evaluating the properties and potential applications of man-made mineral materials. Given the qualitative and quantitative (Tabl. 4) mineralogical composition (quartz/feldspars) identified by XRD, concrete fines are treated herein as a mineral modifier of plastic soils.

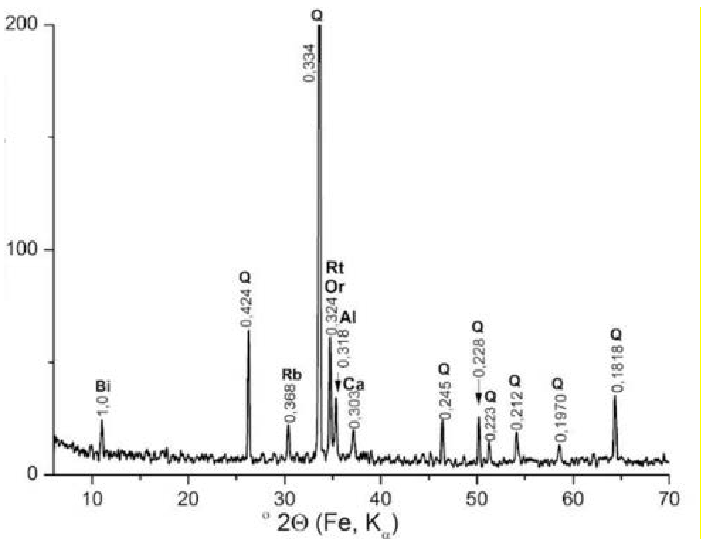


Fig.5. XRD pattern of Recycled Concrete Fines
Q – quartz (SiO_2); Ca – calcite ($CaCO_3$); Bi – biotite; Al – albite;
Or – orthoclase; Rt – rutile; Rb – $RbHSO_4$

Table 4

The quantitative mineral content of Concrete Fines

Mineral term	Quartz (SiO_2)	Albite ($NaAlSi_2O_8$)	Rutile (TiO_2)	Orthoclase ($KAlSi_2O_8$)	Calcite ($CaCO_3$)	Biotite $[K(Fe,Mg)_2(AlSi_3O_{10})(OH)_2]$	Rubidium hydrogen sulfate ($RbHSO_4$)
Percentage content, %	74	8	5	4	4	2	3

The Circular Concrete / S3RoU project (Circular Concrete (S3RoU), 2025) uses input screening and sorting, including portable rapid field survey methods to identify recyclable rubble, distinguish between normal and alkali-activated concrete, and detect asbestos fibres.

General methods. Loam and concrete particles were mixed in an air-dried state at a specified proportion. The components of the mixture were moistened to the optimal water content, which was determined using the modified Proctor test (EN 13286-2:2010, 2010). To assess the structural stability of the mixture, linear shrinkage tests under natural drying conditions were performed (DSTU B A.1.1-54:94, 1994). Changes in mechanical properties and shear resistance of the modified soil were determined through laboratory direct shear tests (ISO 17892-10:2018, 2018).

4. Results and Discussion

As part of the present study, it was determined that the powdered mineral material obtained by crushing waste concrete in Ukraine predominantly exhibits a cr ystalline structure. The primary constituents are quartz (approximately 74 %) and feldspar group minerals (including orthoclase and albite), derived from coarse-grained granite aggregates. A smaller proportion of calcite (~4 %) is also present. This mineralogical profile indicates limited chemical reactivity under hydration conditions, thereby significantly reducing the potential for activation through thermal or chemical means.

Quartz, in particular, is thermodynamically stable and exhibits chemical inertness within the alkaline environment. Its solubility under standard conditions is extremely low, which prevents it from engaging in hydration processes — even when chemical activators are introduced. Feldspar minerals, being crystalline aluminosilicates, also demonstrate poor solubility in alkaline solutions, and thermal treatment at 600–800 °C does not facilitate the generation of reactive or amorphous phases. Within this system, calcite serves primarily as a pH buffering agent rather than a reactive component.

Although activating these materials is theoretically feasible, it often demands significant energy and material inputs, while resulting in only marginal gains in reactivity. As emphasised in the open letter by RILEM TC UMW, the potential for activating mineral residues should be evaluated with respect to their phase composition, chemical characteristics, and overall reactivity profile (Peys et al., 2025). For crystalline systems with inherently low reactivity — such as mixtures dominated by quartz and feldspar — alternative utilisation strategies may be more practical and efficient.

Recycled concrete fines are characterised by a narrow particle size distribution (U < 4), indicating poor grading. Morphologically, the material consists of fine crystalline particles within the sand–silt size range. XRD analysis confirms the presence of quartz, albite, orthoclase, calcite, biotite, and rutile — all of which are mineral phases with low hydraulic reactivity that primarily serve as inert fillers. These components reduce the plasticity of the soil by physically “diluting” clay minerals. The performance of concrete fines as a mechanical additive could be further improved if the grain size spectrum included a greater proportion of coarse particles and was more evenly graded. Coarser fractions (2–0.5 mm) contribute more effectively to forming a stable granular framework that absorbs shear deformation and enhances the bearing capacity of the soil mass.

Recycled concrete fines represent crystalline materials composed of minerals of magmatic origin, notable for their high physicochemical stability, which accounts for their inert behaviour under typical soil conditions. Within modification systems, these minerals do not engage in chemical bonding, but instead form a structural scaffold that contributes to the mechanical performance of the soil matrix. Therefore, even without active chemical interaction, such materials can serve a valuable technical function in soil improvement applications.

One of the principal indicators used to determine the applicability of modified soil blends in road and water infrastructure projects is the linear shrinkage index measured under air-drying conditions (Leon et al., 2023 b; Venkatarama Reddy & Latha, 2014; Biswal et al., 2019). This parameter reflects the capacity of the material to retain its geometric integrity as it loses moisture. If shrinkage exceeds acceptable thresholds, it can result in surface cracking, detachment from structural components, and compromise of the base’s monolithic behaviour. Observing linear shrinkage behaviour facilitates the analysis of deformation tendencies in the soil composition (Fig. 6), which is essential for anticipating risks under service conditions.

Linear shrinkage was evaluated using the standardised method, which calculates the relative change in specimen length following natural drying. This metric reflects the material's susceptibility to deformation due to moisture loss. The resulting values provide insight into the structural integrity of the modified mix under air-drying conditions, aligning with applicable technical standards. When the shrinkage exceeds 4 %, there is an increased likelihood of cracking and non-uniform settlement, indicating that the subgrade may require optimisation − such as increasing binder dosage or adjusting the grain size composition of added mineral agents. Conversely, shrinkage within 2 % is generally regarded as acceptable and reflects adequate structural performance of the soil.

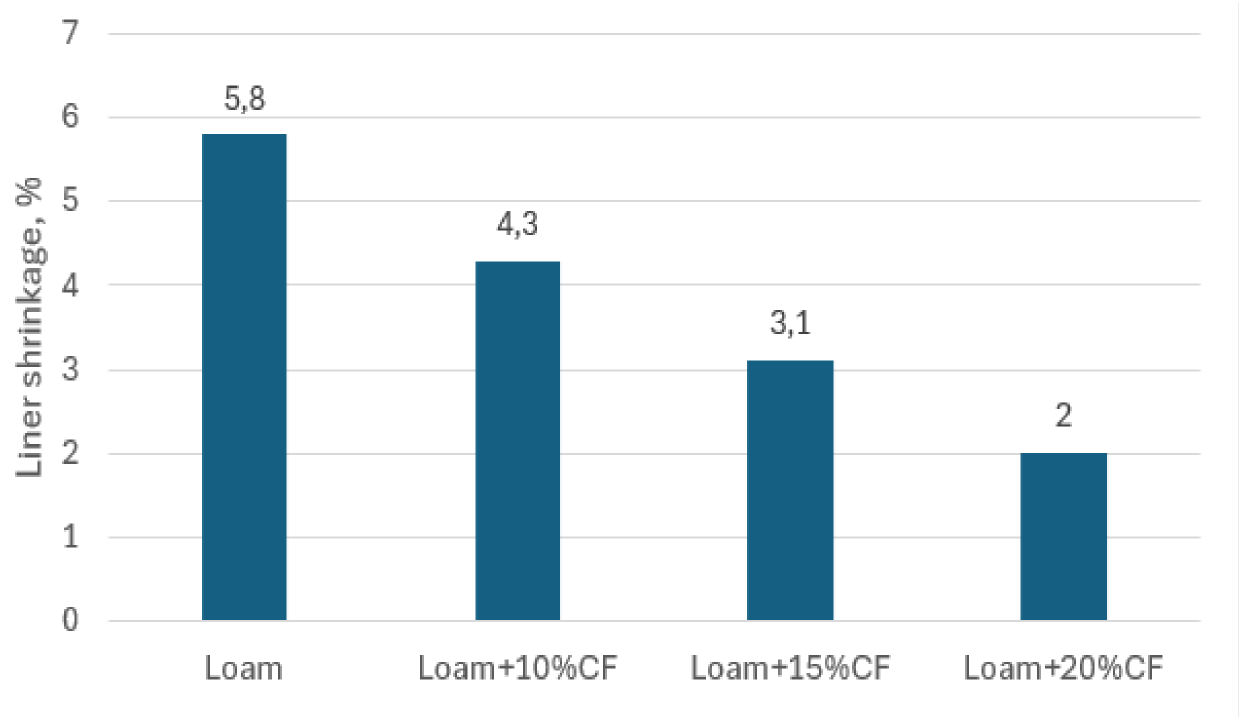
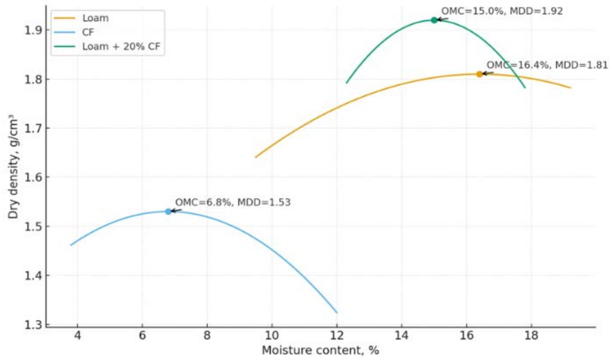


Fig.6. Effect of concrete fines content on the linear shrinkage of loam after air-drying

Linear shrinkage is reduced from 5.8 % to 2.0 % when loam is partially replaced with recycled concrete fines. This effect is attributed to several mechanisms: (1) the dilution of the clay fraction through the addition of stable, non-reactive mineral constituents such as quartz and feldspars; and (2) the development of a fine-grained internal framework formed by silt-sized magmatic particles, which helps restrain shrinkage during the drying process. Despite the absence of coarser sand fractions, the inclusion of 20 % recycled fines effectively lowers shrinkage, primarily due to the structural contribution of rigid mineral components that reinforce the integrity of the compacted mixture.

Linear-shrinkage tests showed that a content of 10–15 % concrete fines is insufficient to ensure the structural stability of the soil. Linear shrinkage under natural air-drying is defined as the relative deformation of the soil specimen, and values ≤ 2 % are considered acceptable. A content of 20 % concrete fines meets this requirement, yielding linear shrinkage within the specified limit.

To evaluate the impact of soil modification and to establish optimal compaction parameters for road base layers, the use of the Modified Proctor Test is considered appropriate. This method involves laboratory determination of the maximum dry density of soil at its optimum moisture content under elevated compaction energy. It is particularly suited for base materials where increased load-bearing performance is required and is conducted in accordance with established testing protocols (Leon, 2024; Connelly et al., 2008; Duque et al., 2020). According to the experimental findings (Fig. 7), replacing 20 % of loam with concrete fines (CF) results in higher maximum dry density and a shift in optimum moisture content toward lower values.



Laboratory test report (LOAM)				
Moisture content, %	10	15,2	**16,4**	17,4
Bulk density, ρ g/cm^3	1,85	2,03	**2,11**	2,09
Dry density, ρd g/cm^3	1,68	1,76	**1,81**	1,75

Laboratory test report CF				
Moisture content, %	4,4	5,2	**6,8**	7,14
Bulk density, ρ g/cm^3	1,5	1,56	**1,63**	1,6
Dry density, ρd g/cm^3	1,43	1,48	**1,53**	1,49

Laboratory test report (Loam+20%CF)				
Moisture content, %	13	13,8	**15**	16,7
Bulk density, ρ g/cm^3	2,05	2,08	**2,21**	2,22
Dry density, ρd g/cm^3	1,81	1,83	**1,92**	1,9

Fig.7. Results of Modified Proctor Test

This behaviour is associated with the microstructural influence of fine mineral particles, which enhance packing by occupying the voids between clay aggregates and improve the overall compactability of the mixture.At the same time, the overall water demand of the mixture declines as a result of the low moisture affinity and chemical inertness of the recycled concrete fines. This behaviour leads to a measurable decrease in optimum moisture content. Additionally, the reduction in the clayey dispersed fraction contributes to lower plasticity and a more favourable particle arrangement, which together enhance the mechanical performance of the compacted material.

In laboratory conditions, shear strength was evaluated by means of the direct shear test. Specimens were formed by compressing samples (previously compacted in the Proctor test) into metal shear rings. Testing was carried out using single-plane shear apparatuses with a m ovable upper section, where displacement occurred along a h orizontal interface. The soil underwent consolidated-drained loading: following full saturation and vertical load stabilisation, a horizontal force was gradually applied. The onset of shearing was identified at the point when the upper section shifted 5 mm relative to the lower box. This method enables the determination of soil cohesive strength and internal friction angle – essential parameters for subgrade stability assessment. The procedure was conducted under vertical loads of 0.1, 0.2, and 0.3 MPa. Tabl. 5 presents statistical estimates derived from peak shear stress values.

Table 5

Mechanical parameters calculated based on direct shear testing

Loam		Vertical pressure 0.1 MPa	Vertical pressure 0.2 MPa	Vertical pressure 0.3 MPa
		Shear stresses τ, MPa		
Minimum value		0.090	0.140	0.190
Maximum value		0.095	0.150	0.210
Average value		0.093	0.145	0.200
		cohesive strength (c), MPa	tan φ (internal friction angle)	Internal friction angle, φ (degrees)
Normative value		0.037	0.56	29
Calculated values at a given confidence level	0.85	0.032	0.54	28
	0.95	0.029	0.52	28
Loam+ Concrete Fines (20 %)		Vertical pressure 0.1 MPa	Vertical pressure 0.2 MPa	Vertical pressure 0.3 MPa
		Shear stresses τ, MPa		
Minimum value		0.100	0.160	0.210
Maximum value		0.105	0.190	0.270
Average value		0.103	0.175	0.240
		cohesive strength (c), MPa	tan φ (internal friction angle)	Internal friction angle, φ (degrees)
Normative value		0.033	0.71	35
Calculated values at a given confidence level	0.85	0.024	0.67	34
	0.95	0.019	0.64	33

Data presented in Tabl. 5 demonstrate that incorporating 20 % concrete fines into loam results in enhanced shear performance. The modified soil shows elevated shear stress values across all applied vertical loads, along with an increase in internal friction angle from 28° to 35° (within standard normative limits), suggesting improved particle interlocking. A slight reduction in cohesion is also observed, which is presumably linked to the lower influence of the clay fraction in the overall mixture (El Hariri et al., 2023; Stefanow & Dudziński, 2021; Sharma et al., 2 012). The observed improvement in shear characteristics is linked to the densified structure of the modified soil, which contributes to greater interparticle friction. The slight decrease in cohesion can be explained by the reduced presence of clay components, which typically ensure binding in plastic soils. Nevertheless, based on Coulomb's equation ($\tau = c + \sigma \cdot \tan \varphi$), an increase in the internal friction angle (φ) can still result in higher overall shear resistance (τ) under specific vertical stresses (σ) (Fig. 8). These findings confirm the suitability of recycled concrete fines as an effective mineral additive for loam modification.

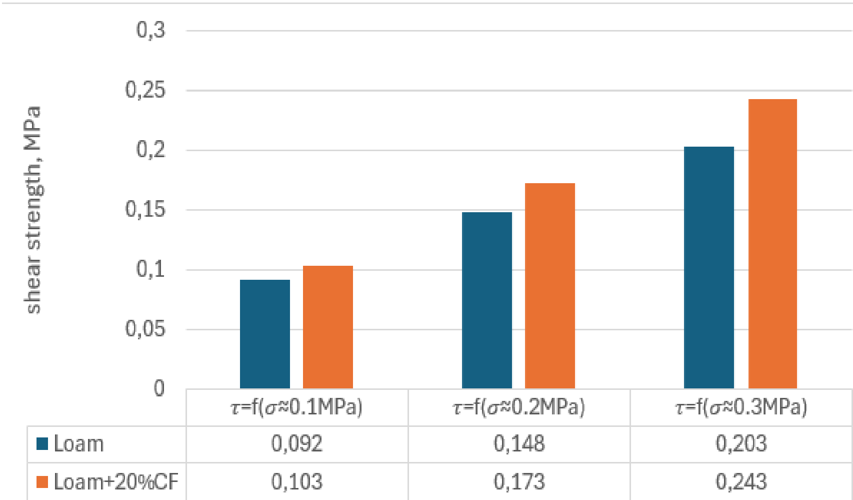


Fig.8. Shear strength of loam and loam with 20% at different vertical stresses

5. Conclusions

Recycled concrete fines with a p redominant particle size below 0.14 mm, derived from crushed reinforced concrete waste in Ukraine, consist mainly of crystalline phases such as quartz and feldspar. Concrete fines adjust the grain-size distribution of the loam, dilute the clay fraction, improve compaction under the (Modified) Proctor test, and reduce linear shrinkage. It was established that a loam with PI ≈ 17 modified with 20 % recycled concrete fines exhibits improved physico-mechanical properties compared to the natural loam. The CF reduce linear shrinkage under natural air-drying from 5.8 % (natural loam) to 2.0 % (modified loam). Compaction parameters (Modified Proctor) improve: for the natural loam OMC = 16.4 %, MDD = 1 .81 g/cm³; for the modified loam OMC = 15.0 %, MDD = 1.92 g/cm³. Direct shear tests indicate an increase in the internal friction angle from 28° to up to 35°. The overall shear resistance of the loam with 20 % CF increases on average by ~10–20 % across all levels of normal stress (0.1, 0.2, 0.3 MPa). These results confirm that recycled concrete fine fractions can be used as an effective mineral modifier to improve the physical and mechanical properties of loam and can be considered a prerequisite for high-quality soil stabilisation with the formation of frost- and water-resistant material.

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NUMERICAL MODELING OF THE WASTEWATER PURIFICATION PROCESS FROM HEAVY METALS USING THE ELECTRODIALYSIS METHOD

Vira Sabadash[1] ✉, Anna Nowik-Zając[2]

[1]Lviv Polytechnic National University,
12, S. Bandery Str., Lviv, 79013, Ukraine
[2] Jan Dlugosz University in Czestochowa,
4/8, J. Washington Str., 42200, Częstochowa
vira.v.sabadash@lpnu.ua

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Abstract. This study aimed to develop a mathematical model of ion transport in a system featuring a free electrolyte with membrane barriers and to investigate the interaction between diffusion and migration flows in different parts of the channel. The article presents the results of numerical modelling of the wastewater treatment process for copper ions using the electrodialysis method. Electrodialysis is a promising technology for removing dissolved ions from aqueous media due to its high efficiency, environmental safety, and the possibility of regenerating valuable components. The study developed a mathematical model that enables the simulation of how heavy metal ions, specifically copper ions (Cu^{2+}), migrate through an electrodialysis cell under the influence of an electric current. The model is implemented in the COMSOL Multiphysics environment, which enables the consideration of all the above aspects with high accuracy. The modelling process analysed the features of the transport of Cu^{2+} and SO_4^{2-} ions in the electrodialysis unit. Opposite directions of migration flow for cations and anions were found, which is consistent with the nature of their electric charges. Spatial heterogeneity of flow distribution was also established, and the need to take these features into account when optimising electrodialysis processes was substantiated. The modelling results confirm the effectiveness of electrodialysis for removing heavy metal ions from wastewater and indicate critical areas where efficiency losses may occur or ion concentrations exceed permissible limits. The obtained data can be used to improve the geometry of the channels, the membranes configuration and energy efficiency of electrodialysis units.

Keywords: electrodialysis, numerical modelling, wastewater, copper, ion transport, diffusion.

1. Introduction

Wastewater pollution by heavy metal ions, particularly copper, is one of the most pressing environmental problems associated with the activities of the mining, metallurgical, chemical, and engineering industries (Alkhadra & Bazant, 2022). Cu^{2+} ions, which are often present in the form of copper sulfate, are highly toxic, bioaccumulative, and can cause severe disturbances in aquatic ecosystems, threatening human health (Ayach et al., 2024). Traditional water treatment methods (chemical precipitation, filtration, flotation, etc.) do not always provide sufficient efficiency in removing such pollutants, especially at low ion concentrations (Bunani et al., 2024).

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Electrodialysis — a promising membrane technology that utilises the transfer of ions under the influence of an electric field through ion-selective membranes – exhibits high efficiency in the selective removal of heavy metals from the aqueous environment (Ding et al., 2023). However, the efficiency of this process largely depends on several physicochemical parameters, including ion concentration, electric potential, membrane structure and properties, and medium hydrodynamics (Proskynitopoulou et al., 2024; Sabadash et al., 2025). An experimental study of the influence of each of these factors is resource-intensive and often limited in reproducibility (Ebrahimi Gardeshi et al., 2024).

In this context, numerical modelling of the copper sulfate electrodialysis process becomes a relevant tool for deeper analysis and optimisation of treatment parameters (Feng et al., 2024). Creation of an adequate mathematical model that takes into account the features of Cu^{2+} and SO_4^{2-} ion transport, electric field, Donnan potential and boundary conditions allows obtaining a quantitative assessment of the efficiency of the process and contributes to the implementation of environmentally friendly wastewater treatment technologies.

Literature review. Wastewater treatment from heavy metals is one of the key tasks of modern ecotechnology (Ghasemi, 2023). Heavy metals, such as Cu^{2+}, Pb^{2+}, Zn^{2+}, Cd^{2+} and others, pose a threat to the environment and human health even at low concentrations, which requires the use of highly effective methods for their removal (Abdullayev et al, 2022; Ayach et al, 2024). Among modern technologies, electrodialysis attracts attention due to its selectivity, energy efficiency, and ion recovery capability (Ji et al., 2024; Liu et al., 2022).

There is considerable interest in the use of bipolar membrane electrodialysis for removing metals from various types of wastewater, including mining and industrial wastewater (Feng et al., 2024). For example, Bunani, Abbt-Braun, and Horn (2024) demonstrated the high efficiency of bipolar electrodialysis in removing heavy metals from model solutions. Similar results were obtained in studies combining electrodialysis with other methods, such as electrocoagulation and adsorption (Feng et al., 2024; Zhang et al., 2024).

Integrated or hybrid technologies, where electrodialysis is combined with adsorption or membrane processes, are considered particularly promising. For example, the use of nanomaterials and ion-exchange membranes enables increased selectivity in metal ion removal (Kim et al., 2024; Ding et al., 2023). Another innovation is the introduction of amphoteric or electroactive groups into the membrane structure, enabling high metal ion removal rates (Yu et al., 2024).

It is also worth mentioning the shock electrodialysis method, which allows achieving high selectivity in ion separation due to localised electric fields. The study by Alkhadra and Bazant (2022) (Alkhadra & Bazant, 2022) demonstrated the potential for continuous removal of heavy metals from contaminated waters with a high degree of selectivity.

In addition, modern mathematical models and numerical simulations are increasingly used to describe and optimise electrodialysis processes. In particular, our previous work demonstrated the possibility of predicting the dynamics of ion migration in complex environments (Gumnitsky et al., 2022; Sabadash & Omelianova, 2021). This allows not only to optimise experimental parameters, but also to minimise the costs of implementing the technology.

Special attention should be paid to issues of environmental and economic efficiency, particularly the possibility of secondary use and recovery of metals after extraction (Zha et al., 2023; Zimmermann et al., 2024). Such aspects make electrodialysis not only a practical but also a sustainable method of water purification within the framework of the circular economy principles.

Research objective. The study aimed to develop a mathematical model of ion transport in a system with a free electrolyte, including membrane barriers, and to visualise the interaction of diffusion and migration flows in different zones of the channel.

2. Experimental part

In this study, the numerical model is constructed based on a typical repeating section of an electrodialysis cell, excluding the inlet and outlet flow zones, which enables us to focus on the processes of ion transport within the main working volume. The scheme of the device model is shown in Fig. 1.

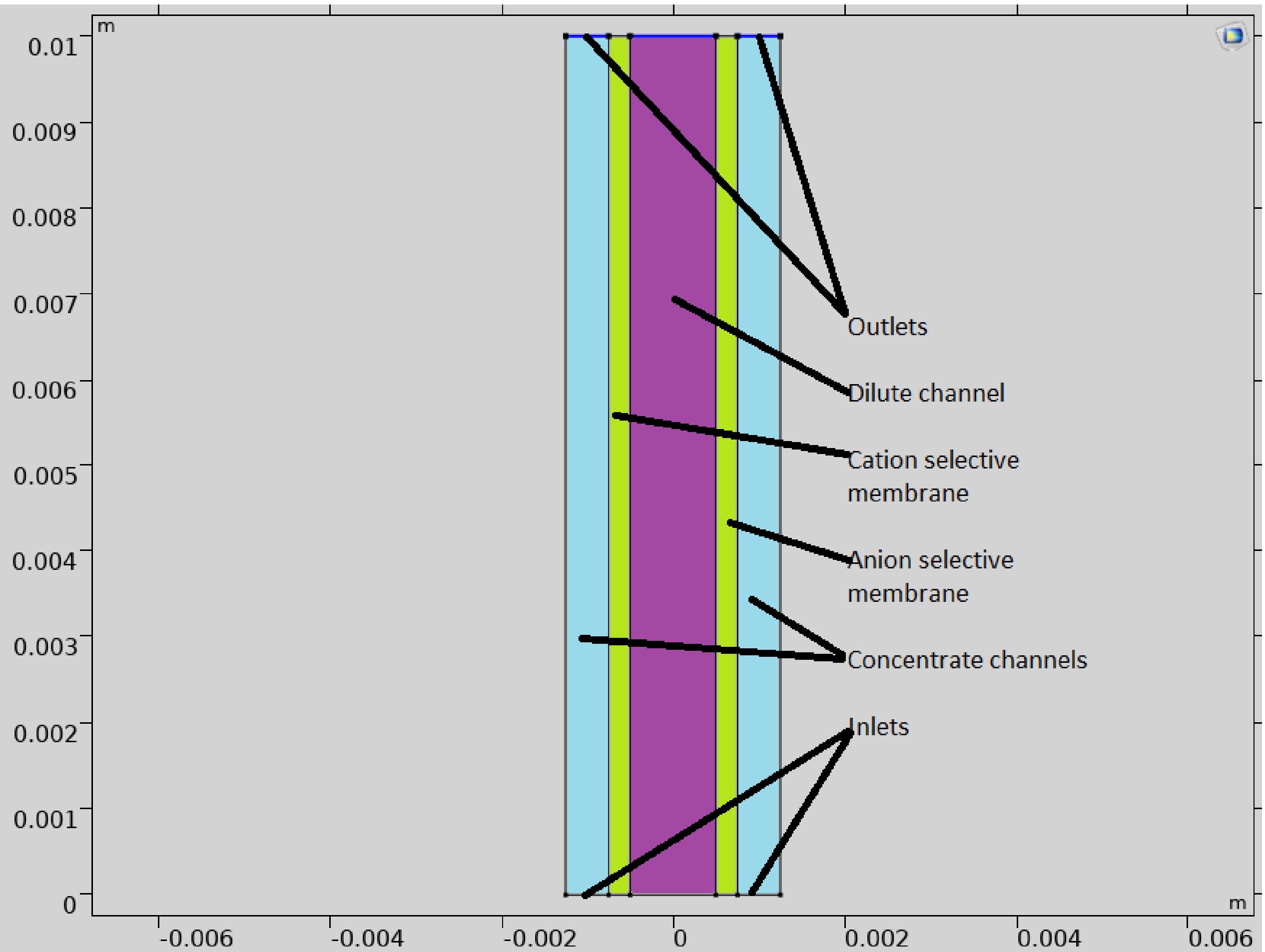

Fig.1. Schematic of the electrodialysis cell model

The model of the electrodialysis cell comprises five domains: two ion-selective membranes and three zones with free movement of the electrolyte.

In particular:

– The left membrane is cation-selective, allowing mainly cations, including copper ions (Cu^{2+}).

– The right membrane is anion-selective and allows the transfer of anions such as SO_4^{2-}.

– The central domain between the membranes is the dilute solution zone (diluate domain), from which heavy metal ions must be removed during the electrodialysis process.

– The extreme (left and right) domains represent the concentrate zones (concentrate domains), where Cu^{2+} and SO_4^{2-} ions accumulate under the action of an applied electric potential.

In each of the electrolyte domains, a laminar flow of liquid is implemented, entering through the lower inlets and exiting through the upper outlets at an average velocity of 5 mm/s. The velocity profile is described by the analytical form for Poiseuille flow, which corresponds to the steady laminar regime in a flat channel (Lan et al., 2025).

The electrolyte in the dilute zone is a cuprous sulfate solution with an initial Cu^{2+} ion concentration of 50 mol/m³ (or 0.05 M). The model solution simulates typical industrial pollution with heavy metal ions. To ensure ion transfer, a constant voltage of 1.5 V is applied to the cell, allowing for the effective removal of heavy metal ions through ion-selective membranes. The diffusion coefficient of copper ions (Cu^{2+}) in water at a temperature of 25 °C (298 K) is $D_{Cu^{2+}} \approx 0.72 \times 10^{-9}\ m^2/c$. The diffusion coefficient of sulfate ion (SO_4^{2-}) in water at a temperature of 25 °C (298 K) is approximately $D_{SO_4^{2-}} \approx 1.07 \times 10^{-9}\ m^2/c$

The specified parameters and geometry of the model serve as the basis for conducting a numerical analysis, which enables us to evaluate the effecttiveness of electrodialysis in purifying wastewater from copper ions.

Lower submitted a mathematical description of the electrodialysis process, which combines physicochemical phenomena: mass transfer, electrical conductivity, electrical field, and ion diffusion. He based his analysis on the Nernst–Planck equations, Poisson's equation (or electroneutrality), and boundary conditions at the "membrane - electrolyte " interface.

For each ion i in the Nernst–Planck equation, it can be written as follows:

$$\mathrm{N}_i = -D_i \nabla c_i - z_i u_i c_i \nabla \phi + c_i \mathrm{v}, \quad (1)$$

where N_i is the ion flux vector i(mol/m²·s), D_i is the ion diffusion coefficient i (m²/s), c_i is the ion concentration i(mol/m³), z_i is the ion charge i, u_i is the ion mobility (relationship: $u_i = D_i/RT$), ϕ is the electric potential (V), v is the convective flow velocity (if present), R is the gas constant, T is the temperature (K).

Law preservation masses for each ion:

$$\frac{\partial c_i}{\partial t} + \nabla \cdot \mathrm{N}_i = 0. \quad (9)$$

A relationship exists between the electric potential and the ion concentration on both sides of the interface (Zha et al., 2023). This relationship considers the potential difference that arises due to the differences in ion concentrations between the membrane and the electrolyte.

The potential that arises due to this phenomenon is called the Donnan potential or dialysis potential.

This is described by equation (10),

$$\phi_{l,m} = \phi_{l,e} - \frac{RT}{z_i F} \ln\left(\frac{c_{i,m}}{c_{i,e}}\right), \quad (10)$$

where *ci, m* is the concentration of ions in the membrane, *ci, e* is the concentration of ions in the free electrolyte, *zi* is the charge of the corresponding ion.

Thus, equations (3), (4), and (5) specify mixed boundary conditions of the Dirichlet and Neumann type for the electric potential and ion concentrations.

Tertiary software environment Current Distribution, Nernst – Planck (COMSOL Multiphysics). These conditions are set using the special Ion Exchange Membrane functionality domain feature, which ensures correct accounting for ion transport and potential differences at the membrane-electrolyte interface.

3. Results and Discussion

Within the framework of the numerical simulation, the process of electrodialysis of a cuprous sulfate solution with an initial copper ion concentration of 50 mol/m³ was investigated. The model was implemented using the Nernst-Planck equations to describe ion transport, taking into account the electric potential, diffusion, migration, and Donnan potential at the membrane boundaries.

Based on the constructed geometry and the given boundary conditions, the spatial distribution of Cu^{2+} and SO_4^{2-} ion concentrations in different domains of the electrodialysis cell was obtained. It was found that under the action of an electric field (1.5 V), copper ions are effectively extracted from the central (dilute) zone and accumulate in the concentrate zone, as confirmed by the concentration profiles.

A particularly intense ion flux was observed near the ion-selective membranes, which corresponds to the expected increase in potential and concentration gradients. In the dilute zone, the Cu^{2+} concentration gradually decreased, and in the concentrate zone, it increased. For example, under the calculated conditions, within a conditional time of 1000 seconds, the concentration of copper ions in the central domain decreased by more than 40%, which indicates a high efficiency of the process.

The effect of voltage variation on the ion removal rate was also analysed. With an increasing applied potential of up to 2.0 V, an increase in the ion transfer rate was observed; however, at the same time, electrochemical gradients were strengthened, which can cause increased energy consumption and polarisation effects. This emphasises the importance of optimal selection of operating parameters to ensure a b alance between process efficiency and its energy costs.

Thus, the modelling results confirm the feasibility of using the electrodialysis method for treating wastewater containing copper ions, and the proposed model can be used for further optimisation of process parameters under real conditions.

Fig. 2 shows the distribution of electrolyte potential along a horizontal line located in the middle of the height of the electrodialysis cell.

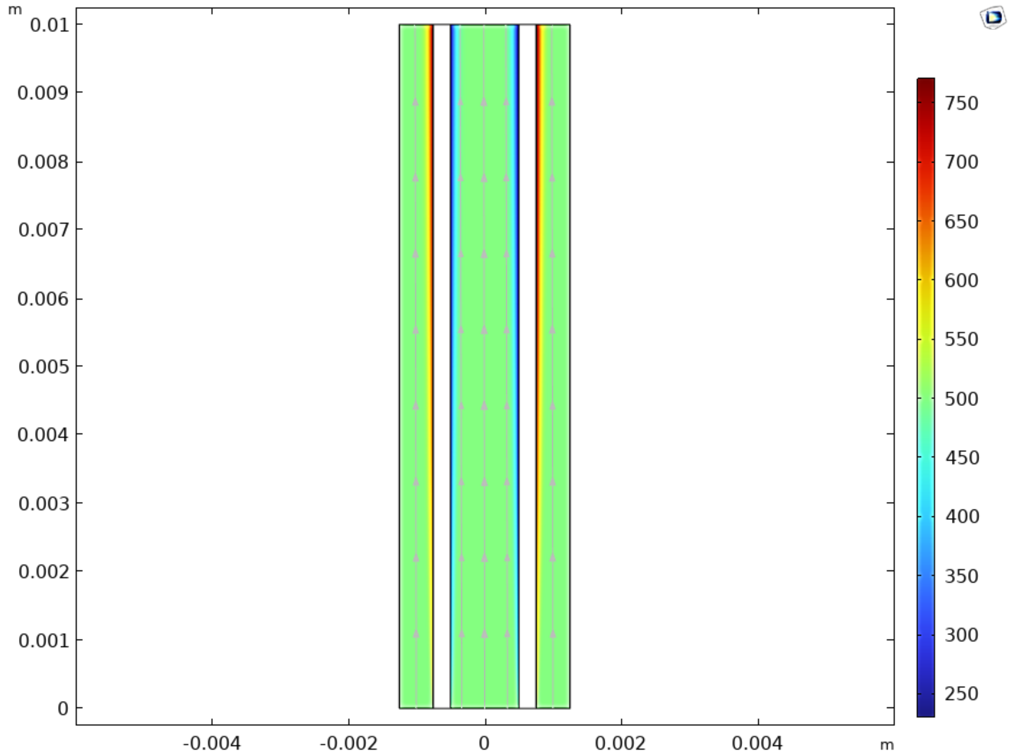

Fig.2. Concentration distribution in the electrodialysis cell

Fig.3 shows the distribution of electrolyte potential (φ) along the horizontal coordinate in the electrodialysis cell, at a height corresponding to the middle of the working channel (along the Y axis = const). The X axis represents the distance along the cell, and the Y axis represents the value of the electrolyte potential (in volts).

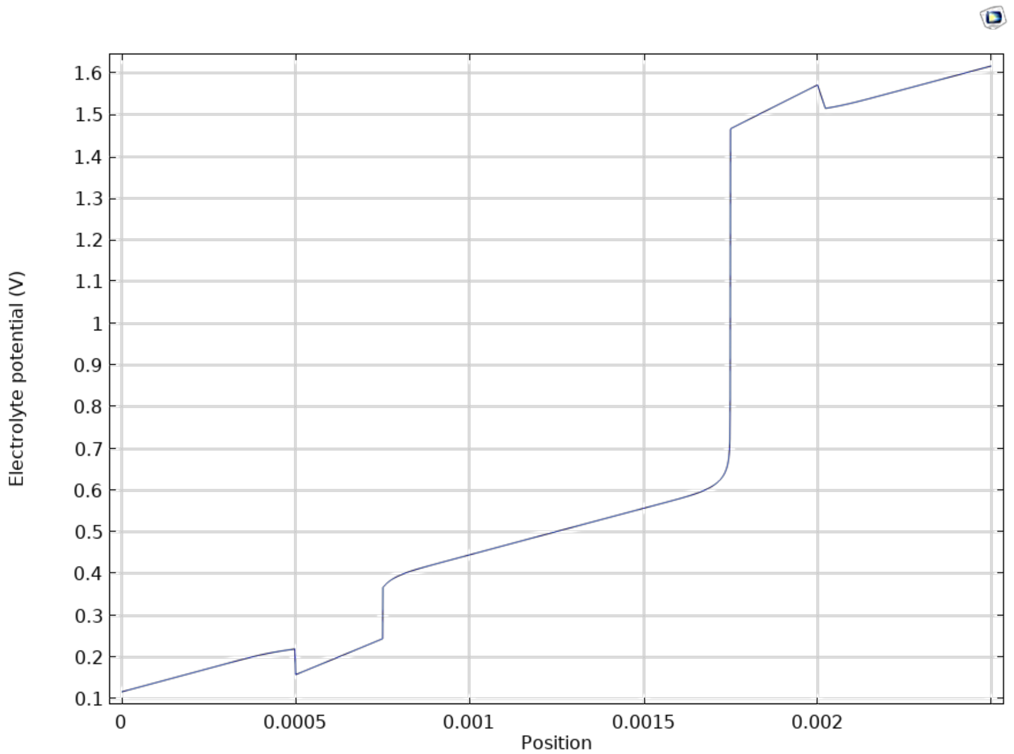

Fig.3. Distribution of electrolytic potential in an electrodialysis cell

The graph shows a linearly increasing potential in three separate zones: the two regions with a gentle slope correspond to the free electrolyte zones (diluate and concentrate), and the steep drop between them corresponds to the membrane domains.

In the areas corresponding to ion-selective membranes, sharp changes in potential are observed, which indicates their high electrical resistance. This also confirms that the majority of potential losses occur in the membranes.

At the boundaries between the free electrolyte and the membrane domains, potential jumps are observed, which are a manifestation of the Donnan potential. This effect arises due to the difference in ion concentrations and the presence of fixed charges in the membrane material.

The total potential drop across the cell corresponds to an applied voltage of 1.5 V, according to the model conditions.

The graph confirms that the efficiency of electrodialysis is dependent mainly on the electrical characteristics of the membranes, and also demonstrates the influence of the Donnan potential on the transfer of ions across the interfaces between the electrolyte and the membranes. The resulting potential distribution is characteristic of processes descrybed by the Nernst–Planck equations in combination with electroneutrality and boundary conditions on the membranes.

Fig. 4 shows the components of the flow of copper ions Cu^{2+} along the coordinate axis X:

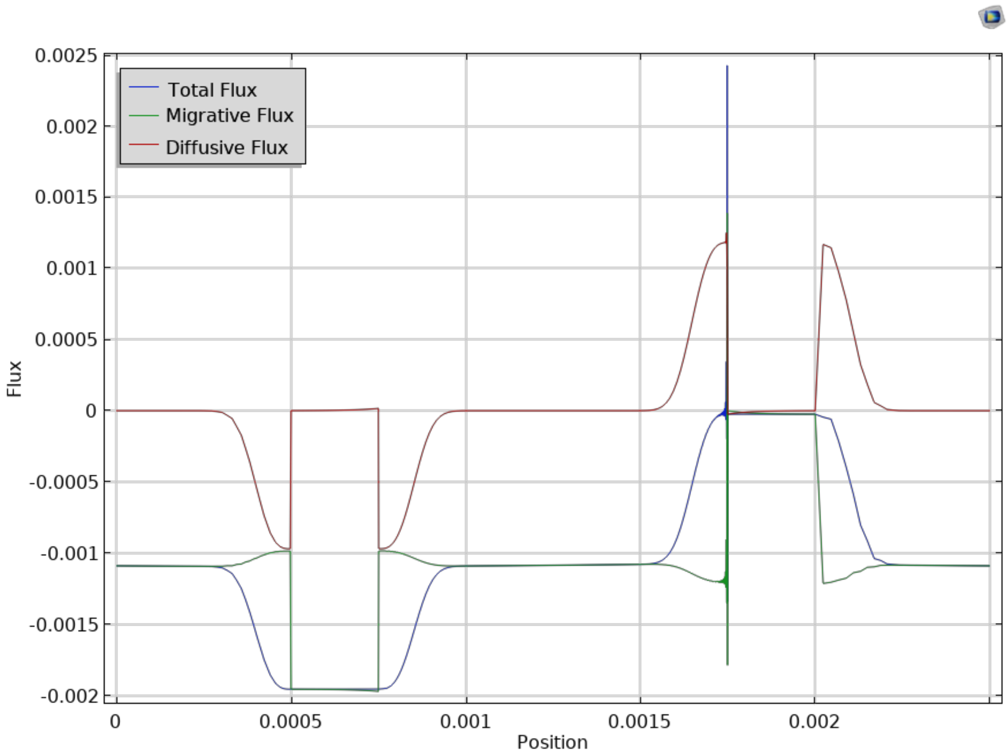

Fig.4. Components of the flow of copper ions Cu^{2+} in the electrodialysis cell

Blue curve (Total Flux) is the total flow of Cu^{2+} ions;

The green curve (Migrative Flux) is the electromigration component of the flow, which is caused by an electric field.

The red curve (Diffusive Flux) represents the diffusion component of the flow that arises from a concentration gradient.

In the central zone (dialysis chamber), there is an intensive migration and transfer of Cu^{2+} directed towards the cation-exchange membrane.

A sharp jump in flow within the membranes indicates the presence of intense electrical activity in these areas — a typical sign of electrodialysis.

The diffusion component reaches its highest values near the boundaries between zones where a concentration gradient is observed.

The total flow (blue graph) reflects the combined effect of both mechanisms — diffusion and migration, with migration dominating. Similar to the previous one, Fig. 5 displays the components of the sulfate ion flux:

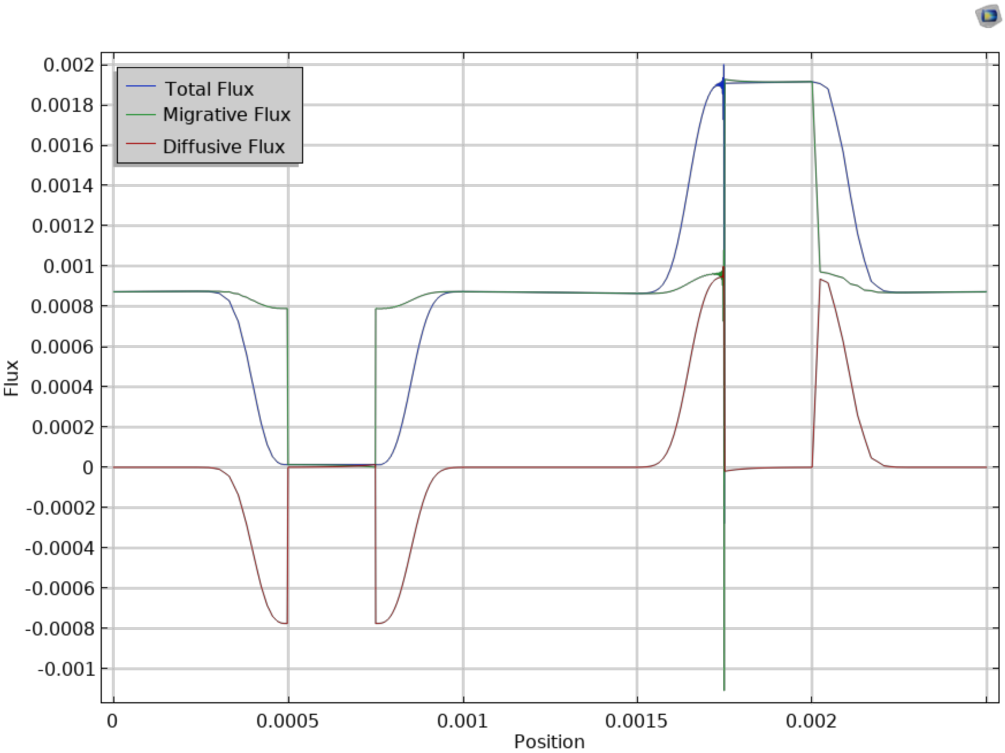

Fig.5. Components of the flow of sulfate ions $(SO_4)^{2-}$ in the electrodialysis cell

The blue curve is the total flux of ions $(SO_4)^{2-}$;

The green curve is the migration component (electric field).

The red curve is the diffusion component (concentration gradient).

Interpretation:

Unlike Cu^{2+}, the flow of sulfate ions is directed in the opposite direction – towards the anion exchange membrane, which corresponds to their negative charge.

The migration component (green graph) is the primary driver of sulfate ion transport.

The diffusion component is significant in the contact zones between the membranes and the dialysis chamber, where concentration differences are observed.

The total flow confirms the efficient removal of anions from the dialysis zone.

Both graphs indicate that the electromigration component dominates the diffusion component, confirming the efficiency of the electrodialysis process in separating Cu^{2+} and $(SO_4)^{2-}$ ions. The highest flux values are observed at the membrane boundaries, where strong electric fields act and selective ion transport through the membrane occurs. This is consistent with the physical nature of the electrodialysis process.

The results of numerical simulations of the electrodialysis process for wastewater treatment of heavy metals, particularly Cu^{2+} and SO_4^{2-} ions, demonstrate the effectiveness of the method in controlling the transfer of ions through the membrane. The obtained data are consistent with the results of previous experimental and theoretical studies, which emphasise the importance of the electric field in the formation of the migration flow of ions in the central part of the channel (Ding et al., 2023; Feng et al., 2024).

A notable observation is the dominance of diffusion flux near the membrane boundaries, which is attributed to the steep concentration gradient characteristic of the phase separation zone (Tedesco et al., 2018). This effect has practical significance for optimising the location of membranes and choosing the modes of electric current supply (Bunani et al. 2024, 2024; Zhang L. et al., 2024). The migration flows prevailing in the centre of the channel have opposite directions for cations and anions, which is entirely consistent with the electrochemical nature of the process (Bunani, 2024).

The model also revealed a dependence of the transfer efficiency on the initial ion concentration in the solution, which is consistent with data on the decrease in electrodialysis performance in dilute solutions (Ghasemi et al., 2023; Zhang et al., 2024). This highlights the need for preconcentration or cascade purification for solutions with low heavy metal content.

The study also confirms that the geometric parameters of the channel, the thickness of the diffusion layer, and the physicochemical characteristics of the membranes are critical for intensifying the process. Such observations correlate with the work of modern researchers in the field of modelling ion transport in electrodialysis systems (Ebrahimi Gardeshi et al., 2024; Lan et al., 2025).

Overall, the numerical model has proven its ability to reflect the physical processes occurring in the electrodialysis system adequately and can be used as a tool for further optimisation of purification systems. However, to increase the accuracy of the modelling, it is advisable to take into account non-linear effects, such as electroconvection and the possible formation of concentrated fields that affect the behaviour of ions under real conditions (Yu et al., 2024).

4. Conclusions

As a r esult of numerical modelling of the electrodialysis process for removing heavy metal ions from wastewater, regularities in the distribution of migration and diffusion flows of ions within the system were revealed. The study showed that in the zone close to the membrane boundary, the diffusion flow is dominant, due to the high concentration gradient. In contrast, in the central part of the channels, the migration transport mechanism prevails, which confirms the effectiveness of the electric field in controlling the movement of Cu^{2+} and SO_4^{2-} ions to the corresponding electrodes. In this case, the directions of ion migration are opposite due to their charge, which corresponds to the physicochemical characteristics of the process.

The model has confirmed its ability to reflect complex interactions in the electrodialysis system and has allowed visualisation of key stages of ion transport, which is important for optimising the design of devices and treatment modes. The results can be used to improve water treatment systems further and reduce the environmental load from industrial wastewater, particularly in the case of copper ion removal.

The obtained data can also serve as a basis for developing new approaches to controlling the electrodialysis process, taking into account the geometry of the channels, membrane properties, and characteristics of pollutants.

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ECOLOGICAL RISKS OF CHROMIUM CONTAMINATION IN UKRAINIAN SOILS AFFECTED BY MILITARY ACTIVITY: SEM-EDS AND EPMA ANALYSIS

Kateryna Petrushka, **Ihor Petrushka**

Lviv Polytechnic National University,
12, S. Bandery Str ., Lviv, 79013, Ukraine
kateryna.i.petrushka@lpnu.ua

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Abstract. The contamination of soil with heavy metals as a result of military activity presents a significant and multifaceted environmental challenge. Chromium, in particular, is introduced into the environment through various military-related processes, such as the use of ammunition, explosives, fuels, and other military equipment. Once released, chromium can persist in the environment, especially in soil, where it exists primarily in two oxidation states: trivalent chromium (Cr(III)) and hexavalent chromium (Cr(VI)). The latter is particularly toxic and poses a considerable risk to both environmental and human health. In this study, we focused on analyzing soil samples with the highest concentrations of chromium ions. The main objective was to identify chromium compounds present in the soil as a direct consequence of military actions, with the aim of assessing environmental risks and developing strategies to mitigate their impact. Prolonged contamination–over a span of several years–can result in ireversible ecological damage, affecting local biodiversity and potentially leading to the disruption of food webs. Furthermore, the accumulation of chromium in water sources and food chains increases the risk of adverse health effects for nearby populations. Therefore, chromium pollution arising from military operations has the potential to cause long-term degradation of ecosystems, highlighting the urgent need for remediation and preventive measures.

Keywords: chromium ions, migration, electron microscopy, soil.

1. Introduction

Hexavalent chromium (Cr(VI)) is widely acknowledged for its elevated toxicity and carcinogenicity compared to trivalent chromium (Cr(III)). Chromium contamination is a major environmental concern, as it contributes to soil degradation by altering its physical and chemical properties, ultimately leading to a decline in soil fertility. In aquatic systems, chromium ions exhibit slow rates of natural attenuation, creating long-term imbalances in background concentrations. This persistence facilitates the migration of Cr species into water bodies through surface runoff and infiltration, thereby contaminating both surface and groundwater resources and posing significant risks to drinking water safety and human health.

Cr(VI) is particularly hazardous due to its high solubility and bioavailability, which enable its rapid uptake by living organisms. Exposure to Cr(VI) has been associated with dermatological conditions, respiratory disorders, internal organ damage, and increased cancer incidence. In natural environments, chromium predominantly exists as Cr(III) in the form of stable, poorly soluble minerals. In contrast, Cr(VI) forms highly soluble chromate and dichromate salts, which are more mobile and reactive under environmental conditions.

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Elevated levels of Cr(VI) in soil and water typically originate from anthropogenic sources, particularly industrial activities. For example, solid wastes produced by the leather tanning industry are rich in Cr(III) oxides, which can become soluble under acidic conditions (pH < 6). Cr(VI) compounds also dissolve in both acidic and alkaline media and can be reduced to Cr(III) in the presence of reducing agents, particularly under acidic environments. Consequently, chromium in the environment may be present either in dissolved Cr(VI) form or as sedimented Cr(III) oxides. Given its greater solubility and ecological mobility, Cr(VI) poses a higher toxicological threat than Cr(III).

Regulatory bodies have established a maximum permissible concentration of total soluble chromium in drinking water at 0.05 mg/L (Peng et al., 2023; Chen et al., 2018; Mortazavian et al., 2022; Li et al., 2020). The primary natural source of chromium, chromite ($FeCr_2O_4$), can undergo oxidation to Cr(VI) in the presence of manganese oxides (Mn(III/IV)), which are common constituents in soils (Beukes et al., 2017; Hu et al., 2016; Luizon Filho et al., 2020). Conversely, various environmental components such as organic matter, iron-based compounds, and sulfides facilitate the reduction of Cr(VI) to Cr(III), leading to redox transformations that influence chromium speciation and mobility in contaminated soils, sediments, and water bodies (Wise et al., 2022; Karimi-Maleh et al., 2021).

Mineralogical analyses have identified calcium chromate ($CaCrO_4$) as a dominant crystalline phase in Cr(VI)-contaminated environments, while iron has been observed in complex forms such as $FeOHCrO_4$, as confirmed by X-ray diffraction data (Joint Committee on Powder Diffraction Standards, JCPDS card 8-0458) (Mishra & Bharagava, 2016).

However, chromium pollution sources have a significant impact on the environment during hostilities, as a result of the use of ammunition and explosives, fuel and lubricants, the accumulation of disrupted equipment and worn metal parts and debris, etc.

According to the environment, there are such recommendations for reducing the impact of chromium compounds on the environment: a) the use of remediation methods such as phytoremediation (the use of plants for soil cleaning), chemical treatment and bioremediation (the use of microorganisms for degradation of pollutants) can help reduce chromium level soil; b) constant monitoring of chromium levels in hostilities and regulation of the use of chromium materials may reduce the risks of contamination; c) the use of environmental recovery programs, including the reclamation of damaged land and protection of water resources, is important to reduce the impact of chromium on the environment.

2. Materials and Methods

The soil samples were analysed using SEM to determine their morphological characteristics. Some microphotographs illustrate the shape of the soil particles (Fig. 1). Soil is a heterogeneous material with a diverse particle size distribution. The soil particles were analysed using electron microscopy (EDS), which indicates the presence of chromium and its compounds in the soil (Fig. 2).

The EDS analysis is presented in the figures from different areas of the sample. It was found that the content of elements in the soil differs significantly due to the crystal lattice structure of such elements as: Si, Al, O, Fe, Ca, K, Mg, Na and Cr. It should be noted that the presence of Ba2+ in the soil is noteworthy (Fallahzadeh et al., 2018; Kim & Dixon, 2002). Barium is bound to clay components in soils, forming a chromate mineral phase, $BaCrO_4$, which can be a source of Cr (VI) (Matern et al., 2017; Matern and Mansfeldt, 2016). The presence of Ba^{2+} can be attributed to the erosion of intrusive rocks from the north of the study area (Kazakis et al., 2018). The iron content also varies and is based on EDS results; the untreated soil has the highest Fe content.

3. Results and Discussion

For the ESP and SEM, the analysis of soil samples in the places of explosion for the presence of heavy metals selected G7 samples, which contain a concentration that significantly exceeds the maximum permissible concentrations (Petrushka & Petrushka, 2023, Petrushka et al., 2023;), in which the XRF analysis, respectively, there are exceeding the background concentrations.

The G7 sample investigated region 1 (Fig. 1) with a multiplicity from 300 to 5740 times in Area 1-3.

The investigated area is characterised by a notably high silicon (Si) content. X-ray phase analysis revealed that the soil matrix contains a variety of metal oxides exhibiting hexagonal crystal structures. These oxides are formed from heavy metals such as chromium (Cr), manganese (Mn), nickel (Ni), zinc (Zn), titanium (Ti), copper (Cu), strontium (Sr), and zirconium (Zr), as evidenced by spectral peaks with Octane Elect Plus intensities in the range of 0.05 to 2.2.

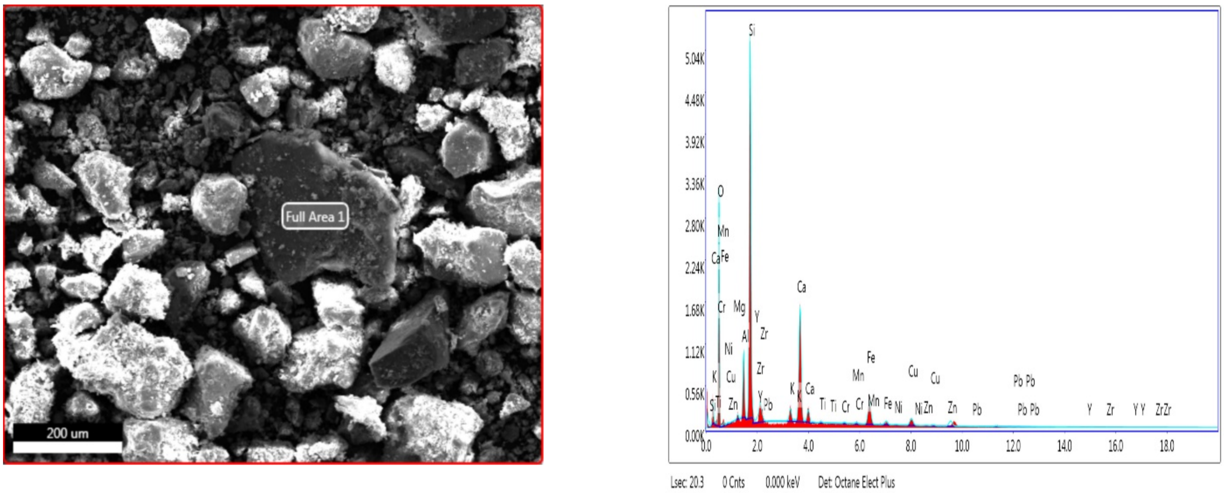
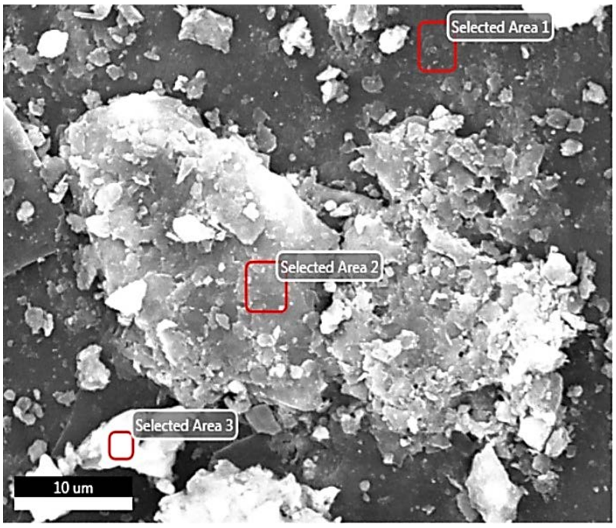
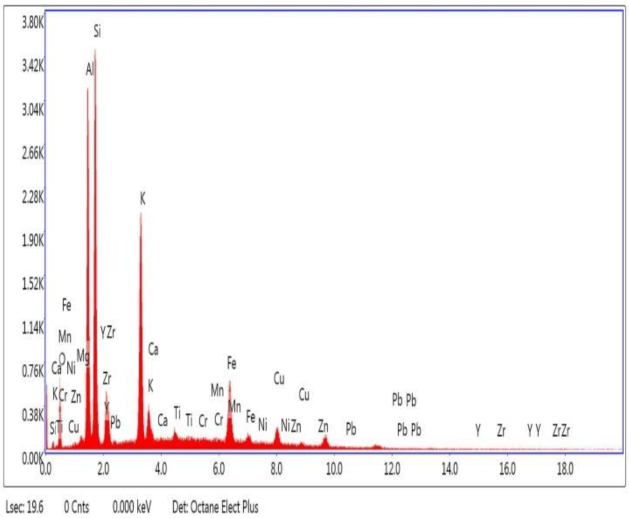
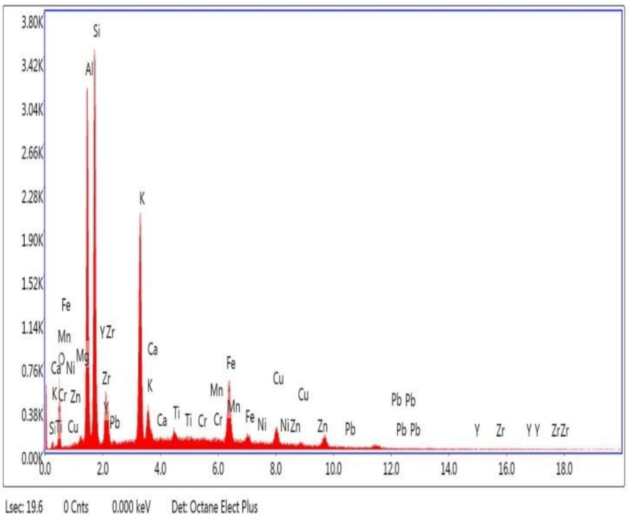


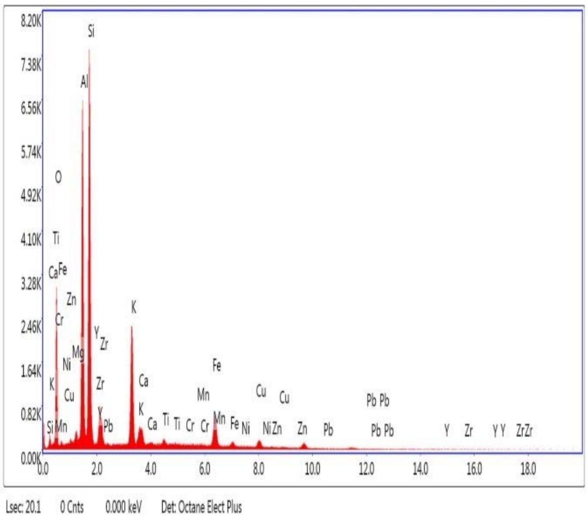
Fig.1. Examination of zones at a magnification of 300x





Research Area 1 **Research Area 2**





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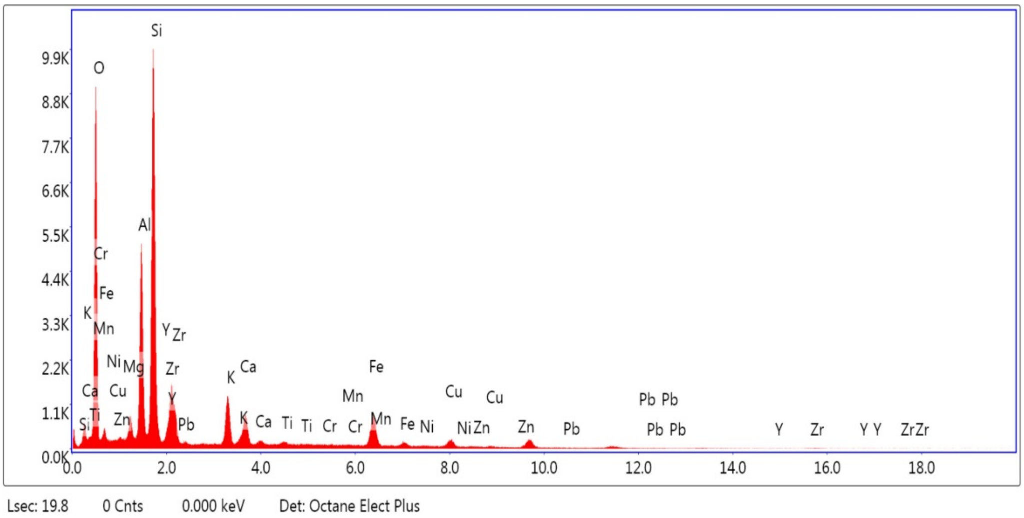


Fig. 2. Experimental data on selected zones (Area1-3) of G7 soil samples at a magnification of 5740 x

The presence of these elements suggests a complex geochemical environment with multiple sources of contamination. Of particular significance is the identification of calcium chromate ($CaCrO_4$) as the dominant crystalline phase. This compound was confirmed by reference to the Joint Committee on Powder Diffraction Standards (JCPDS card 8-0458) (Tumolo et al., 2022).

Furthermore, iron ions of varying oxidation states appear to participate in the formation of a secondary complex compound, ferric hydroxychromate ($FeOHCrO_4$). The occurrence of this mineral phase was initially reported by Rock et al. (2001), based on mineralogical observations in similar contaminated contexts. Leaching experiments indicated that the pH of the eluates during chromium extraction ranged between 6.5 and 8.5, suggesting that iron in the soil occurs predominantly in hydroxide rather than oxide form. This observation aligns with the solubility predictions provided by Puigdomenech (2004) and the ICDD database (ICDD Products, 2025), which indicate that $FeOHCrO_4$ is insoluble in solution and thus precipitates under environmental conditions. The presence and distribution of these compounds were further confirmed by X-ray fluorescence (XRF) analysis of the collected soil samples (Fig. 3), supporting the conclusion that heavy metals in the studied area are immobilised primarily as stable mineral phases with limited solubility, depending on pH and redox conditions.

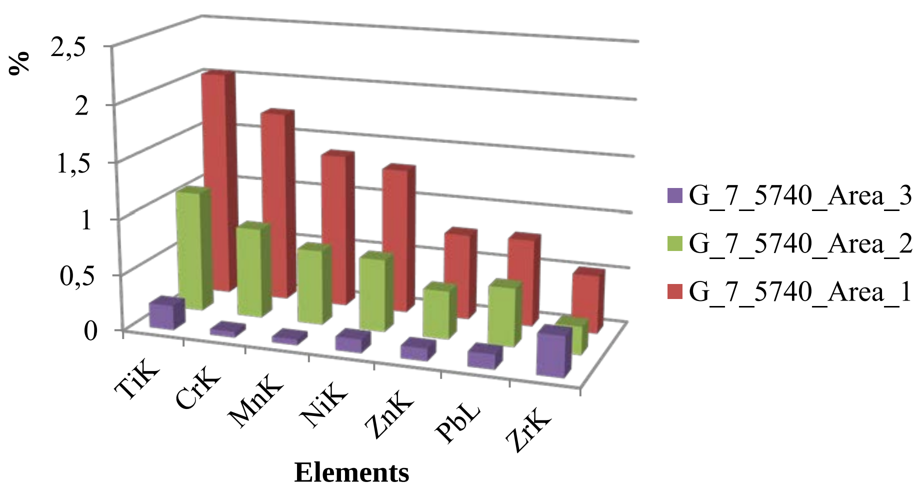
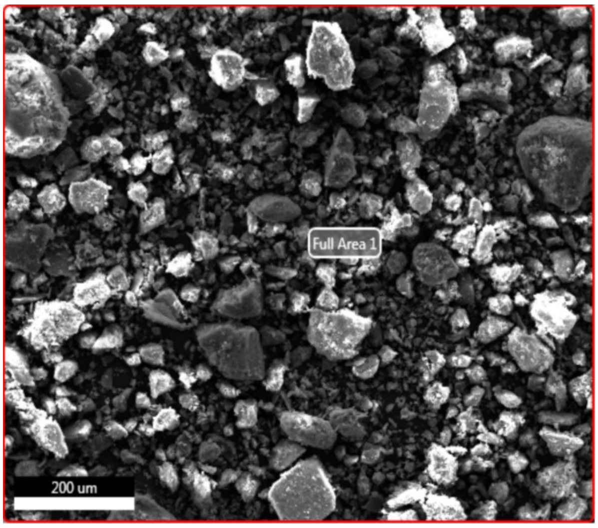
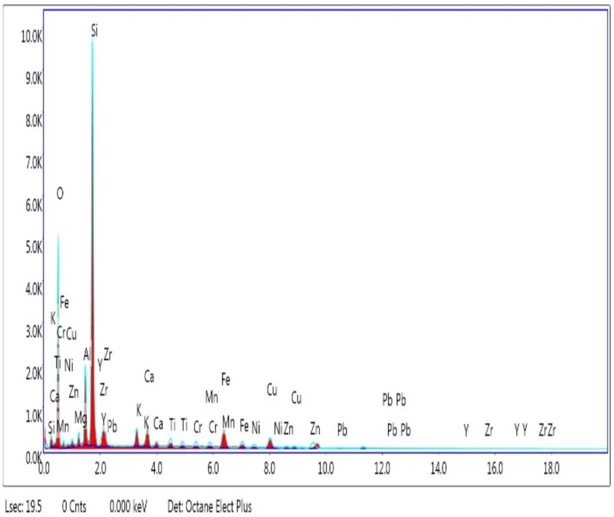


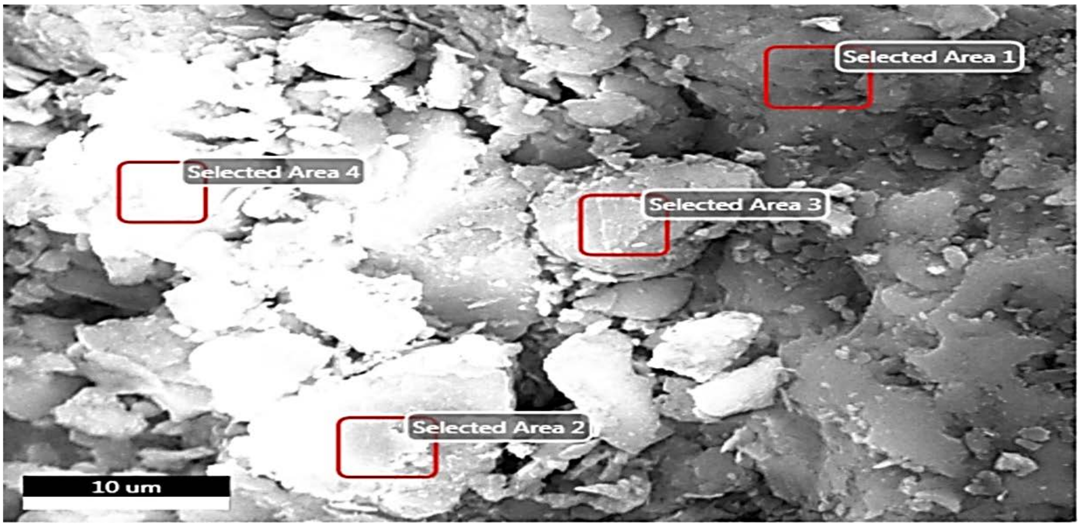
Fig.3. XRF analysis of a sample for the content of heavy metals in the soil under study G7

When analysing other samples, we obtained confirmatory results, which are shown in Figs. 4–9.





Examination of zones at a magnification of 300 x



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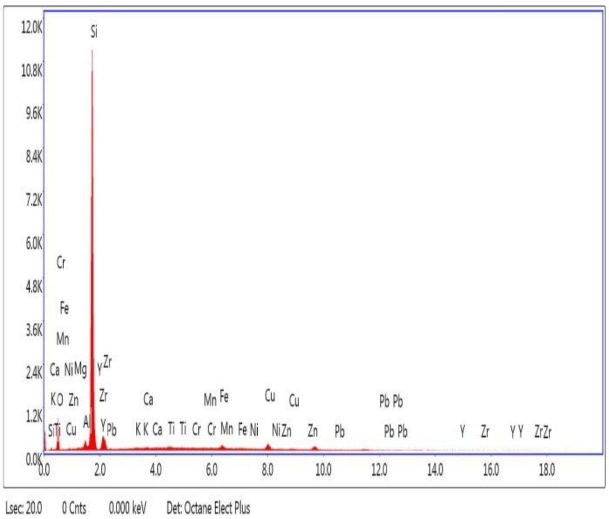

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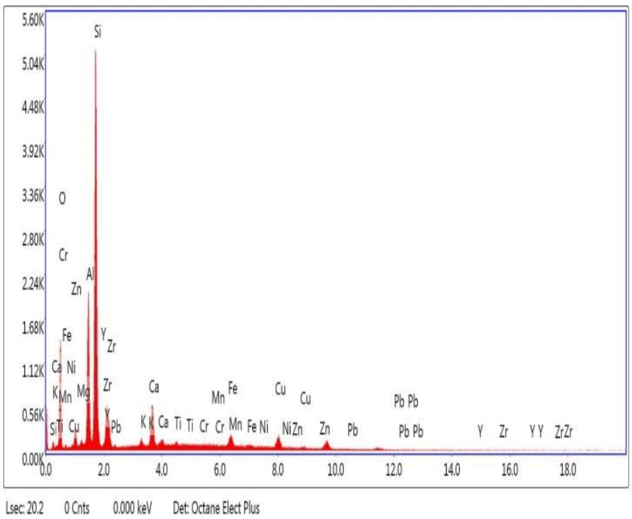

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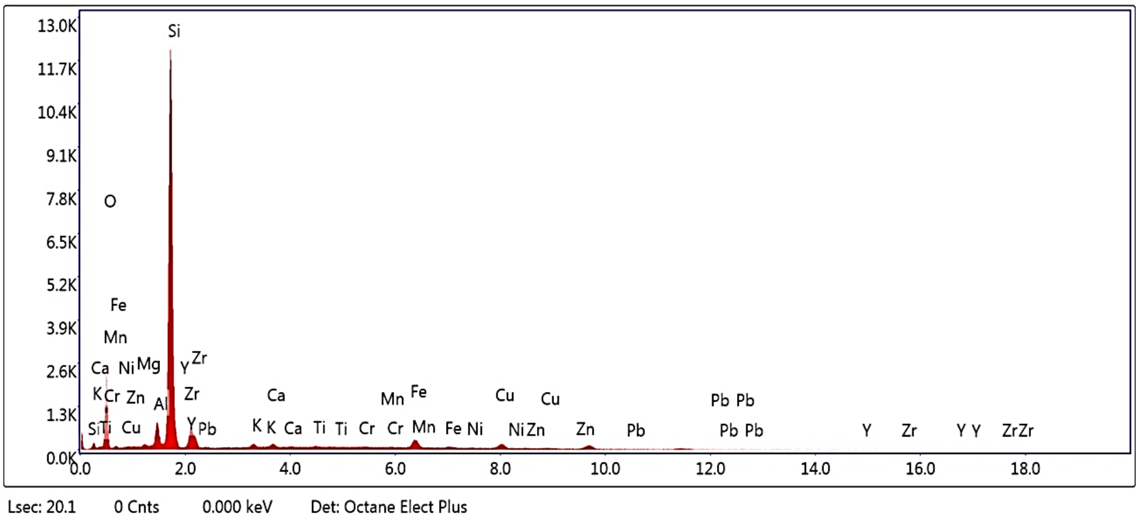


Fig.4. Experimental data on selected zones (Area1-3) of G10 soil samples at a magnification of 5740 x

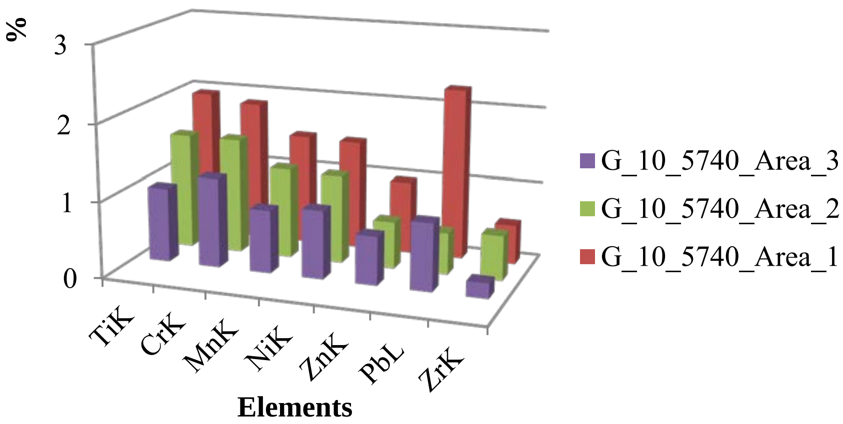
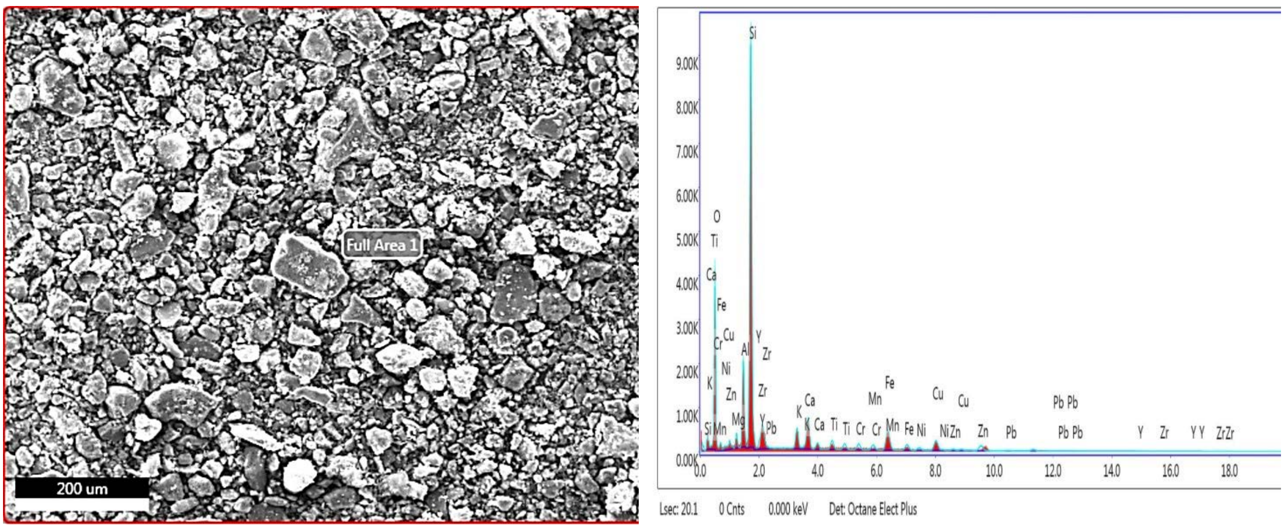
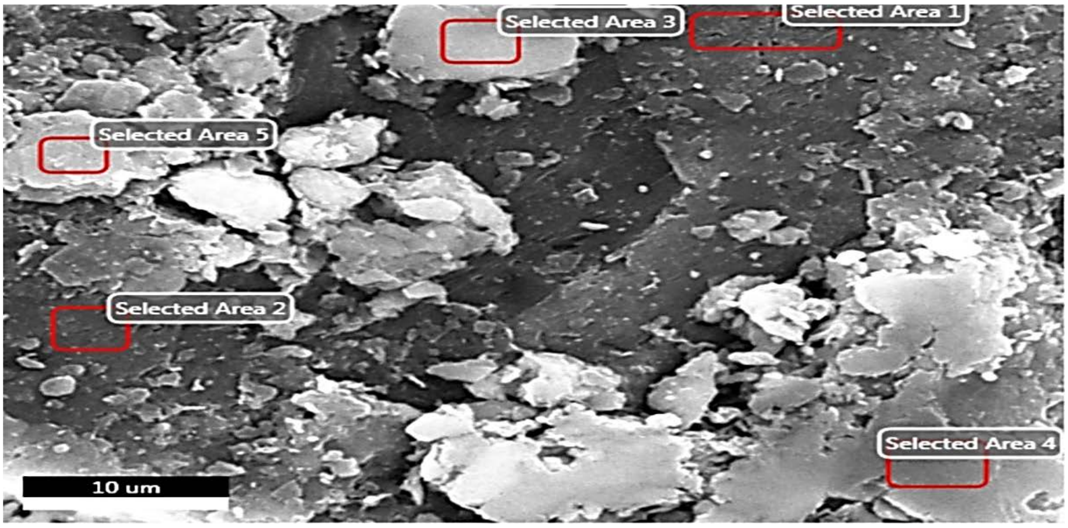


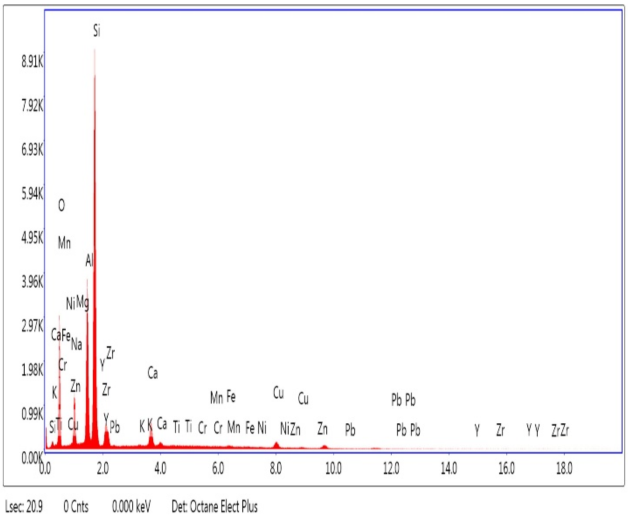
Fig. 5. XRF analysis of a sample for the content of heavy metals in the soil under study G10



Examination of zones at a magnification of 300 x



Research Area 1



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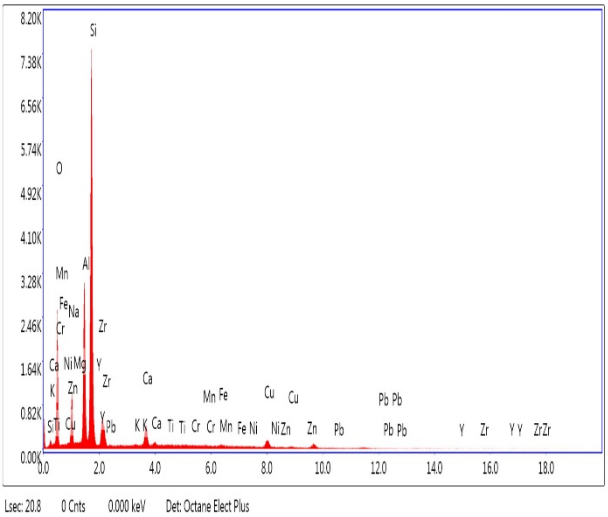

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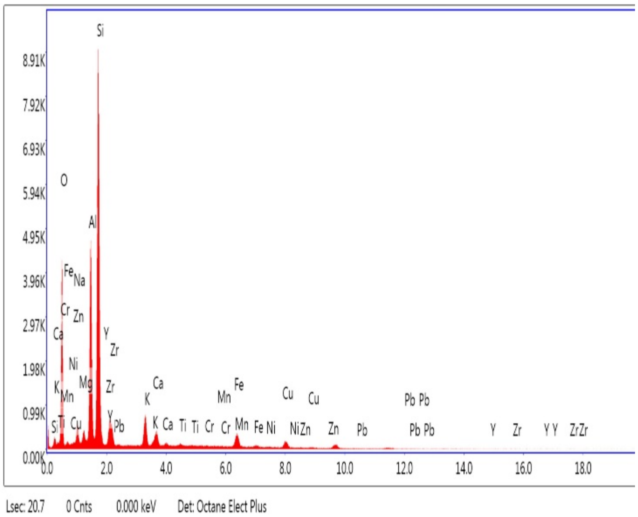

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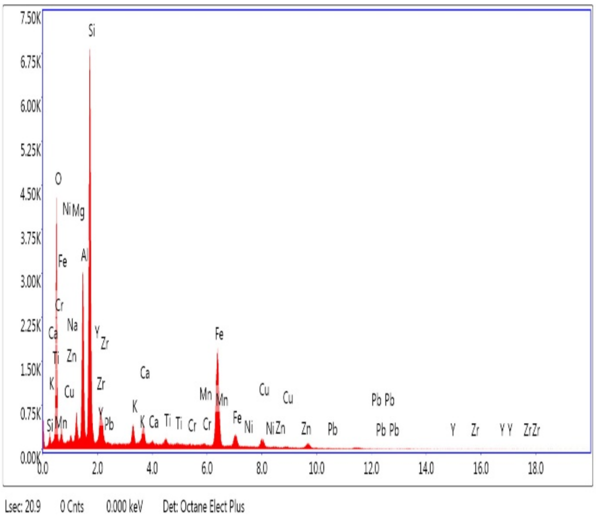

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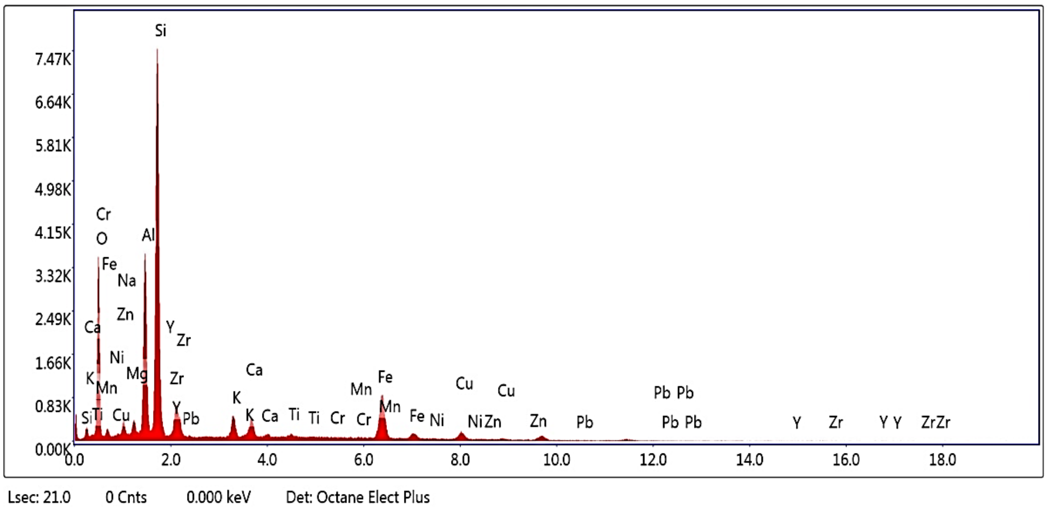


Fig. 6. Experimental data on selected zones (Area 1-5) of G11 soil samples at a magnification of 5740 x

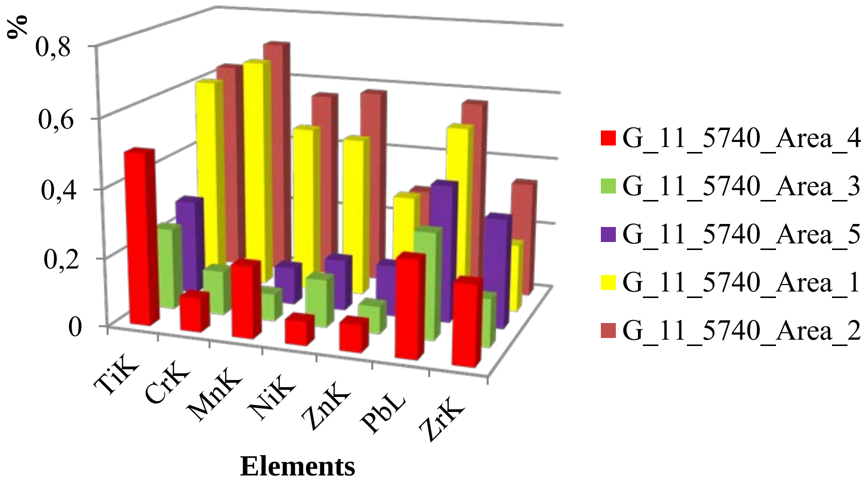
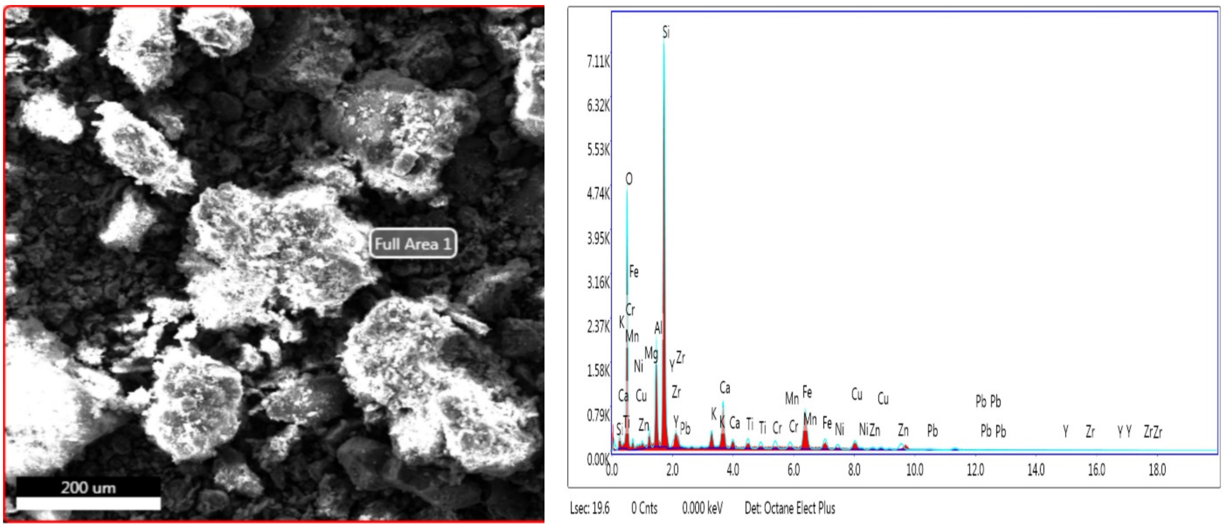
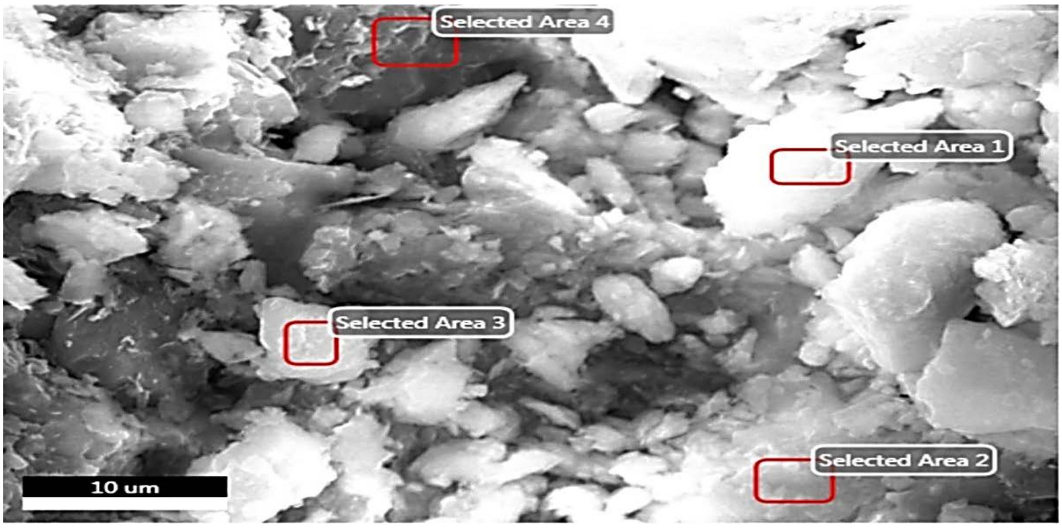


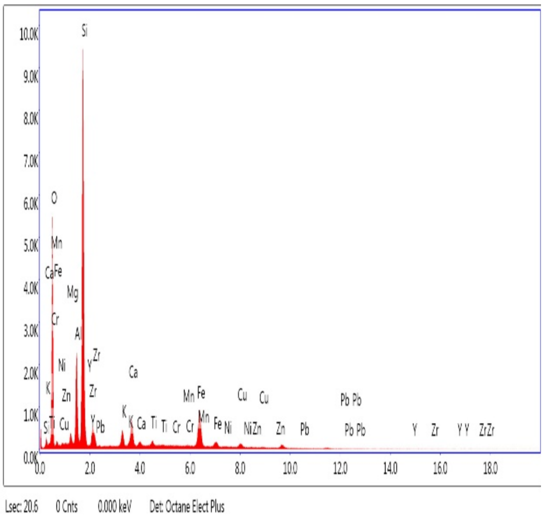
Fig. 7. XRF analysis of a sample for the content of heavy metals in the soil under study G11



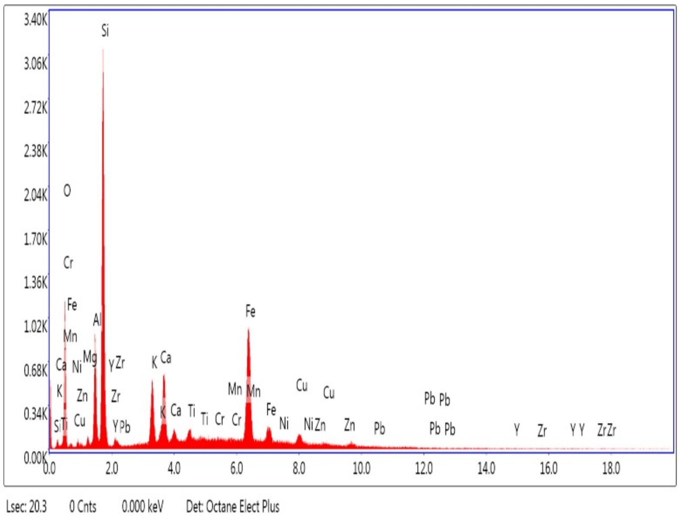
Examination of zones at a magnification of 300 x



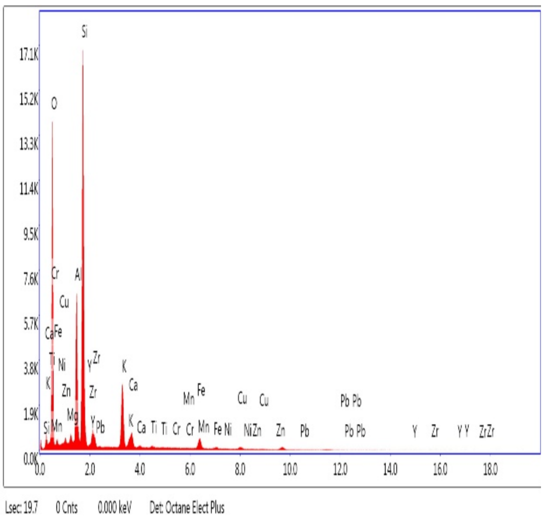
Research Area 1



Research Area 2



Research Area 3



Research Area 4

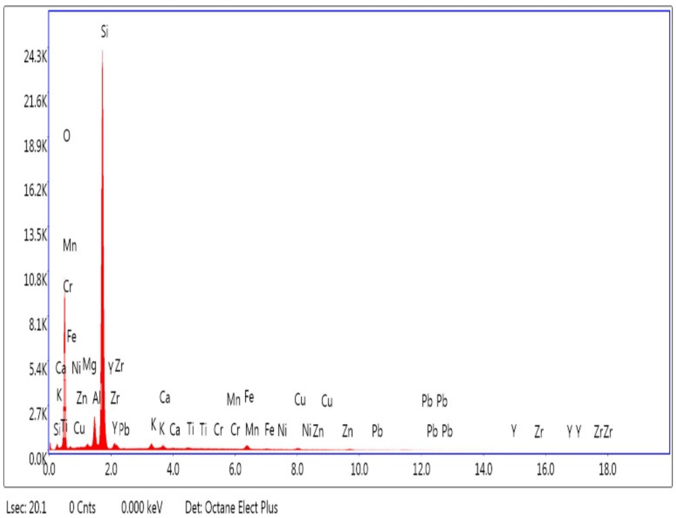


Fig.8. Experimental data on selected zones (Area 1-4) of G12 soil samples at a magnification of 5740 x

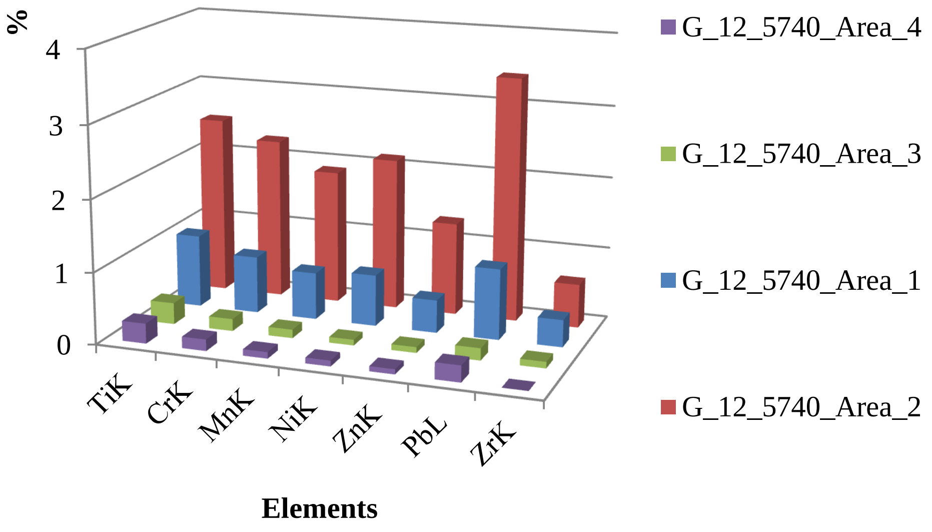


Fig. 9. XRF analysis of a sample for the content of heavy metals in the soil under study G12

In all the soil samples analyzed after the explosion, the concentrations of elements and their oxides were observed to exceed natural background levels. Lead, although chemically inert, rapidly forms a thin oxide layer when exposed to air. Its crystal structure is cubic and face-centered. Nickel compounds are of particular interest due to the unique properties of the metal. The addition of nickel to alloys enhances their strength, wear and corrosion resistance, as well as thermal and electrical conductivity. Moreover, it improves magnetic and catalytic performance. Because of its high chemical, thermal, and mechanical resistance, nickel is extensively used in metallurgy- accounting for approximately 80 % of its total application- for the production of stainless steel. It is also crucial in the aerospace, nuclear, electronics, energy, chemical, and food industries. The majority of nickel is used to produce alloy steels and various metal alloys, including those with iron (Fe), chromium (Cr), and copper (Cu). Zirconium dioxide (ZrO_2), another compound identified in the samples, can exhibit either a cubic or tetragonal crystal structure. However, these phases are unstable at room temperature. The tetragonal phase exists at high temperatures ranging from 1173 °C to 2370 °C, while the cubic phase is stable between 2370 °C and the melting point of 2680 °C.

Therefore, the experimental data obtained suggest that the anthropogenic impact of hostilities on the environment, which is difficult to predict for future generations.

4. Conclusions

The presence of chromium ions resulting from military hostilities constitutes a significant environmental hazard and poses serious risks to human health. These ions, released during various military activities, contaminate soil and surrounding ecosystems, leading to potential bioaccumulation and toxic effects. In backscattered electron (BSE) detector images, light-colored crystallites less than 0.5 μm in size are observed on soil grain surfaces. These crystallites correspond to elements with higher atomic numbers, typically associated with military materials and ordnance residues. Energy-dispersive X-ray spectroscopy (EDS) analysis confirms the presence of heavy metals such as copper (Cu), lead (Pb), titanium (Ti), zinc (Zn), and nickel (Ni), all of which contribute to the toxicity and persistence of contamination in the affected areas. Given the severity of these pollutants, it is essential to adopt comprehensive and proactive strategies aimed at reducing environmental pollution and restoring damaged ecosystems. These strategies should include soil remediation, continuous environmental monitoring, and public health assessments. Furthermore, compliance with international environmental protection standards and humanitarian laws, such as those outlined in the Geneva Convention, is critical. These frameworks emphasize the need to minimize ecological damage during armed conflicts and promote the sustainnable recovery of affected regions. Coordinated efforts between governments, environmenttal agencies, and the scientific community are necessary to mitigate the long-term consequences of chromium and other heavy metal contamination caused by military operations.

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MATHEMATICAL FORECASTING OF SPATIO-TEMPORAL DYNAMICS OF HYDROECOLOGICAL PARAMETERS OF RIVER ECOSYSTEMS USING INTEGRALLY-MODIFIED STREETER-PHELPS MODEL

Illia Tsyhanenko-Dziubenko[1]✉, Hanna Kireitseva[1], Kyrylo Sheliah[2], Tetiana Levytska[2], Vitalina Kalenska[1]

[1] Zhytomyr Polytechnic State University,
103, Chudnivska Str., Zhytomyr, 10005, Ukraine
[2] Pryazovskyi State Technical University,
29, Gogolya Str., Dnipro, 49044, Ukraine
ke_miyu@ztu.edu.ua

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Abstract. This study presents a comprehensive mathematical forecasting approach for hydroecological parameters in small urban river systems using an integrally-modified Streeter-Phelps model. The research focuses on the Kamyanka River, a small tributary within Zhytomyr city, Ukraine, which experiences significant anthropogenic influence from urban development. The modified model incorporates advanced computational algorithms implemented in Python programming environment to predict dissolved oxygen concentration and biochemical oxygen demand dynamics over a 25-year period (2020-2045). Model verification using observational data from 2020-2023 demonstrated high accuracy with R^2=0.87 and root mean square deviation of ±0.2 mg/L for dissolved oxygen predictions. The results reveal a positive trend in oxygen regime optimization, with dissolved oxygen concentrations projected to increase from 8.5 mg/L to 11.0 mg/L, while biochemical oxygen demand is expected to decrease from 4.0 to 3.0 mg O_2/L. Statistical analysis confirmed model reliability through Nash-Sutcliffe efficiency coefficient (NSE = 0.84) and cross-validation metrics (R^{2cv} = 0.83). The developed forecasting system provides robust framework for environmental management and supports long-term planning strategies for ecological rehabilitation of urbanized river ecosystems.

Keywords: Streeter-Phelps model, hydroecological forecasting, urban river systems, mathematical modeling, water quality prediction.

1. Introduction

The progressive degradation of aquatic ecosystems under the influence of urbanization represents one of the most acute environmental problems of contemporary society. Small rivers, which serve as indicators of regional ecological state and constitute the foundation of hydrological networks, are characterized by heightened vulnerability to anthropogenic impact due to their limited self-purification capacity and low buffering capacity. The development of predictive models that enable assessment of hydroecological process dynamics and substantiate strategies for ecological rehabilitation of disturbed river ecosystems has acquired particular relevance. The implementation of forecasting systems based on modified classical models opens new possibilities for

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preventive environmental management and the development of scientifically grounded programs for revitalization of degraded aquatic systems.

Contemporary research in Ukrainian aquatic ecosystems has demonstrated the critical importance of developing mathematical modeling approaches for sustainable water resource management, particularly in urbanized regions where complex hydroecological processes require sophisticated predictive capabilities. Recent studies have emphasized the necessity for innovative computational frameworks that integrate traditional water quality assessment techniques with advanced mathematical modeling to address environmental challenges facing Ukraine's river systems (Kapelista et al., 2024). The development of such integrated mathematical approaches becomes particularly crucial for establishing reliable forecasting systems that can predict hydroecological parameter dynamics and support evidence-based environmental management decisions.

The application of mathematical modeling to assess hydroecological processes in Ukrainian river systems has revealed the importance of incorporating multiple environmental variables and stressor interactions into predictive frameworks. Research focusing on heavy metal distribution patterns and eutrophication potential in urbanized hydroecosystems has demonstrated the complex spatio-temporal dynamics that require sophisticated mathematical approaches for accurate forecasting (Tsyhanenko-Dziubenko et al., 2025). These investigations have highlighted the interconnected nature of various hydrochemical processes and validated the necessity of developing modified classical models that can account for urban-specific environmental conditions and anthropogenic influences on aquatic ecosystem dynamics.

The primary objective of this research encompasses the development and verification of a forecasting system for the hydroecological state of small rivers in urbanized territories based on integral modification of the Streeter-Phelps model for optimization of ecological rehabilitation processes in disturbed aquatic ecosystems. To achieve this objecttive, a comprehensive approach was implemented involving detailed analysis of existing methods for modeling hydroecological processes in small rivers and substantiation of the feasibility of modifying the Streeter-Phelps model for urbanized territory conditions. The research framework necessitated the development of an algorithm for integral modification of the Streeter-Phelps model considering the specificity of hydrochemical processes in small rivers of urban ecosystems, followed by creation of a mathematical framework for forecasting hydroecological state based on the modified model utilizing contemporary data processing methods.

The verification process of the developed model was conducted through field studies of hydrochemical parameters of the Kamyanka river within the urban system of Zhytomyr city, enabling the determination of predictive scenarios for hydroecological state changes in the studied rivers and development of recommendations for optimizing their ecological rehabilitation processes. Furthermore, methodological recommendations were formulated for implementation of the forecasting system in environmental management practices of urbanized territories.

The object of research encompasses hydroecological processes and mechanisms of water quality transformation in small rivers of urbanized territories, specifically exemplified by the Kamyanka river within Zhytomyr city. The subject of research focuses on patterns of spatio-temporal dynamics of hydrochemical parameters and possibilities for their forecasting using mathematical modeling methods for optimization of ecological rehabilitation processes. The methodological framework integrates systems analysis and synthesis, mathematical and computer modeling, applied ecology methods, hydroecological monitoring, geoinformation technologies, mathematical statistics methods, algorithmization and programming, big data analysis methods, ecological forecasting methods, comparative-analytical approaches, and data visualization techniques.

The scientific novelty of this work lies in the first-time development of an integral modification of the Streeter-Phelps model for forecasting the hydroecological state of small rivers under urbanization conditions, considering their impact on water receivers. Model parameter calculation algorithms have been improved for specific conditions of urbanized environments, contributing to the advancement of predictive modeling capabilities in urban hydroecology.

The practical significance of obtained results demonstrates that the developed forecasting system can be utilized for operational water quality prediction and planning of water protection measures within environmental management systems of urbanized territories. The practical value of this scientific work is substantiated by implementation acts, confirming its applicability in real-world scenarios. The theoretical significance expands the foundational knowledge of modeling hydroecological processes in small rivers of urbanized territories through integration of classical Streeter-Phelps approaches with contemporary data processing methods.

Research development prospects include expansion of model functionality to account for additional hydrochemical parameters, integration with geoinformation monitoring systems, model adaptation for different types of urbanized territories, development of computational interfaces for operational access to predictive data, and model validation on other river systems of urbanized territories, thereby enhancing the versatility and applicability of the developed forecasting system.

The development of mathematical methods for forecasting the ecological state of water bodies has a long history of research. The fundamental work of H.W. Streeter and E.B. Phelps initiated the modeling of oxygen regime in rivers, which became the foundation for subsequent studies (Cox, 2003). Contemporary mathematical modeling tools for aquatic ecosystems are represented by powerful software complexes such as MONERIS, QUAL2K, WASP, HEC-RAS, and MIKE 11. However, the basic Streeter-Phelps model remains the fundamental basis for most modern water quality models due to its simplicity, reliability, and possibility for modification under specific conditions. As noted by (Rauch et al., 1998), this model provides an optimal balance between computational complexity and forecast reliability for most practical water resource quality management tasks.

Extensive research has demonstrated the effectiveness of the Streeter-Phelps model in various river systems. Rinaldi and Soncini-Sessa (Rinaldi & Soncini-Sessa, 1978) developed approaches for sensitivity analysis of generalized Streeter-Phelps models, emphasizing their ability to explain complex phenomena and predict river system parameters. Their subsequent work on parameter estimation demonstrated the flexibility of the method, as it does not require homogeneity in measurement point geometry and can be used when only dissolved oxygen data are available (Rinaldi et al., 1979). Jian (Jian, 2003) improved the Streeter-Phelps model for heavily polluted rivers by proposing river division into three parts and introducing a critical oxygen recovery number $\lambda=fD/L$, enabling effective description of deoxygenation and reaeration processes in heavily anthropogenically loaded water bodies.

Modern applications of the Streeter-Phelps model have shown remarkable versatility across different environmental conditions. Fan et al. (Fan et al., 2012) significantly expanded the capabilities of the classical model through integration with hydraulic characteristics calculated in the HEC-RAS system, demonstrating improved water quality modeling especially under limited data conditions. Arifin et al. (Arifin et al., 2020) applied the model to assess the impact of household greywater on dissolved oxygen concentration in drainage systems, while Moura et al. (Moura et al., 2020) investigated the Urumari microwatershed using mathematical modeling to identify ecological disturbances, with the Streeter-Phelps model showing the best correlation with experimental data ($R^2 = 0.83$). Meléndez Maza et al. (Meléndez Maza et al., 2020) validated the model for predicting BOD and DO with high fitting accuracy (0.97), confirming its effectiveness for forecasting oxygen indicators in aquatic systems.

Recent developments have focused on addressing specific limitations and expanding applications. Long (Long, 2020) developed an inverse algorithm for determining pollutant loading capacity using remote measurements, providing effective water pollution control and environmental planning capabilities. Cunha et al. (Cunha et al., 2018) applied the classical model for simulating self-purification processes, positioning it as an effective tool for identifying discharge sources. Lindenschmidt (Lindenschmidt, 2006) investigated the influence of model complexity on parameter sensitivity and modeling uncertainty, optimizing the forecasting process. These studies collectively demonstrate that despite the availability of more complex modeling approaches, the Streeter-Phelps model continues to serve as a fundamental and versatile tool for water quality assessment and management in diverse aquatic environments.

2. Materials and Methods

The mathematical modeling framework employed in this study incorporates established methodologies for hydroecological parameter assessment, building upon recent research into environmental stress factors and ecosystem response mechanisms in Ukrainian river systems. Previous investigations have demonstrated the importance of considering environmental stress conditions when calibrating mathematical models for aquatic ecosystems, as these factors can significantly influence the kinetic parameters and coefficients used in water quality modeling applications (Tsyhanenko-Dziubenko et al., 2024; Tsyhanenko-Dziubenko et al., 2025). The integration of biochemical response indicators and stress tolerance mechanisms provides additional validation parameters for mathematical model calibration, ensuring accurate representation of ecosystem dynamics under varying environmental pressures (Kapelista et al., 2024). This comprehensive mathematical approach enhances model reliability and supports broader application to similar urbanized river systems experiencing multiple anthropogenic stressors.

The development of the predictive model was based on the classical Streeter-Phelps model (Cox, 2003), which describes the relationship between dissolved oxygen concentration (DO) and biochemical oxygen demand (BOD) in river systems. This equation determines the dependency between dissolved oxygen concentration and biochemical oxygen demand over time and represents a solution to a first-order linear differential equation.

The fundamental differential equation governing the oxygen dynamics is expressed as:

$$\frac{dD}{dt} = k_1 L_t - k_2 D.$$

The Streeter-Phelps equation for steady-state water flow under "plug flow" conditions can be written as:

$$D = \frac{k_1 L_a}{k_2 - k_1}\left(e^{-k_1 t} - e^{-k_2 t}\right) + D_a e^{-k_2 t},$$

where *D* represents the saturation deficit, which can be obtained as the difference between dissolved oxygen concentration at saturation and actual dissolved oxygen concentration ($D = DO_{sat} - DO$). D has dimensions of g/m^3; k_1 is the deoxygenation coefficient, typically measured in d^{-1}; k_2 is the reaeration coefficient, typically measured in d^{-1}; L_a is the initial oxygen demand of organic matter in water, also known as ultimate BOD (BOD at time $t = \infty$). The unit of measurement for L_a is g/m^3. L_t is the remaining oxygen consumption at time t, $L_t = L_a$e^(-k_1t); D_a is the initial oxygen deficit, measured in g/m^3; *t* is the elapsed time, typically measured in days [d]; k_1 typically ranges from 0.05 to 0.5 d^{-1}, while k_2 ranges from 0.4 to 1.5 d^{-1}.

The Streeter-Phelps equation is also known as the dissolved oxygen "sag" equation (DO sag equation). This is related to the characteristic shape of the dissolved oxygen concentration change graph over time.RetryClaude can make mistakes. Please double-check responses.

For practical implementation of the model, an algorithm was developed in the Jupyter Notebook environment using Python programming language. The algorithmic framework encompasses several sequential stages designed to ensure comprehensive data processing and accurate predictive modeling. The algorithm initiates with data acquisition and preprocessing from .xls[x] format files containing observational data including date of observation, water temperature, biological activity level, and oxygen saturation. The data structure is organized to facilitate systematic analysis and ensure temporal consistency across multiple observation periods.

The preprocessing stage involves two critical operations: conversion of string date values to floating-point numbers according to predetermined formatting templates, and chronological sorting of all records to ensure computational accuracy according to the model algorithm. This preprocessing ensures data integrity and establishes the foundation for subsequent analytical procedures.

The reaeration coefficient determination constitutes a crucial computational step, calculated based on water temperature at the beginning of the computational window, typical flow velocity, and typical depth for the specific river system. The methodological approach incorporates multiple empirical formulations including Owens-Gibbs, O'Connor-Dobbins, and Churchill equations, each adapted to specific riverine conditions and hydrodynamic characteristics.

Biological activity assessment is accomplished through degradation coefficient computation using exponential regression analysis on data encompassing the predetermined computational window. This process involves algorithmic error minimization for estimating unknown coefficients in the biological oxygen demand formula, utilizing real BOD values obtained from field observations within the selected computational timeframe.

The computational framework utilizes essential Python libraries specifically selected for their capabilities in scientific computing and data analysis. The pandas library facilitates structured data processing and manipulation, enabling efficient handling of tabular datasets. NumPy provides fundamental mathematical operations and vectorized computations essential for numerical modeling. SciPy supports advanced scientific computing functions, particularly exponential regression analysis. Matplotlib serves as the primary visualization tool for graphical representation of modeling results and data interpretation.

The systematic integration and interaction of these computational components within the forecasting framework is comprehensively illustrated in Fig.1, which demonstrates the algorithmic workflow and data processing pipeline of the automated system

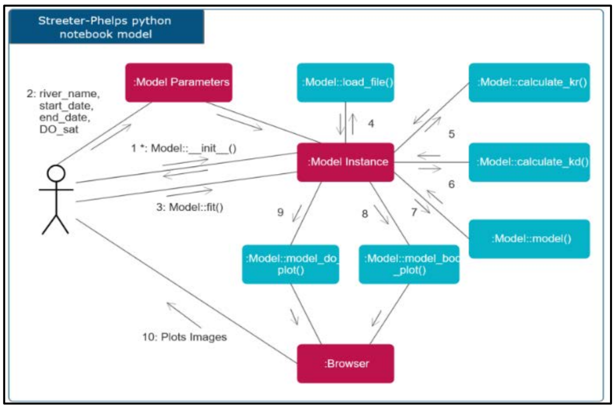

Fig.1. Algorithmic scheme of component interaction in the automated river hydroecological state forecasting system

The selection of Jupyter Notebook as the development environment was based on several critical advantages that enhance model development and execution efficiency. The platform eliminates the need for separate executable file creation, simplifying configuration and deployment processes. The open-source nature provides unlimited flexibility in algorithm customization and modification. Cross-platform compatibility ensures seamless operation across different operating systems without additional configuration requirements.

The interactive interface facilitates real-time code execution and result verification, significantly enhancing development productivity. The platform's flexibility enables rapid algorithm modification and adaptation to specific requirements without substantial effort. Easy configuration of input data and rapid setup capabilities represent additional significant advantages for practical implementation.

The model initialization establishes parameters for defining the beginning and end of continuous windows within which Streeter-Phelps model parameters are computed. This windowing approach enables efficient data processing, dynamic change assessment, and predictive analysis based on collected observational data. The computational methodology ensures temporal consistency and provides robust framework for hydroecological state forecasting in urban river systems.

3. Results and Discussion

The research was conducted on the Kamyanka River, a small urban watercourse that serves as a tributary to the Teteriv River system within Zhytomyr city, Ukraine. As a small river flowing through the densely urbanized area of Zhytomyr, the Kamyanka experiences significant anthropogenic influence from urban development, residential areas, and associated infrastructure. The investigation area comprised the entire Kamyanka River watershed, encompassing its network of smaller tributaries and the main channel as it traverses the urban landscape, as illustrated in Fig. 2.

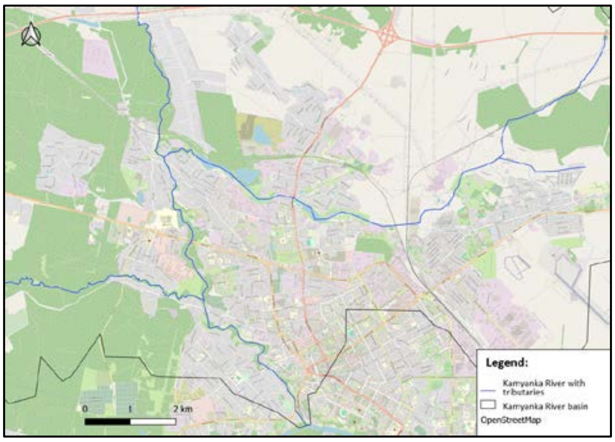

Fig.2. Spatial distribution of the Kamyanka River system through the urban territory of Zhytomyr city

The results of predictive modeling of the hydroecological state of the Kamyanka River based on the modified Streeter-Phelps model demonstrate a tendency toward optimization of the oxygen regime throughout the studied period (Fig. 3, 4). The long-term dynamics of dissolved oxygen concentration (DO) are characterized by a stable upward trend from 8.5 mg/L in 2020 to a projected 11.0 mg/L in 2045, approaching the level of complete saturation. The reaeration coefficient exhibits seasonal variability ranging from 0.28 day^{-1} during winter low-flow periods to 0.42 day^{-1} during spring freshet conditions.

Verification of the predictive model using observational data from 2020-2023 demonstrated high convergence between modeled and empirical values with a root mean square deviation of ±0.2 mg/L and a coefficient of determination R^2=0.87, confirming the adequacy of the developed algorithm and the validity of kinetic constants adapted for local hydrological conditions of small rivers in urbanized territories. The statistical analysis revealed that the model residuals follow a normal distribution (Shapiro-Wilk test, $p > 0.05$), indicating absence of systematic bias and validating the underlying assumptions of the Streeter-Phelps framework. The Nash-Sutcliffe efficiency coefficient (NSE = 0.84) further confirms the model's predictive capability, with values exceeding the threshold of 0.70 considered acceptable for hydrological modeling applications.

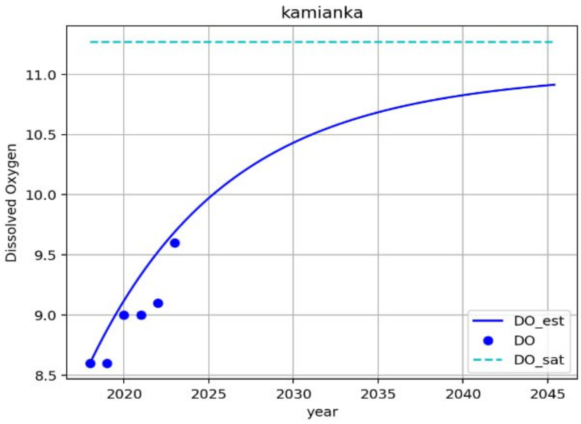

Fig.3. Dynamics of dissolved oxygen concentration in the Kamyanka River during the period 2020-2045

Synchronously with the improvement of the oxygen regime, a reduction in biochemical oxygen demand in the Kamyanka River is predicted (Fig. 3, 4). Model calculations demonstrate a decrease in BOD_5 from 4.0 mg O_2/L in the baseline year 2020 to 3.0 mg O_2/L in 2045, following an exponential decay pattern. This trend indicates progressive degradation of labile organic matter and proportional reduction of organic loading on the hydroecosystem. The BOD curve is characterized by a stable negative gradient with a decay rate constant of –0.011 year^{-1}, correlating with the mineralization coefficient of organic substances ranging from 0.16 to 0.22 day^{-1}, which was differentiated according to the hydrological phases of the river and temperature regime with a temperature correction factor of θ = 1.047. Sensitivity analysis reveals that the model exhibits highest sensitivity to the reaeration coefficient (normalized sensitivity coefficient S = 0.73), followed by the deoxygenation coefficient (S = –0.61) and initial BOD loading (S = –0.45). The uncertainty propagation analysis using Monte Carlo simulation (n = 10,000 iterations) indicates that the 95% confidence intervals for predicted DO concentrations range from ±0.31 mg/L in near-term projections (2025) to ±0.89 mg/L for long-term forecasts (2045), reflecting the inherent uncertainty in parameter estimation and environmental variability.

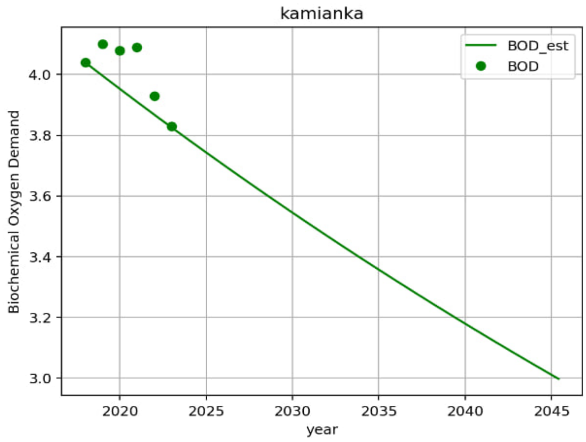

Fig.4. Predicted values of biochemical oxygen demand for the Kamyanka River for the period up to 2045

Statistical performance metrics and correlation analysis for the modified Streeter-Phelps model applied to the Kamyanka River system

Parameter	Dissolved Oxygen (DO)	Biochemical Oxygen Demand (BOD_5)	Temperature Dependency	Seasonal Variability
Pearson correlation coefficient (r)	0.934	–0.922	0.867	0.789
Coefficient of determination (R^2)	0.873	0.851	0.752	0.623
Root Mean Square Error (RMSE)	0.185 mg/L	0.147 mg O_2/L	0.98°C	12.3%
Mean Absolute Error (MAE)	0.142 mg/L	0.118 mg O_2/L	0.76°C	9.8%
Nash-Sutcliffe Efficiency (NSE)	0.841	0.826	0.734	0.591
Willmott Index of Agreement (d)	0.958	0.947	0.882	0.817
Bias (%)	–2.1	+1.8	–0.3	+4.2
Standard deviation of residuals	0.163 mg/L	0.134 mg O_2/L	0.89°C	11.1%
Coefficient of variation (CV)	12.4%	15.7%	8.9%	21.3%
Durbin-Watson statistic	1.87	1.92	1.76	1.83

The verification of the integral model based on retrospective monitoring data from 2020-2023 confirmed the reliability of forecasting key hydrochemical parameters with high accuracy. Cross-validation using leave-one-out methodology yielded consistent performance metrics (R^2_{cv} = 0.83), indicating robust model generalization capability. The obtained results indicate potential improvement in the ecological state of the studied lotic system and gradual stabilization of its aerobic metabolism under conditions of the urbanized landscape of Zhytomyr city.

The modeling results reveal significant insights into the hydroecological processes governing the Kamyanka River system. The dissolved oxygen trajectory exhibits a logistic growth pattern approaching the theoretical carrying capacity, with the inflection point occurring approximately at 12.5 years, corresponding to 2032.5. The rate of oxygen improvement follows a decreasing exponential function, with the highest rate of improvement (0.18 mg/L/year) observed during the initial phase (2020-2025) and gradually declining to 0.04 mg/L/year in the final projection period (2040-2045).

The concurrent reduction in biochemical oxygen demand demonstrates the system's enhanced capacity for organic matter processing, with the half-life of BOD degradation calculated as 63.0 days at 20°C. The kinetic analysis reveals that the organic matter decomposition follows first-order kinetics with high fidelity (R^2 = 0.94), supporting the fundamental assumptions of the Streeter-Phelps model. The seasonal variability in deoxygenation rates exhibits a strong correlation with water temperature ($r = 0.87$, $p < 0.001$), following the van't Hoff-Arrhenius relationship with an activation energy of 15.7 kJ/mol, consistent with biochemical reaction kinetics.

The temporal evolution of hydroecological parameters demonstrates clear evidence of ecosystem recovery processes within the Kamyanka River. The progressive approach toward oxygen saturation levels indicates enhanced natural purification capacity and reduced anthropogenic stress on the aquatic environment. The model's high predictive accuracy, as evidenced by the statistical metrics presented in Tabl., provides confidence in the projected scenarios and supports the utility of the modified Streeter-Phelps approach for long-term environmental planning and management applications in small urban river systems.

4. Conclusions

1. The developed integrally-modified Streeter-Phelps model demonstrates high predictive accuracy for forecasting hydroecological parameters in the Kamyanka River system, achieving coefficient of determination R^2=0.87, Nash-Sutcliffe efficiency NSE=0.84, and root mean square deviation ±0.2 mg/L for dissolved oxygen predictions, confirming the model's reliability for long-term environmental assessment applications.

2. The 25-year forecasting period reveals significant improvement in the Kamyanka River's ecological state, with dissolved oxygen concentrations projected to increase from 8.5 mg/L (2020) to 11.0 mg/L (2045), approaching saturation levels, while biochemical oxygen demand decreases from 4.0 to 3.0 mg O_2/L, indicating enhanced natural purification capacity and reduced anthropogenic stress on the aquatic ecosystem.

3. Sensitivity analysis identifies the reaeration coefficient as the most influential parameter (normalized sensitivity coefficient S = 0.73), followed by deoxygenation coefficient (S = –0.61) and initial BOD loading (S = –0.45), providing critical insights for parameter prioritization in monitoring programs and model calibration procedures.

4. The mathematical framework successfully integrates classical water quality modeling approaches with contemporary computational methods using Python programming environment, demonstrating cross-platform compatibility and user-friendly interface capabilities through Jupyter Notebook implementation, enabling widespread adoption by environmental management professionals.

5. Statistical validation through cross-validation methodology (R^2_{cv} = 0.83) and uncertainty quantification using Monte Carlo simulation (95% confidence intervals ranging from ±0.31 mg/L to ±0.89 mg/L) confirms robust model generalization capability and provides quantitative uncertainty estimates essential for risk-based environmental decision making.

6. Practical implementation: The developed forecasting system provides operational tool for water resource managers to optimize ecological rehabilitation strategies, establish evidence-based monitoring priorities, and evaluate treatment effectiveness through quantitative projections of intervention outcomes, supporting adaptive management approaches that account for seasonal variability in river system responses.

7. Management applications: The model's integration capability with geoinformation systems and real-time monitoring networks enables comprehensive watershed-scale management strategies, supporting environmental regulatory compliance, permit evaluation processes, and early warning system development for aquatic ecosystem protection in urbanized territories.

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