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Method of preparing oat straw for biofuel production

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Abstract. As a leading agro-industrial country, Ukraine generates significant amounts of by-products every year, including oat straw, which, given its lignocellulosic composition, is a valuable resource for meeting bioenergy needs. The aim of this work was to investigate the effectiveness of treating oat straw with a mixture of acetic acid and hydrogen peroxide for effective delignification and obtaining a substrate with a high content of polysaccharide component for potential use in the production of second-generation biofuel. Mathematical modelling and regression equation analysis were applied based on experiments with varying hydrogen peroxide concentrations (10-30 vol. %) and treatment

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durations (60-120 min) to determine the optimal compromise between lignin removal and cellulose preservation. It was found that hydrogen peroxide consumption and treatment duration have a predominantly negative effect on substrate yield, while a positive effect is observed for lignin removal. It was shown that the optimal conditions are a hydrogen peroxide content of 30 vol. % in the mixture with a treatment duration of 60 min, which ensures the maximum value of the desirability function and the production of a substrate with a yield of 52.8%, a lignin content of 2.1% and a cellulose content of 66.8%. Experimental verification of these conditions confirmed the reliability of the obtained model: a substrate with a yield of 52.1%, lignin content of 2.3% and cellulose content of 65.9% was obtained. Thus, the work demonstrates the effectiveness of a sound approach to the processing of agro-industrial waste, opening up prospects for the production of second-generation biofuels. The results obtained have scientific and practical significance, as they confirm the effectiveness of optimised delignification of oat straw and create a scientifically sound basis for the development of resource-efficient technologies for the production of second-generation biofuels

Keywords: substrate; lignin; cellulose; waste processing; delignification

Introduction

The urgent need to abandon fossil fuels, linked to resource depletion, climate change and greenhouse gas emissions, is driving the search for alternative energy sources. Biofuel can be considered one of the most promising types of alternative energy, as its use helps to reduce dependence on oil, natural gas and coal, and also reduces the anthropogenic impact on the environment. First-generation biofuels, produced from food crops, are characterised by certain problems, which consist in reducing the amount of food available to people, which can lead to an increase in food prices. Unlike first-generation biofuels, second-generation biofuels are produced from non-food lignocellulosic biomass, agricultural residues and waste, which is a promising solution for creating alternative energy sources. However, technological and economic improvements in its production processes remain a pressing issue, especially in terms of processing lignocellulosic biomass, which is the most accessible type of raw material for producing second-generation bioethanol.

In their work, M. Jayakumar *et al.* (2023) emphasise that bioethanol from lignocellulosic biomass is a key element of energy transformation, as it allows for the combination of resource renewability and CO_2 emission reduction. It is noted that agricultural waste – straw, corn stalks, husks, i.e. materials that do not compete with the food sector – has the greatest potential. N. Novia *et al.* (2025) noted that for the full-scale implementation of second-generation biofuels, it is necessary to improve biomass pre-treatment technologies, which determine the efficiency of further hydrolysis and fermentation. The importance of optimising economic production indicators is also emphasised, as high production costs are the main obstacle to the commercialisation of these processes. The studies by B. Correia *et al.* (2024) indicate that realising the full potential of second-generation biofuels requires overcoming technical, economic and logistical barriers, as well as continuous investment in research, innovation and supportive policy initiatives to ensure their sustainable and widespread implementation.

S. Roy & S.P. Chundawat (2023) studied the use of ionic liquids for biomass delignification, proving that these compounds provide a high degree of lignin dissolution (up to 95%). At the same time, such reagents are expensive and require further regeneration, which limits their industrial application. Another group of authors, R.S. Abolore *et al.* (2024), showed that the use of organic solvents could be an environmentally acceptable alternative. The study demonstrated the possibility of effective delignification (removal of more than 90% of lignin) under relatively mild processing conditions (temperature 80-100°C) without the formation of toxic by-products. In their work, S. Das *et al.* (2024) analysed in detail the physicochemical properties of lignocellulosic biomass and proposed a concept of multistage conversion taking into account thermomechanical and chemical processes. The authors showed that pre-treatment is a crucial stage that ensures the availability of cellulose for further hydrolysis. Ukrainian researchers have also paid considerable attention to this area. Thus, the authors of the work A. Dankevych *et al.* (2023) emphasised that Ukraine has one of the largest potentials in Europe for agricultural waste, which can provide more than 10 million tonnes of fuel equivalent annually. The authors proposed using cereal straw as a stable source of raw material for the production of second-generation bioethanol.

Despite significant scientific achievements, the studies leave open the question of finding affordable, safe and environmentally friendly pre-treatment methods suitable for large-scale implementation. The conditions for the delignification of specific types of biomass, in particular oat straw, using an acetic acid-hydrogen peroxide system remain insufficiently studied. The influence of process parameters (time, reagent concentration) on the degree of lignin removal and the quality of the substrate obtained for further fermentation also needs to be clarified. The aim of this study was to investigate the effectiveness of treating oat straw with a mixture of acetic acid and hydrogen peroxide in order to establish the conditions for effective delignification and obtain a substrate for further bioethanol production. Particular attention was paid to determining the effect of hydrogen peroxide consumption and treatment time.

Materials and Methods

In laboratory conditions at the Department of Ecology and Technology of Plant Polymers of Igor Sikorsky KPI, research was conducted on the isolation of the polysaccharide component from oat straw by delignifying it with a mixture of acetic acid and hydrogen peroxide under various conditions. Oat straw collected in 2024 in the fields of the Chernihiv region was used as lignocellulosic raw material in the study. The straw was first sorted by hand, separating the leaves and nodes, after which only the internodes were selected for further work. The selected fragments were crushed to a length of 1.5-2 cm to ensure uniformity during the subsequent processing stages. The prepared biomass was stored in sealed plastic bags at room temperature. The chemical composition of oat straw was as follows: cellulose content – 36.7%, lignin – 18.1%, substances extractable with hot water, 1% NaOH solution and alcohol-benzene mixture – 11.6%, 37.3% and 3.2%, respectively, ash content – 6.2% (according to the results of laboratory analysis conducted in accordance with the methods of V.A. Barbash *et al*. (2003), which are generally accepted for determining the chemical composition of plant raw materials). The weight of the raw material in each experiment was 15 g of absolutely dry raw material. The hydromodule was 10:1 and ensured complete wetting of the raw material with a reaction mixture based on acetic acid and hydrogen peroxide.

Oat straw was treated with different ratios of acetic acid to hydrogen peroxide, ranging from 90:10 to 70:30 vol. % respectively. The treatment duration was 60-120 minutes. The treatment time was selected based on previous experience, since it is in this range of treatment duration for different types of raw materials that intensive lignin removal occurs, but with varying efficiency (Barbash *et al*., 2022). The pre-prepared biomass was poured into a reaction mixture and heated in heat-resistant glass flasks in a boiling water bath using reflux condensers to minimise the loss of liquid phase components. After completion of the treatment process, the solid phase – the cellulose product – was separated by filtration, thoroughly washed with water to a neutral pH and dried in air to a residual moisture content of 6%.

The effectiveness of the treatment was evaluated based on the yield of the cellulose product (y_1), its residual lignin content (y_2), cellulose content (y_3) and ash residue (y_4). The effectiveness of the treatment was assessed visually, based on the substrate yield and its chemical composition. Each of the experiments was conducted three times, based on which the average values were calculated. This approach minimised the relative measurement error, which is critical for the reliable construction of a mathematical model of the process. The experimental results were processed using the least squares method to construct a mathematical model of the process. To describe the relationship between the technological parameters and the output characteristics of the cellulose product, a second-order polynomial was used:

$$y_i = b_0 + b_1x_1 + b_2x_2 + b_3x_1x_2 + b_4x_1^2 + b_5x_2^2, \quad (1)$$

where y_i – dependent variable (cellulose substrate indicator); x_1, x_2 – independent variables (hydrogen peroxide content in the mixture and treatment duration); b_0-b_5 – regression coefficients that quantitatively characterise the contribution of each corresponding member to the formation of the model. Regression equations were used to visualise the effect of oat straw treatment conditions on substrate properties by constructing 3D models in MATLAB. The substrate production process was optimised using a multi-criteria evaluation method based on Harrington's generalised desirability function. For this purpose, each substrate parameter (y_i) was converted into a dimensionless desirability scale (d_i) with values ranging from 0 ("very poor") to 1 ("very good"). Next, the generalised desirability function was calculated as the geometric mean of individual indicators, reflecting the overall quality of the substrate. To determine the optimal parameters of oxidative treatment, one-sided Harrington desirability profiles were used, and the search for the optimum was carried out by scanning the generalised function with high accuracy (step 0.001), which allowed establishing the optimal conditions of the process.

Results and Discussion

Pre-treatment processes play a key role in preparing biomass for the extraction of the polysaccharide component and the subsequent production of biofuel from it. The efficiency of this process largely depends on the ratio of reagents and the duration of treatment, which lead to structural changes in plant raw materials, resulting in an increase in the yield of cellulose and hemicellulose for subsequent maximum bioethanol yield. Figure 1 shows the effect of treatment duration on the appearance of oat straw substrate when exposed to a mixture of acetic acid and hydrogen peroxide for different periods of time.

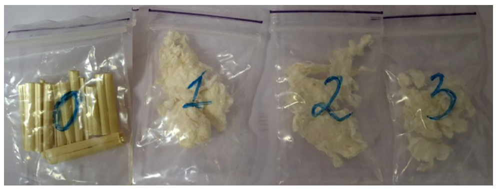

Figure 1. Visual changes in the structure of lignocellulosic substrate based on oat straw

Note: 0 – initial straw; 1 – substrate after treatment of oat straw with a mixture of acetic acid : hydrogen peroxide (70:30 vol. %) for 60 min; 2 – substrate after treatment of oat straw with a mixture of acetic acid : hydrogen peroxide (70:30 vol. %) for 90 min; 3 – substrate after treatment of oat straw with a mixture of acetic acid and hydrogen peroxide (70:30 vol. %) for 120 min

Source: developed by the authors

Destruction of the lignocellulose complex structure was observed, resulting in fibrous products. The structure and colour of the obtained substrate samples clearly demonstrated the destructive effect of the reaction mixture components, in particular the oxidative effect on the aromatic component – lignin, which acts as a binding component and is part of the structural component of the cell wall, the removal of which led to the destruction of the cell wall (Bao *et al.*, 2025). The oxidation and dissolution of lignin led to the enrichment of the obtained products with cellulose, which is a fibrous component of the cell wall. Visual assessment of the substrate samples led to the conclusion that the lignin removal process was sufficiently effective after 60 minutes and that further increases in the duration of treatment had no significant effect on the appearance of the cellulose materials. The change in colour from yellowish for the raw material to white for the obtained samples also indirectly indicates the removal of the aromatic component. A similar effect was observed in cases of delignification of deciduous and coniferous wood in a study by C. Kundu *et al.* (2021). However, in the case of wood processing, it took twice as long to achieve the bleached product effect. This was due to differences in the structure of wood and non-wood plant raw materials, as the former had a denser structure.

Visual assessment of the samples gave a general idea of the processing process, but further detailed analysis of the yield of the processed products and their chemical composition made it possible to substantiate the effect of the reaction mixture on the structure of the raw material and to conclude on the effectiveness of delignification. Treatment of oat straw with a mixture of acetic acid and hydrogen peroxide at a reagent ratio of 70:30 vol. % for 60 min resulted in a substrate yield of 52.1%. The lignin and cellulose content under these conditions was 2.4% and 66.0%, respectively. A further increase in the treatment time to 120 minutes led to a decrease in product yield and lignin content to 46.2% and 1.2%, respectively. Under these conditions, the cellulose content increased and reached 72.9%. Extending the treatment time had a slight positive effect on the mineral content, in particular, the ash content decreased from 2.8% to 2.5%.

In general, the decrease in yield was the result of the removal of non-cellulose components from the plant raw material under the influence of peracetic acid, which was formed in the reaction mixture during heating (Tian *et al.*, 2021). During processing, peracetic acid acts as an effective oxidant capable of breaking down the ether and carbon-carbon bonds between the structural units of lignin, leading to the destruction of its polymer structure, dissolution and diffusion into the liquid phase. Increasing the duration of treatment naturally intensified the oxidative reactions, ensuring the gradual destruction of a larger number of aromatic fragments and contributing to an increase in the degree of delignification. Thus, prolonged exposure to an oxidative environment affected the overall yield of the cellulose product. Similar patterns were noted by other researchers, in particular in the work of Z. Lin *et al.* (2023), which states that during the treatment of poplar chips, prolonging the reaction time contributed to deeper lignin removal. A similar pattern in the change in yield and chemical composition was observed during the treatment of straw with a mixture of acetic acid and hydrogen peroxide at a reagent ratio of 90:10 vol. %. However, due to the lower content of hydrogen peroxide, the efficiency of the process was slightly different. In particular, when the treatment time was increased in the range of 60-120 minutes, the yield of the substrate, its lignin, cellulose and ash content varied within the range of 70.8-63.6%, 2.7-2.5%, 53.9-58.2% and 2.7-2.1%, respectively.

Comparing the efficiency of raw material processing at different ratios of components in the reaction mixture, a positive effect of increasing the hydrogen peroxide content was clearly observed. Thus, in the case of a reagent ratio of 70:30 vol. %, more peracetic acid was generated, which acted as a selective delignifying agent. The results obtained are consistent with the data presented in the work of R. Ma *et al.* (2021), where it was also noted that an increase in the concentration of hydrogen peroxide contributes to a more efficient formation of peracetic acid and, accordingly, an increase in the degree of delignification while maintaining the high integrity of cellulose fibres. As a result of mathematical processing of experimental data, regression equations were obtained that adequately describe the process of chemical treatment of oat straw stalks with a mixture of acetic acid and hydrogen peroxide. For substrate yield:

$$y_1 = 105.65 - 3.61x_1 - 0.124x_2 + 0.046x_1^2 + \\ + 0.0002x_1\,x_2 + 0.0003x_2^2.$$

For residual lignin content:

$$y_2 = 4.32 - 0.11x_1 - 0.022x_2 + 0.002x_1^2 - \\ - 0.0002x_1\,x_2 + 0.002x_2^2.$$

For cellulose content:

$$y_3 = 83.01 + 3.23x_1 + 0.07x_2 - 0.049x_1^2 - \\ - 0.0006x_1\,x_2 - 0.0007x_2^2.$$

For ash content:

$$y_4 = 4.07\text{-}0.15x_1 - 0.0003x_2 + 0.002x_1^2 + \\ + 0.00004x_1\,x_2 - 0.00003x_2^2.$$

The analysis of the models allows to quantitatively assess the impact of two key factors – hydrogen peroxide consumption (x_1) and treatment duration (x_2) – on the quality characteristics of the substrate. Each of the four equations describes a nonlinear relationship that reflects the complex interaction between the process parameters and its results. Hydrogen peroxide consumption and treatment duration show a predominantly negative linear effect on substrate yield and lignin content. This indicates that more intensive treatment, although effective for lignin removal, inevitably leads to some degradation of valuable material. However, positive coefficients for quadratic terms indicate that the rate of this degradation is not constant but slows down over time. On the other hand, reducing the residual lignin content is the main goal of the treatment, and the equation confirms that both factors contribute to this. It is noteworthy that the interaction coefficient ($x_1 x_2$) for this indicator is negative, indicating a synergistic effect: a simultaneous increase in peroxide consumption and treatment duration gives a better result in lignin removal than the general separate application. The ash content proved to be the least sensitive to changes in treatment duration, as confirmed by a very low coefficient. This means that the decisive factor for its control is the concentration of hydrogen peroxide, which has a significantly greater influence.

Based on the obtained regression equations, three-dimensional response surfaces were constructed, which clearly demonstrate the nature of changes in substrate properties depending on the process conditions. The constructed models reflect the relationship between the studied factors and the main technological indicators, which allows them to be used for forecasting and optimising the process. Figure 2 shows 3D models of the effect of processing conditions on the properties of the substrate based on oat straw.

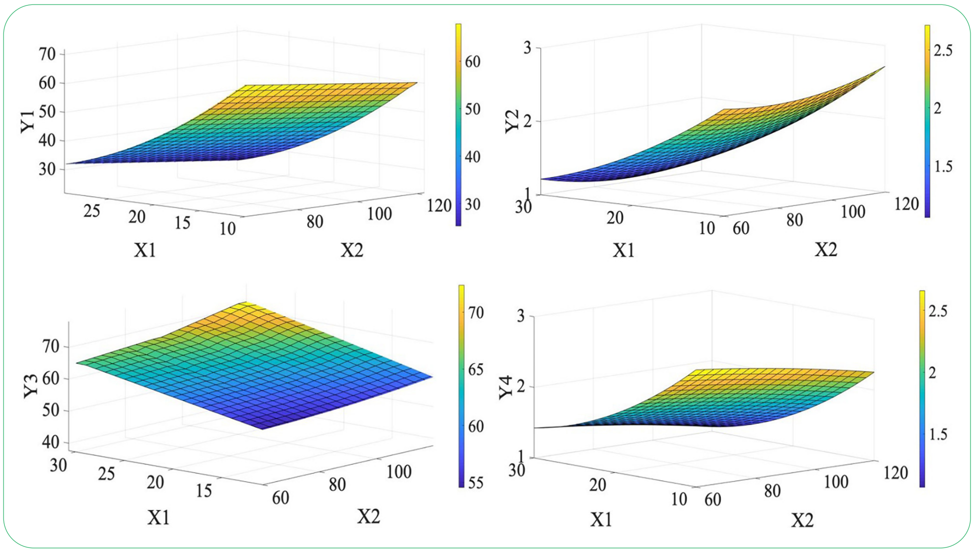

Figure 2. 3D models of the effect of processing conditions on the properties of oat straw-based substrate
Source: developed by the authors

The models presented allow for a quantitative assessment of the impact of key technological parameters – treatment duration and reagent consumption – on solid residue yield and delignification efficiency. The calculated results showed that at an acetic acid : hydrogen peroxide ratio of 70:30 vol. % with an increase in duration from 60 to 120 min, a gradual decrease in yield by 10% was observed. This effect was associated with the destruction and removal of various biomass components, in particular lignin, hemicellulose, and partially extractive substances that were easily subjected to oxidative-hydrolytic processes. At the same time, the reduction in lignin was intense and was due to the selective action of peracetic acid, which acts as an oxidising agent capable of breaking aromatic bonds in the lignin structure.

The delignifying effect of peracetic acid is also mentioned in the works of other researchers who studied the delignification of wood chips and confirmed the selective delignifying effect. In particular, in the case of poplar chips treatment in the study by P. Wen *et al.* (2025), maximum lignin removal with minimal degradation of cellulose and hemicellulose was demonstrated. The authors P.-O. Westin *et al.* (2021) obtained a holocellulose complex from wood chips using a single-stage peracetic acid delignification method. In the work of M.K. Esmaeil *et al.* (2019), the possibility of delignification of sugar cane bagasse was investigated, and a cellulose product with a yield of about 50% was obtained. In the case of wheat straw processing by D.U. Pascoli *et al.* (2022), high-quality cellulose suitable for the production of nanocellulose was obtained. In all cases, the efficiency of the process depended on the conditions of its implementation. In the case of wood, slightly harsher processing conditions are required than when using non-wood plant raw materials, such as cereal straw. Wood raw materials (eucalyptus, poplar, spruce chips) are characterised by a higher lignin content with a more condensed aromatic structure. In such materials, the delignification process was slower, requiring higher temperatures or longer processing times. In contrast, non-wood raw materials had a lower lignin content but a higher hemicellulose content, and their cell walls were more porous and less dense. This allowed acetic acid to penetrate the fibrous structure more easily, promoting faster lignin breakdown even under mild conditions.

The results also showed that, along with the removal of lignin, the cellulose content in the obtained products increased, reaching up to 73%. This is not due to the formation of additional cellulose, but to the enrichment of its relative content in the product as a result of the removal of accompanying components (lignin, partially hemicellulose). In all cases of peracetic acid use, part of the hemicellulose component was preserved (Geng *et al.*, 2018). Thus, the selective effect of the oxidative reagent on the aromatic component has been confirmed. An increase in cellulose content during changes in the concentration-time regime has also been observed by other researchers, in particular N. Muna *et al.* (2019) during the processing of fibrous mass based on coconut shells. As for the removal of mineral components, the treatment also contributed to the partial removal of mineral components, but did not lead to the complete removal of ash substances, which can be considered a disadvantage. However, when using the obtained products as substrates for the production of second-generation liquid biofuels, this does not significantly affect the efficiency of the biochemical conversion process.

Thus, in order to achieve the desired result – maximum removal of lignin with minimum loss of cellulose and substrate yield – it was necessary not only to increase the intensity of the process, but also to optimise it. The use of multi-criteria optimisation was extremely important for the effective processing of oat straw and the extraction of a substrate with a high polysaccharide content from it. This made it possible to achieve the specified indicators for the cellulose product. In this case, the main task was to maximise lignin removal while minimising substrate and cellulose yield losses. To solve this problem, multi-criteria optimisation was performed, in particular, using Harrington's generalised desirability function, which is a reliable tool for finding the optimum of various processes. The calculations showed that the optimal parameters for extracting substrate from oat straw were a hydrogen peroxide content of 30 vol. % in the mixture and a processing time of 60 minutes. It was for these processing parameter values that the generalised Harrington desirability function had its maximum value of 0.797. The optimisation results were presented in Table 1.

Table 1. Desirability scale and optimisation results

Indicator y_i	Desirability scale		Optimal value
	Ideal option (very good)	Unacceptable option (very poor)	
y_1	70.8	46.2	52.8
y_2	1.2	2.8	2.1
y_3	72.9	53.9	66.8
y_4	2.2	2.8	2.7

Source: developed by the authors

Experimental studies conducted under the established optimal parameters confirmed the effectiveness of the optimisation of the delignification process. The results obtained show that, with the optimal ratio of reagents and treatment duration, it was possible to achieve a high yield of cellulose product with minimal losses of the polysaccharide part of the biomass. As a result, a substrate with a yield of 52.1% was obtained, characterised by a low lignin content of 2.3%, a high cellulose content of 65.9% and a low ash content of 2.8%. These indicators indicate deep delignification of oat straw and a significant increase in the purity of the cellulose fraction, which is an important prerequisite for further effective enzymatic hydrolysis and biotechnological conversion to bioethanol. In general, the approach used has opened up new opportunities for the valorisation of large-tonnage plant waste from the agro-industrial complex with the production of new valuable products.

The conversion of lignocellulosic biomass is a key process in the development of sustainable biofuels (Woźniak *et al.*, 2025). It involves breaking down the complex structure of plant materials. Effective conversion requires overcoming the natural resistance of plant biopolymers, in particular through pre-treatment methods. Pre-treatment is important for disrupting the rigid structure of lignocellulosic biomass, making cellulose and hemicellulose available for further processing (Hu *et al.*, 2022; Limeneh *et al.*, 2025). Treatment methods include mechanical, thermal, acid, alkaline, and novel methods based on green solvents such as ionic liquids, deep eutectic solvents, steam explosion, etc. Combining pretreatment methods can increase its efficiency, as shown in the works of S. Baksi *et al.* (2023) and L.G. Nair *et al.* (2023). However, for the scalability of second-generation biofuel production processes, it is necessary to develop affordable and cost-effective pretreatment methods that allow for the utilisation of processing by-products (Amini *et al.*, 2021). Such methods include organosolvent treatment using a mixture of glacial acetic acid and hydrogen peroxide, as discussed by Z. Lin *et al.* (2023) and W. Ying *et al.* (2023). This treatment can remove up to 97% of lignin from lignocellulosic biomass, significantly improving the availability of cellulose for enzymatic hydrolysis and subsequent fermentation. This method ensures a high cellulose content in the substrate (up to 87%), which is crucial for maximising sugar yield, as shown in a study by T.K. Bedru *et al.* (2025). It is also important that the process takes place under relatively mild conditions, which reduces energy consumption and minimises the formation of fermentation inhibitors (Ummalyma *et al.*, 2024).

Ukraine is one of Europe's leading agro-industrial countries, producing significant volumes of grain crops and by-products of their cultivation every year (Talavyria *et al.*, 2025). Oat production in Ukraine is estimated at hundreds of thousands of tonnes annually. This means that, along with the grain, a large amount of straw is produced, most of which has no profitable use. However, this biomass is a valuable renewable resource and a potential raw material for bioenergy needs (Błaszczyk *et al.*, 2023). The study showed that oat straw is a promising raw material for the production of second-generation bioethanol, as it is characterised by a high content of cellulose components, availability and belongs to renewable types of lignocellulosic biomass. The use of this type of agricultural waste in bioenergy technologies contributes to the more efficient use of agricultural resources and a reduction in organic residues, which is an important factor in the context of developing a circular bioeconomy and reducing greenhouse gas emissions.

Conclusions

Experimental studies have shown that treating oat straw with a mixture of acetic acid and hydrogen peroxide ensures effective delignification of biomass and the formation of a fibrous substrate enriched with cellulose. During the reaction, peracetic acid is formed, which acts as a selective oxidising agent and promotes the breakdown of lignin structures without significant destruction of the carbohydrate part. It has been proven that increasing the hydrogen peroxide content in the reaction mixture enhances the delignification effect, but excessive treatment time can lead to partial degradation of hemicellulose and a decrease in solid residue yield. In particular, at an acetic acid : hydrogen peroxide ratio of 70:30 vol. %, with an increase in the reaction time from 60 to 120 minutes, a decrease in yield of approximately 10% is observed, indicating the destruction of part of the carbohydrate complex. This pattern indicates the need for an optimal combination of technological parameters that ensure a rational compromise between the efficiency of delignification and the preservation of the quantitative yield of the substrate.

Mathematical processing of experimental data allowed to build regression models and 3D response surfaces that quantitatively reflect the effect of hydrogen peroxide consumption and treatment duration on substrate yield, lignin, cellulose and mineral component content. The models demonstrate a negative linear effect of treatment intensity on substrate yield and residual lignin, while quadratic and interactive terms show a synergistic effect between factors. Ash components were found to be less sensitive to changes in conditions. To solve this problem, a multi-criteria optimisation method was applied using Harrington's generalised desirability function, which made it possible to find the optimal compromise between conflicting indicators. The optimal conditions were determined to be a hydrogen peroxide content of 30 vol. % and a treatment duration of 60 min.

Experimental verification of the modelling results confirmed the adequacy of the constructed regression equations. Under the specified optimal parameters, a substrate with a yield of 52.1%, lignin content of 2.3%, cellulose content of 65.9% and ash content of 2.8% was obtained. These indicators demonstrate the high efficiency of the acetic acid-hydrogen peroxide organosolvent system as a reagent medium for the preliminary treatment of oat straw. The results obtained have both theoretical and practical significance, as they expand scientific understanding of the peculiarities of delignification processes. The proposed technology can be used as a basis for further research in the direction of scaling up the process, optimising energy costs and integrating it into second-generation bioethanol production lines. Further research will focus on optimising the processes of hexose sugar extraction and their conversion to bioethanol.

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Conflict of Interest

None.

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Анотація. Україна як провідна агропромислова держава щорічно генерує значні обсяги побічних продуктів, зокрема вівсяну солому, яка з огляду на лігноцелюлозний склад є цінним ресурсом для забезпечення потреб біоенергетики. Метою цієї роботи було дослідити ефективність обробки вівсяної соломи сумішшю оцтової кислоти та пероксиду водню для ефективної делігніфікації та одержання субстрату з високим вмістом полісахаридної складової для потенційного використання для одержання біопалива другого покоління. Застосовано математичне моделювання й аналіз регресійних рівнянь на основі експериментів із варіюванням концентрації пероксиду водню (10-30 об. %) і тривалості обробки (60-120 хв) для визначення оптимального компромісу між видаленням лігніну й збереженням целюлози. Встановлено, що витрати пероксиду водню та тривалість обробки мають переважно негативний вплив на вихід субстрату, тоді як для видалення лігніну спостерігається позитивний ефект. Показано, що оптимальними умовами є вміст пероксиду водню у суміші 30 об. % при тривалості обробки 60 хв, що забезпечує максимальне значення функції бажаності та одержання субстрату з виходом 52,8 %, вмістом лігніну 2,1 % та целюлози 66,8 %. Експериментальна перевірка цих умов підтвердила достовірність отриманої моделі: одержано субстрат з виходом 52,1 %, вмістом лігніну 2,3 % та целюлози 65,9 %. Таким чином, робота демонструє ефективність обґрунтованого підходу до переробки агропромислових відходів, відкриваючи перспективи для виробництва біопалива другого покоління. Отримані результати мають наукове й прикладне значення, оскільки підтверджують ефективність оптимізованої делігніфікації вівсяної соломи та створюють науково обґрунтовану основу для розроблення ресурсоефективних технологій виробництва біопалива другого покоління

Ключові слова: субстрат; лігнін; целюлоза; переробка відходів; делігніфікація

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Vegetation cover dynamics of the Dniester basin under climate change influence in the 21st century

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Abstract. The increasing climate instability in the Carpathian Region of Ukraine highlights the need for long-term monitoring and quantitative assessment of vegetation cover changes in the Dniester River basin. The aim of this study was to analyse vegetation cover change trends in the Dniester basin within Ivano-Frankivsk Region during 2001-2024 and to identify relationships between these trends and key climate variables. Research methods included time series analysis of median summer vegetation index values based on MODIS satellite data, application of the Mann-Kendall test to detect monotonic trends, calculation of Pearson correlation coefficients to assess linear relationships, and use of Random Forest regression to model the nonlinear impact of temperature, precipitation, land cover types, and elevation on vegetation dynamics. The main results showed an overall positive trend in vegetation index growth, with the lowest value in 2003 and the highest in 2023. Statistically significant summer trends cover 43.2% of the territory, of which 38.8% are positive and 4.4% are negative trends. The most pronounced positive changes were observed at medium elevations in the Carpathian foothills, where broadleaf and mixed forests dominate. The Random Forest model achieved a coefficient of determination of 0.718, identifying temperature as the primary predictor of vegetation dynamics, followed by land cover type, precipitation, and elevation. The practical value of the study lies in providing a scientific basis for planning conservation measures, adapting forestry to climate change, and developing sustainable ecosystem management strategies for the Carpathian Region

Keywords: vegetation index; Mann-Kendall test; Pearson correlation coefficient; Random Forest; Carpathian Region; satellite remote sensing; ecosystems

Introduction

The Dniester River basin, which covers a significant part of western Ukraine, is characterised by high heterogeneity of vegetation cover – from mountainous forest ecosystems of the Carpathians to lowland agricultural landscapes. For the western region of Ukraine throughout the 21st century, substantial transformation of climatic conditions is expected: an increase in extreme precipitation and rain floods, reduction of snow cover, elevated risk of fire-hazardous weather and droughts (Glibovytska *et al.*, 2024). Scientists S. Krakovska & L. Kryshtop (2024) in their report on climate change impacts in Ukraine established that the cumulative threat from changing climatic factors in the region may reach 50-72.5% over the century. Such climate changes directly affect vegetation cover dynamics, as vegetation is

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sensitive to temperature fluctuations and moisture regime variations (Kravchynskyi *et al.*, 2021).

To assess the impact of climate change on vegetation dynamics, it is necessary to conduct long-term analysis of large territories with high spatial and temporal coverage. Researchers S. Huang *et al.* (2020) noted that one of the most effective approaches for such monitoring is the use of satellite remote sensing data, particularly the Normalised Difference Vegetation Index (NDVI), which is calculated as the normalised difference between red and near-infrared spectral bands and serves as a sensitive indicator of photosynthetically active biomass. The authors emphasised that NDVI enables quantitative assessment of vegetation cover status and its changes over extended periods, making this indicator an indispensable tool for studying climate change impacts on ecosystems.

E. Sanz *et al.* (2021) investigated NDVI dynamics and its relationship with temperature and precipitation in arid pastoral ecosystems of south-eastern Spain for the period 2002-2019. Using correlation and regression analysis, the authors established that temperature is the most influential factor in NDVI dynamics, demonstrating a strong negative correlation under limited rainfall conditions and positive correlation during periods of high moisture. The researchers also identified time lags in vegetation response to changing climatic conditions (16-32 days), highlighting the importance of accounting for delayed climate effects on vegetation cover dynamics in arid regions.

L. Klimavičius *et al.* (2023) analysed seasonality and long-term NDVI trends in the eastern part of the Baltic Sea basin during 1982-2015, considering five land use types: croplands, pastures, wetlands, mixed and coniferous forests. The researchers found that temperature is the most important factor, while precipitation had significantly less influence on NDVI dynamics throughout the growing season. The authors established that the onset of the vegetation season became earlier by 3-4 weeks, and its duration increased by 6-7 weeks compared to the beginning of the study period, with these changes being statistically significant for all land use types. Maximum NDVI values were reached fastest in croplands and pastures, emphasising the importance of considering land use type when analysing phenological changes in vegetation.

L. Fathollahi *et al.* (2023) developed a global NDVI forecasting model based on deep neural networks using three climate variables: air temperature, soil moisture, and precipitation for the period 2017-2020. The model demonstrated high prediction accuracy with $R^2 = 0.86$ in temporal analysis and RMSE = 0.092, showcasing the effectiveness of applying machine learning methods for analysing relationships between climate and vegetation. This approach underscores the advantages of applying machine learning algorithms, such as Random Forest and deep neural networks, for modelling complex nonlinear dependencies between NDVI and climatic factors at global and regional scales, offering an alternative to traditional process-based models.

In Ukraine, there is a lack of contemporary research that would examine vegetation cover changes in detail within the context of climate change for the Carpathian Region. V.I. Lyalko *et al.* (2020) analysed long-term trends for the entire territory of Ukraine; however, the study employed indices aimed at detecting soil moisture and droughts. The scale of these investigations is quite large, and the level of detail remains low. V. Ivanyshyn & D. Kasiyanchuk (2024) conducted a local study of climate change impacts on vegetation in the Perehinsk territorial community, applying NDVI and NDWI indices along with correlation analysis. However, this study covers a short time period and a limited territory. In the research by O.S. Glukh *et al.* (2023), an investigation of NDVI changes for the Carpathian Region was also conducted for the period from 2000 to 2022. Nevertheless, the analysis was performed on only 15 images, which is insufficient for quality long-term analysis. In this regard, the aim of this study was a comprehensive examination of vegetation cover dynamics in the Dniester basin within Ivano-Frankivsk Region and determination of linear and nonlinear dependencies between vegetation changes, main climatic factors (temperature and precipitation), and vegetation types.

Materials and Methods

The study area is located within Ivano-Frankivsk Region of Ukraine and encompasses the Dniester River basin, which occupies the northern part of the region. The southern part of the region belongs to the Prut River basin. The relief of the study territory is characterised by considerable diversity. Elevation above sea level varies from 230 m in the Dniester River valley to 1,800 m in the mountainous part (Fig. 1). The hydrographic network of the territory is well-developed. Besides the main waterway – the Dniester River, the basin includes sub-basins of the Limnytsia, Lukva, Bystrytsia, Sivka, Svicha, Svirz, Vorona, and Hnyla Lypa rivers. This extensive river system significantly influences the natural and economic characteristics of the region (Matiyiv *et al.*, 2022).

The land use structure of the region is heterogeneous: approximately 40% of the territory is occupied by forests, predominantly in mountainous and foothill zones. Croplands, as of 2023, constitute over 40% of the area (Fig. 2). In the lowland territories of the northern and eastern parts of the basin, agricultural lands prevail, represented by a mosaic of croplands and pastures. The mountainous part is characterised by the dominance of forest ecosystems, where coniferous species predominate at higher elevations and broadleaf and mixed forests in the foothills and at medium elevations (Rodriguez-Galiano *et al.*, 2012). The spatial distribution of land cover types reflects the natural zonation of the region. In the southwestern high-mountain part, evergreen needleleaf forests prevail, which gradually transition to deciduous broadleaf forests with decreasing elevation. Mixed forests occupy an intermediate position and form a transitional zone between coniferous and broadleaf ecosystems (Prykhodko *et al.*, 2023).

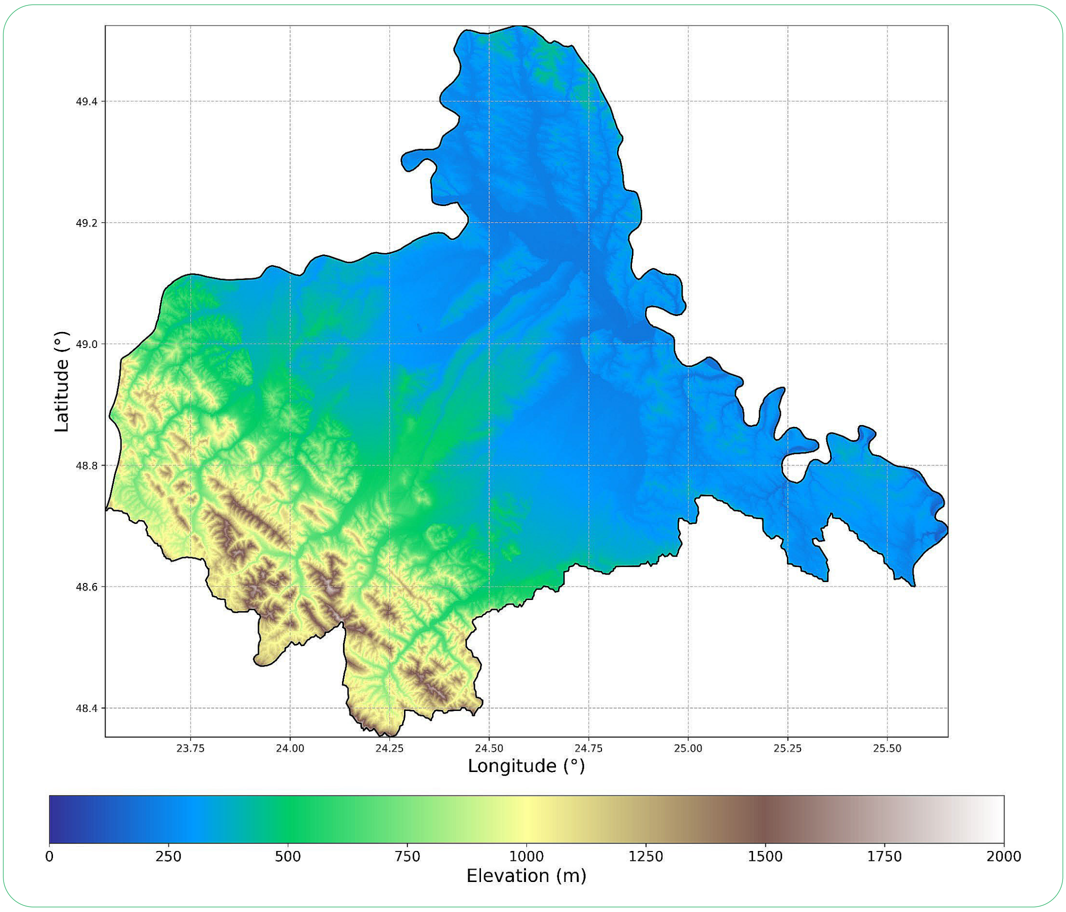

Figure 1. Digital elevation model of the study area of the Dniester basin within Ivano-Frankivsk Region
Source: created by the authors based on NASA SRTM digital elevation 30 m (n.d.)

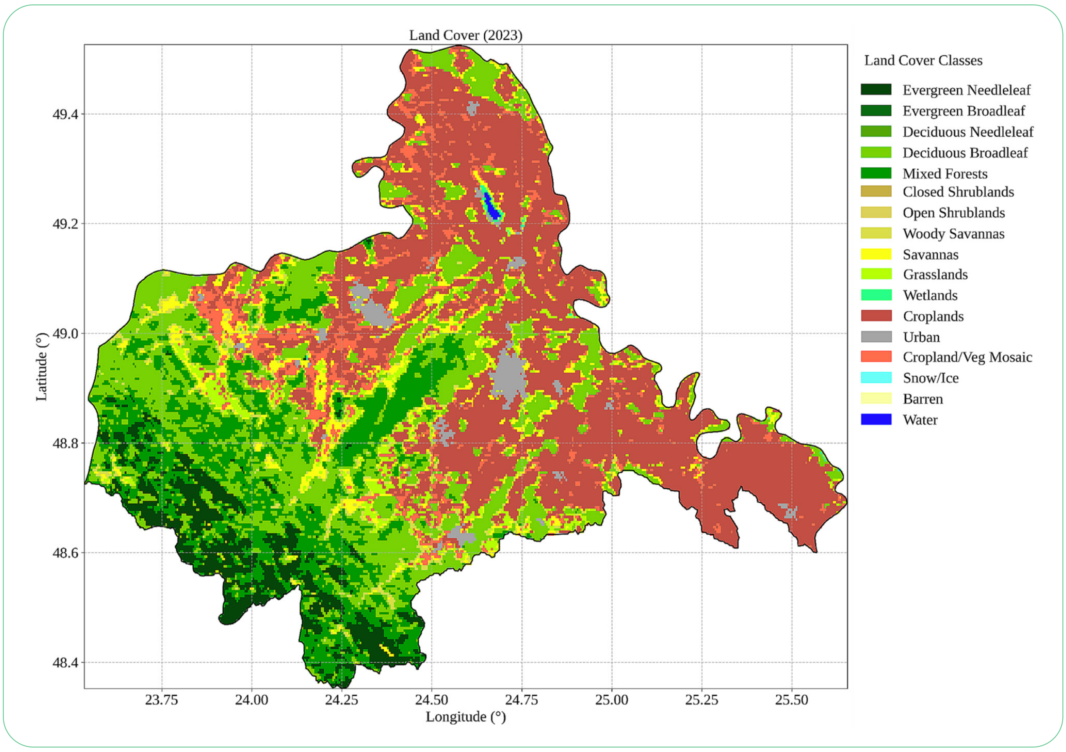

Figure 2. Spatial distribution of land cover types in the study area according to IGBP classification (2023)
Source: created by the authors based on M. Friedl & D. Sulla-Menashe (2022)

The study covered data for the period 2001-2024. All data for the research were obtained using the Google Earth Engine (GEE) platform. For NDVI data, the MODIS/061/MOD13Q1 collection was used (Didan, 2021). The spatial resolution of images in this collection is 250 meters. Images are provided at 16-day intervals, which are compositionally assembled from daily observations by satellites. The MODIS NDVI product is calculated based on atmospherically corrected bidirectional surface reflectances, for which masking of water bodies, clouds, heavy aerosols, and cloud shadows was performed. MODIS was chosen because, although it has somewhat lower image resolution compared to Landsat/Sentinel imagery, its advantage is that MODIS satellites have a revisit time of 1-2 days, unlike Landsat/Sentinel which have temporal coverage of 16 and 5 days respectively (Mao *et al*., 2016). Low imaging frequency reduces the availability of cloud-free and distortion-free surface observation data, which can introduce greater uncertainty. Additionally, conducting long-term analysis at the river basin or regional level using high-resolution imagery such as Landsat or Sentinel requires substantial computational capacity and takes considerably more time, which also influenced the method selection.

Climate data were obtained from two different collections. Surface temperature data were taken from the MODIS/061/MOD11A2 collection (Wan *et al*., 2021). The MODIS/061/MOD11A2 product provides average surface temperature compositionally calculated for 8-day periods. The collection resolution is 1000 meters. Precipitation data were obtained from Climate Hazards Center InfraRed Precipitation with Station (CHIRPS), collection UCSB-CHG/CHIRPS/PENTAD (CHIRPS Pentad…, n.d.). This is a quasi-global precipitation dataset spanning over 30 years. CHIRPS combines satellite imagery with 0.05° resolution with in-situ station data to create gridded precipitation time series for trend analysis. Land cover type data were obtained from the MODIS/061/MCD12Q1 collection, which provides global land cover types at annual intervals (Friedl & Sulla-Menashe, 2022). The collection resolution is 500 meters. For this study, the International Geosphere-Biosphere Programme (IGBP) classification was selected. The digital elevation model with 30-meter resolution was obtained from Shuttle Radar Topography Mission (SRTM) data. The collection identifier in GEE is USGS/SRTMGL1_003 (NASA SRTM digital elevation 30 m, n.d.).

The spatiotemporal variability of NDVI and temperature with precipitation was investigated using two methods (Satti *et al*., 2024). The first method involved time series analysis over 24 years, with appropriate calculation methods applied for each parameter. For NDVI, time series were calculated based on median values, as the advantage of the median over the mean is its greater resistance to outliers, which frequently occur in NDVI values due to, for example, cloud cover. For constructing temperature time series, average values for the summer season were calculated. Time series for precipitation were built based on average precipitation sums for the summer season. The second method for investigating spatiotemporal variability consisted of detecting monotonic trends. For this purpose, the Mann-Kendall algorithm was used (Mann, 1945). The Mann-Kendall test is non-parametric; therefore, it is less sensitive to outliers and uneven data distribution compared to parametric tests. When studying trends using this test, statistically significant trends are conventionally considered those where the p value is less than 0.05, reflecting statistical significance at the 95% level or higher. To investigate the linear interaction between NDVI and climate indicators, Pearson correlation coefficients were calculated, as this method offers a quantitative measure of linear relationship between two variables.

To model the nonlinear impact of temperature, precipitation, land cover types, and elevation on NDVI, Random Forest regression was employed, implemented in Python using the Scikit-learn (n.d.) library. Random Forest was chosen due to its high noise resistance, automatic accounting for interactions between variables, and ability to handle categorical data, which is suitable for heterogeneous geospatial datasets. All input data were aggregated to an annual temporal scale with a spatial resolution of 0.0045° (~500 m), corresponding to the native resolution of land cover data, minimising interpolation errors for categorical data. NDVI, precipitation, temperature, land cover, and elevation data were combined into a one-dimensional array by stacking spatial (latitude, longitude) and temporal dimensions, followed by filtering to eliminate missing values by selecting common samples. Categorical land cover data were converted to numerical format using one-hot encoding – a method that represents each land cover type (e.g., forest or agricultural land) as a set of binary variables (0 or 1). This allows the Random Forest algorithm to effectively process discrete IGBP classes, because machine learning methods perform poorly with categorical data in their raw form, as they require numerical representations for mathematical computations.

Since this study used 7 of 17 possible land cover types, one-hot encoding was employed, providing compact data representation without significant increase in dimensionality. Continuous variables (precipitation, temperature, elevation) were used without normalisation, as Random Forest is insensitive to scaling. The Random Forest model, which creates an ensemble of many decision trees to predict NDVI based on input parameters, was optimised using GridSearchCV, testing combinations of hyperparameters (number of trees: 50, 100; maximum depth: 5, 10; minimum samples for split: 2, 5; minimum samples in leaf: 1, 2) using 5-fold cross-validation to ensure robust performance estimates. In Random Forest, each decision tree analyses a portion of the data and makes its own prediction, and their results are combined. GridSearchCV from the scikit-learn library automatically tests different model settings to find optimal ones, and 5-fold cross-validation divides the data into five parts, training the model on four and testing on the fifth, which was repeated five times to assess model stability.

All stages of the research, including data acquisition and preparation in GEE, were implemented programmatically using Python programming language version 3.11. The following Python libraries were used for research implementation. The "ee" library provided Python API for GEE. The "xarray" library enabled working with data as multi-dimensional arrays, where dimensions can be coordinates, temporal dimension, and any other arbitrary attributes; "xarray" provides the fundamental data structure and API and allows encoding information about how array values correspond to locations in space, time, etc. (Xarray, n.d.). The "xee" library, which is an extension to "xarray", enabled integration of GEE data (Google/Xee, n.d.). The "pymannkendall" library implements almost all known modifications of Mann-Kendall tests and the Theil-Sen slope coefficient (Hussain & Mahmud, 2019). The "scikit-learn" library for machine learning implemented algorithms for performing classification, regression, clustering, and other types of predictive data analysis. The "matplotlib" and "geemap" libraries were used for visualising graphs and maps.

Results

Analysis of changes in land use structure for the period 2001-2023 reveals significant transformations in the landscape structure of the basin (Fig. 3). The most pronounced tendency is the growth in cropland proportion from 20% to 34%, reflecting the intensification of agricultural production in the region. Simultaneously, a drastic reduction in the mosaic agricultural land category is observed, from 25% to 7%, indicating the transformation of mosaic agricultural-natural landscapes into continuous croplands. Among forest ecosystems, multidirectional changes are occurring: the area of broadleaf deciduous forests increased from 16% to approximately 22%, while the share of evergreen needleleaf forests slightly decreased from 9% to 6%. The area of mixed forests remained stable throughout the study period. The proportion of grasslands and steppes increased slightly from 3% to 4%.

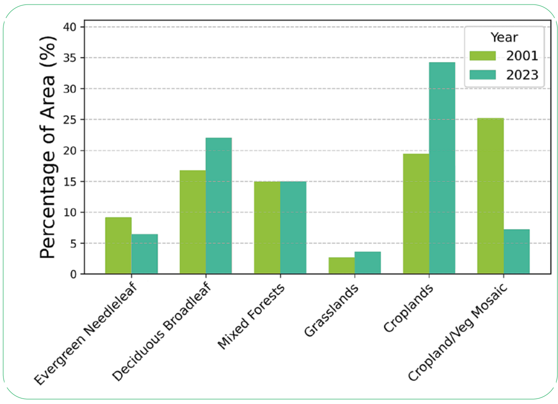

Figure 3. Spatial distribution of land cover types in the study area: 2001 and 2023
Source: created by the authors based on M. Friedl & D. Sulla-Menashe (2022)

Analysis of the median NDVI time series for the summer season in the studied territory of the Dniester basin within Ivano-Frankivsk Region demonstrates a positive tendency throughout the 24-year observation period. Although interannual fluctuations can be observed, the overall trend remains upward. The lowest value was recorded in 2003 (~0.75) and the highest in 2023 (~0.83) (Fig. 4).

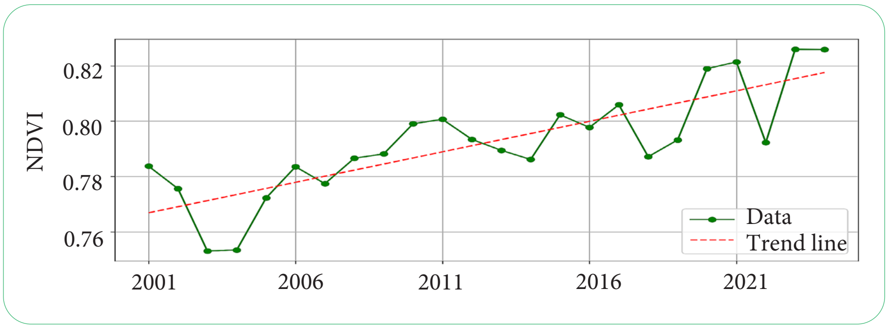

Figure 4. Dynamics of median NDVI values for the summer season in the study area (2001-2024)
Source: created by the authors based on data from GEE collection K. Didan (2021)

Results of the Mann-Kendall tests showed that NDVI changes for the summer season during the period 2001-2024 are distributed unevenly across the study territory (Fig. 5). Overall, statistically significant summer NDVI trends cover approximately 43.2% of the territory, of which 38.8% accounts for positive trends and 4.4% for negative ones. Positive changes nearly nine times outweigh negative ones, indicating overall improvement in vegetation condition in the region.

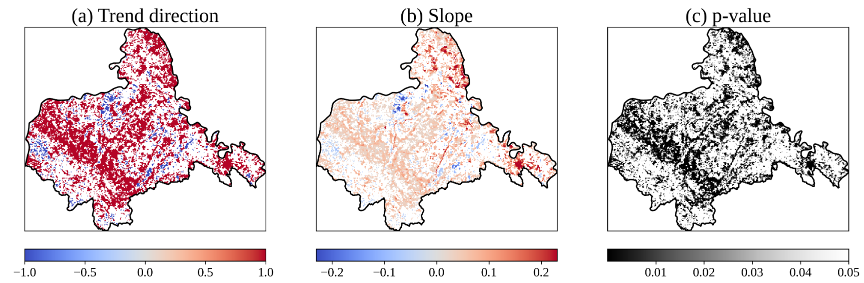

Figure 5. Results of NDVI trend analysis using the Mann-Kendall test
Note: a – trend direction; b – slope magnitude; c – statistical significance (*p* value)
Source: created by the authors based on K. Didan (2021)

Spatial analysis of trends shows that most statistically significant positive tendencies occur at medium elevations (500-800 meters above sea level) within the Carpathian foothills, where broadleaf and mixed forests dominate. In mountainous areas, statistically significant trends are practically not observed. Only in the western part of the mountainous territory can some negative tendencies be noticed, and in the southern part, minor positive trends. This is explained by the fact that broadleaf and mixed forests in highland landscapes are more resilient to global climate changes (Marod *et al.*, 2025). For lowland territories, which are predominantly occupied by agricultural lands, the nature of changes is heterogeneous (Wang *et al.*, 2023). Both negative processes are observed, largely caused by anthropogenic factors (forest exploitation, expansion of urbanised territories, increase in areas with hazardous geological processes, territories occupied by waste and dumps), as well as positive dynamics.

The average magnitude of statistically significant positive changes is 0.069 NDVI units, while for negative changes this indicator equals -0.072 NDVI units over 24 years. Some areas can be noted where the magnitude of changes stands out against others. Among them: negative dynamics in the area of Kalush City; increase in indicators in the valleys of the Limnytsia and Bystrytsia-Nadvirnianska rivers. Also, larger positive changes are observed in some areas in the northern and eastern parts of the territory, which are almost entirely occupied by agricultural lands. Average surface temperature for the summer season shows an upward tendency, although values vary quite strongly from year to year, and monotonic trends are not observed for practically the entire study territory (Fig. 6). The magnitude of change varies depending on the territory, averaging from +1°C to +1.6°C. Average precipitation sums for the summer season show an overall declining tendency, although, similarly to temperature, values vary substantially from year to year, and clear monotonic trends are not observed (Fig. 7).

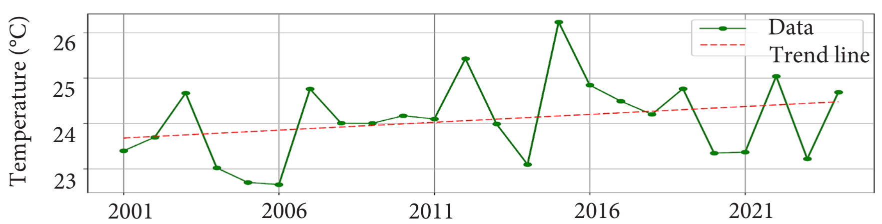

Figure 6. Dynamics of average surface temperature for the summer season in the study area (2001-2024)
Source: created by the authors based on Z. Wan *et al.* (2021)

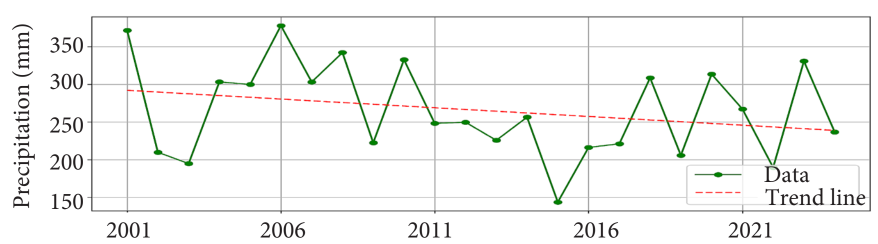

Figure 7. Dynamics of average precipitation sums for the summer season in the study area (2001-2024)
Source: created by the authors based on CHIRPS Pentad: Climate Hazards Center infrared precipitation with station data (Version 2.0 Final) (n.d.)

Pearson correlation test statistics showed a weak relationship between NDVI and climatic characteristics for the studied territory. The average correlation coefficient between NDVI and precipitation is 0.100, and between NDVI and temperature is -0.184. Analysing the spatial distribution of correlations (Fig. 8), it can be concluded that a stronger linear relationship between NDVI and climatic characteristics is observed in the lowland part occupied by agricultural lands, where the relationship with precipitation is positive, i.e., with increasing precipitation amount, NDVI values increase, and the relationship with temperature is negative, i.e., with increasing surface temperature, NDVI values decrease. With increasing elevation, the correlation dependency decreases to statistically insignificant values, which again confirms the greater resilience of highland landscapes to global climate changes.

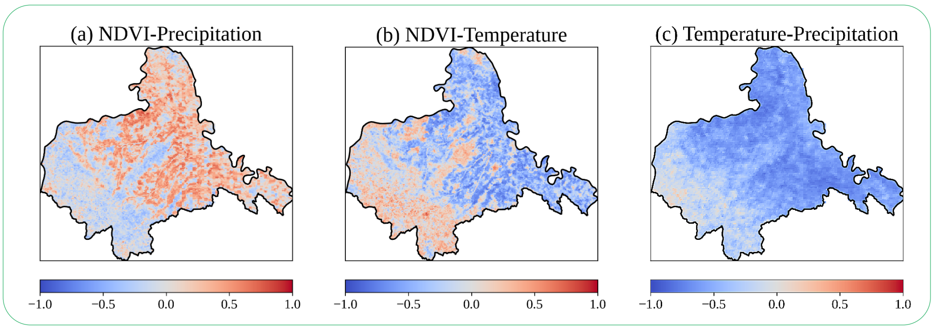

Figure 8. Spatial distribution of Pearson correlation coefficients

Note: a – NDVI and precipitation; b – NDVI and temperature; c – temperature and precipitation

Source: created by the authors based on K. Didan (2021), Z. Wan *et al.* (2021), CHIRPS Pentad: Climate Hazards Center infrared precipitation with station data (Version 2.0 Final) (n.d.)

To assess the nonlinear impact of temperature, precipitation, land cover types, and elevation on NDVI, a Random Forest regression model was applied. The model achieved a coefficient of determination $R^2 = 0.718$, RMSE = 0.038, and cross-validated $R^2 = 0.669 \pm 0.025$ with 5-fold cross-validation at a resolution of 0.0045° (~500 m) due to land cover detail, indicating relatively high prediction accuracy and moderate generalisation ability (Fig. 9).

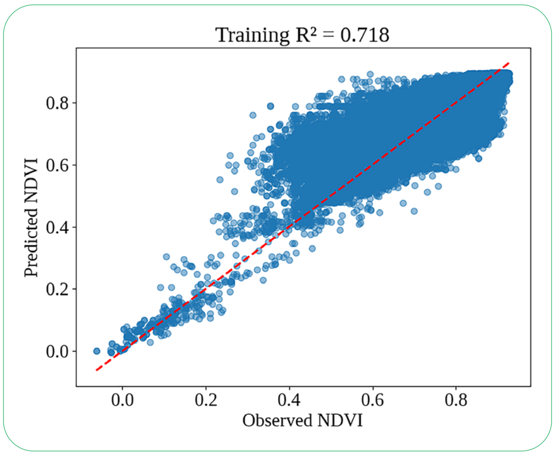

Figure 9. Results of NDVI modeling using Random Forest regression: relationship between observed and predicted values

Source: created by the authors based on NASA SRTM digital elevation 30 m (n.d.), CHIRPS Pentad: Climate Hazards Center infrared precipitation with station data (Version 2.0 Final) (n.d.), K. Didan (2021), Z. Wan *et al.* (2021), M. Friedl & D. Sulla-Menashe (2022)

Feature importance analysis showed that temperature is the primary predictor (55%), followed by land cover type (32%), precipitation (8%), and elevation (5%), emphasising the dominance of climatic factors and vegetation type, with a smaller but noticeable contribution from topography. The low relative importance of elevation is likely explained by its collinearity with temperature (decrease of 0.65°C per 100 m elevation), reflecting the law of altitudinal natural zonation and being partially accounted for through the temperature effect in the model.

Discussion

The overall tendency toward increasing NDVI values is consistent with the results of other studies for various regions. In particular, C. Eisfelder *et al.* (2023), when analysing seasonal NDVI changes for the European continent over a 30-year period, identified statistically significant positive trends in 22% of Europe's territory with an average change magnitude of 0.09. At the same time, the authors noted that for the summer season, changes are less substantial compared to other seasons and are characterised by regional specificity. For northern, central, and south-eastern parts of Europe, tendencies are predominantly positive, while in the western part, particularly in Spain and Ireland, changes are mainly negative in character. The researchers also noted that negative trends are mostly localised in agricultural areas, whereas forests demonstrate predominantly positive tendencies during the vegetation period and minor or positive trends during summer and autumn. The thesis regarding positive changes for forest ecosystems is also confirmed by the results of this study. Concerning negative dynamics for agricultural areas, no pronounced trends were detected within the studied territory, except for individual localised areas that require further analysis to establish the causes of such anomalies. It is assumed that such substantial changes are most likely caused by anthropogenic activity.

Research results by R. Prăvălie *et al.* (2022) for the territory of Romania also demonstrated overall dominance of positive NDVI tendencies. The authors note that positive changes cover 65% of the territory, predominantly in the Carpathian Region with moderate and high elevations, while 35% of negative changes are localised in lowland regions. Within the studied territory, positive dynamics were detected for 40% of the area. Differences in the obtained indicators may be caused by the heterogeneity of the studied territory, a significant part of which is occupied by agricultural lands. Overall, the obtained results are consistent with the conclusions of Romanian researchers. R. Prăvălie *et al.* (2022) also established that approximately 50% of NDVI changes correlate with temperature indicators, particularly forest ecosystems in mountainous environments demonstrate positive response to warming. These results are consistent with the conducted analysis, as the Random Forest model identified temperature as the main predictor (55% importance).

Results by X. Feng *et al.* (2023), obtained for the subtropical metropolitan region of Greater Bay Area (China), also confirm the dominance of positive vegetation cover trends over a 20-year period, which generally agrees with the upward NDVI dynamics identified in this study. The authors recorded EVI growth at a rate of 0.0045/year and significant prevalence of territories with vegetation condition improvement (over 65% of area), while degradation changes cover less than 6%. Such asymmetry between vegetation restoration and degradation processes resonates with results obtained within the Dniester basin, where positive tendencies also dominate, although occupying a smaller share of territory (approximately 39%). These differences can be explained by noticeably different intensities of anthropogenic impact, land use structure, and climatic conditions, as GBA is characterised by high humidity and powerful urbanisation pressure, while the studied territory combines mountainous, forest, and agricultural landscapes. An important distinction between the results of X. Feng *et al.* (2023) and this study is the spectrum of analysed climatic predictors. In the work of Chinese researchers, it was established that relative humidity and wind speed have the strongest relationship with EVI dynamics, while temperature plays a secondary role and is characterised by spatially mosaic influence. In the study, these climatic factors were not considered; instead, primary attention was focused on temperature and precipitation. Despite this, the identified dependencies partially correlate with the conclusions of X. Feng *et al.* (2023), since the Random Forest model in current case also determined temperature as a key factor explaining NDVI changes (55% importance), while precipitation plays a significantly smaller role.

The study by L. Chang *et al.* (2023), conducted for the Yuan River basin in China, also demonstrates the dominance of positive NDVI trends in long-term perspective, which corresponds to the general direction of changes identified within the Dniester basin. The authors note that vegetation cover improvement is most characteristic of rural and mountainous areas, while in urban zones weak NDVI growth or stability is observed, which they associate with increasing land use intensity. Similar spatially differentiated dynamics is observed in the research: mountainous forest landscapes of the foothills demonstrate the most pronounced positive trends, while lowland agricultural territories are characterised by mixed nature of changes. Importantly, L. Chang *et al.* (2023) identified temperature as a key factor most contributing to NDVI increase, while the influence of precipitation proved weaker and depended on local conditions. This agrees well with results of this study, according to which temperature also acts as the primary driver of interannual NDVI variability, while the relationship with precipitation is weak and spatially heterogeneous.

Research results by W. Zhang *et al.* (2020) conducted for the Yangtze and Yellow River basins also demonstrate a general tendency toward increasing vegetation indicators, which is consistent with this study. The authors recorded NDVI increase at a rate of 0.011 per decade and significant spatial heterogeneity of changes: the most intensive growth was observed in central parts of the basins, while degradation was noted in the eastern sector. Similar spatial trend mosaicity is characteristic of the Dniester basin, where positive changes are concentrated primarily in forest landscapes of medium elevations, while degradation is localised and predominantly associated with anthropogenic impact. At the same time, analysis at different temporal scales performed by the authors showed significant strengthening of NDVI correlation with temperature and precipitation in long-term trends (up to 93.6% and 81.5% respectively), indicating the dominance of climatic factors in interannual and multi-year vegetation variability. Current results demonstrate a similar tendency toward the key role of temperature, which the Random Forest model identified as the main predictor of

NDVI changes, but correlation dependencies for precipitation within the Dniester basin proved substantially weaker.

The study by L. Cui *et al.* (2022), conducted in the high-mountain Yarlung-Tsangpo basin, demonstrates clearly pronounced dominance of temperature as the key climatic factor determining NDVI sensitivity of different vegetation types, while the response to precipitation proved significantly weaker. Application of the Random Forest model showed that a temperature increase of 1.5°C causes NDVI growth of 1.6-4.68%, while a precipitation increase of 10% affects only 0.06-0.24%. Similar dominance of the temperature factor is consistent with current results: the Random Forest model within the Dniester basin also identified temperature as the primary predictor of NDVI variability, while the relationship with precipitation remained weak and spatially limited. Additionally, the authors indicate the presence of substantial delayed effects of temperature and precipitation, especially for forest formations, whereas within the Dniester basin such effects were not analysed, which constitutes a potential direction for further research.

Research results by K.M. Al-Kindi *et al.* (2023), conducted for the Dhofar Region in Southern Oman, demonstrate the importance of comprehensive accounting for both climatic and topographic factors in explaining spatiotemporal NDVI variability. Unlike this work, where temperature was identified as the main driver of NDVI changes, in the Omani Region, soils, elevation, slope, and precipitation amount received the highest importance in the Random Forest model, while temperature and humidity played a secondary role. Such a shift in dominant predictors can be explained by substantially different climatic conditions and significant dependence of vegetation productivity on intensive episodic precipitation, particularly rainfall events associated with frequent cyclones. At the same time, the study by K.M. Al-Kindi *et al.* (2023) confirms that NDVI remains sensitive to strong climatic anomalies, especially excessive precipitation in highland areas, which partially agrees with observations of increased sensitivity of lowland agricultural territories to changes in precipitation amount. However, unlike Dhofar, where NDVI responses had a pronounced local character and were clearly associated with cyclone impacts, in the Dniester basin, general tendencies were more stable, and negative or positive anomalies indicated predominantly anthropogenic influence.

Conclusions

The conducted study of vegetation cover dynamics in the Dniester basin within Ivano-Frankivsk Region for the period 2001-2024 enabled obtaining a comprehensive assessment of climatic factors' impact on the region's ecosystems and identifying key patterns of their spatiotemporal variability. Time series analysis of NDVI confirmed an overall positive tendency of vegetation cover growth, with statistically significant positive trends covering 38.8% of the territory. The most pronounced NDVI increases are observed in foothill forest ecosystems at elevations of 500-800 m. Simultaneously, high-mountain areas of the Carpathians show nearly stable NDVI values, indicating high vegetation resilience to global climate changes at these elevations.

Correlation analysis revealed a weak but statistically significant relationship between NDVI and climatic parameters, particularly temperature and precipitation, with the strongest linear dependencies recorded in lowland agricultural territories. The application of machine learning methods, specifically the Random Forest model, allowed identifying nonlinear relationships and establishing that temperature is the dominant factor, explaining 55% of NDVI variability. A secondary role is played by vegetation type, precipitation amount, and elevation above sea level, with precipitation influence being limited by spatial heterogeneity and localised predominantly in lowland zones with agricultural land use. Overall, spatial analysis revealed mosaicity of vegetation responses to climate changes: positive trends are concentrated in forest foothill massifs, while lowland agrolandscapes are characterised by more variable NDVI dynamics.

The obtained results allow making predictive conclusions regarding future vegetation dynamics in the Dniester basin within Ivano-Frankivsk Region. Promising directions for further research include: expansion of temporal frameworks to identify long-term cyclical changes, detailed analysis of extreme climatic events' impact on vegetation cover, assessment of relationships between NDVI changes and regional biodiversity, as well as development of forecasting models to evaluate the effects of different climate change scenarios. It is advisable to conduct similar studies in other parts of the Carpathian Region to create a comprehensive picture of vegetation cover changes in the Ukrainian sector of the Carpathians, which will contribute to effective nature conservation planning, forest and agricultural resource management, as well as assessment of ecosystem resilience to climatic risks.

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Conflict of Interest

None.

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Динаміка рослинного покриву басейну Дністра під впливом кліматичних змін у 21 столітті

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Анотація. Зростаюча кліматична нестабільність у Карпатському регіоні України актуалізує необхідність довгострокового моніторингу та кількісної оцінки змін рослинного покриву басейну Дністра. Мета дослідження – аналіз тенденцій зміни рослинного покриву території басейну Дністра в межах Івано-Франківської області протягом 2001-2024 років та виявлення зв'язків між цими тенденціями й основними кліматичними змінними. Методи дослідження включали аналіз часових рядів медіанних значень індексу вегетації за літній сезон на основі супутникових даних MODIS, застосування тесту Манна-Кендалла для виявлення монотонних трендів, обчислення коефіцієнтів кореляції Пірсона для оцінки лінійних зв'язків та використання регресії Random Forest для моделювання нелінійного впливу температури, опадів, типів земного покриву та висоти над рівнем моря на динаміку рослинності. Основні результати показали загальну позитивну тенденцію зростання індексу вегетації з найнижчим значенням у 2003 році та найвищим у 2023 році. Статистично значущі літні тенденції охоплюють 43,2 % території, з яких 38,8 % припадає на позитивні та 4,4 % на негативні тенденції. Найвиразніші позитивні зміни спостерігаються на середніх висотах у передгір'ї Карпат, де домінують широколистяні та змішані ліси. Модель Random Forest досягла коефіцієнта детермінації 0,718, виявивши температуру як основний предиктор динаміки рослинності, за якою слідують тип земного покриву, опади та висота над рівнем моря. Практична цінність дослідження полягає в забезпеченні науковою основою для планування природоохоронних заходів, адаптації лісового господарства до кліматичних змін та розробки стратегій сталого управління екосистемами Карпатського регіону

Ключові слова: індекс вегетації; тест Манна-Кендалла; коефіцієнт кореляції Пірсона, Random Forest; Карпатський регіон; супутникове зондування; екосистеми

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Comprehensive assessment of heavy metal pollution in urban environme nts: A case study from Jelgava, Latvia

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Abstract. Air quality in urban environments has become a critical global issue and the rate of urbanisation is expected to continue rising. This study aimed to identify, on a theoretical basis, the patterns of technogenic background formation and the spatial structure of pollution in the urban environment of Jelgava. The methodology was based on systematic and statistical analyses to assess the sources and levels of pollution in the city. The duration of the study, from the initiation of data collection to the completion of analysis, covered the period from 2017 to 2023, with annual sampling and extensive monitoring conducted throughout this period. The concentrations of heavy metals in various components of the urban ecosystem in Jelgava were found to be within the following ranges: Ni – 20-60 mg/kg, Cu – 40-90 mg/kg, Pb – 30-70 mg/kg, Zn – 100-200 mg/kg. These values correspond to moderate pollution levels typical of urbanised areas in Northern and Central Europe. The highest concentrations were recorded near major roads and industrial zones, whereas peripheral areas were close to background values. It was established that the integrated environmental quality indicators (pollution index = 1.5-2.2, geoaccumulation index = 1-3) characterise Jelgava as a moderately polluted area while maintaining overall ecological stability. Factor analysis revealed that the pollution structure is shaped by two main sources: transport-related emissions (Ni, Cu, Zn – tyre and brake wear, diesel exhaust) and heating-industrial emissions (Pb, Cd – fuel combustion and local emissions from small enterprises). Jelgava can be classified as a moderately polluted yet resilient urban system, where anthropogenic pressure is balanced by natural self-purification mechanisms. The practical value of the study lies in the fact that its findings may be used by municipal environmental and planning authorities to assess risks and manage urban environmental quality

Keywords: urban ecosystem; technogenic pressure; pollution indexes; atmospheric-seasonal dynamics; ecological resilience

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Introduction

Air quality in urban environments has become one of the key issues in the context of rapid global urbanisation. By 2050, the United Nations predicts that around 68% of the world's population will live in cities, a trend particularly evident in Latvia, where nearly 70% of the population already resides in urbanised areas (UN projection, 2022; World Bank, 2024). The rising level of urbanisation intensifies environmental challenges, especially air pollution, which significantly affects public health, urban resilience and overall quality of life. Air pollution levels in cities are influenced by a range of factors, including urban form and density, traffic flows and industrial activity (Ibraimov *et al.*, 2025). Studies indicate that urban planning plays a critical role in shaping air quality. D. Wang *et al.* (2022) noted that urban form has a substantial impact on air pollution levels, particularly in rapidly growing megacities, where dense and poorly planned development contributes to increased emissions from transport and industry. Similarly, research by O.O. Akomolafe *et al.* (2024) emphasises that anthropogenic factors, primarily industrial emissions and road traffic, are the main sources of harmful pollutants such as particulate matter (PM) and volatile organic compounds. The localised nature of pollution impacts, demonstrated in the study by A. Kramer & L. Minet (2025), further highlights the importance of examining the structure of urban areas, particularly in zones adjacent to motorways and other areas with high traffic intensity.

The health consequences of urban air pollution are extremely serious. Even low concentrations of fine PM2.5 are associated with an increased risk of mortality, as confirmed by the study of S. Weichenthal *et al.* (2022). Chronic exposure to urban pollutants, including heavy metals such as zinc (Zn), copper (Cu), nickel (Ni) and lead (Pb), is linked to a wide range of adverse health effects, from respiratory diseases to cardiovascular and neurological disorders. Q. Chen *et al.* (2021) found that heavy metals contained in PM can induce oxidative stress and DNA damage, increasing the disease burden among vulnerable population groups, such as children and individuals with chronic illnesses. This indicates an urgent need to develop effective air quality management strategies. Mitigation strategies for urban air pollution are gaining increasing attention. Urban vegetation is widely regarded as a natural means of capturing pollutants and improving the microclimate. H. Dadkhah-Aghdash *et al.* (2022) demonstrated that well-designed greening programmes, including the strategic placement of vegetation along roadways, effectively reduce PM levels and contribute to overall air quality improvement.

In the context of Latvia, the study by G. Tabors *et al.* (2023) involved long-term monitoring of atmospheric deposition of heavy metals using moss biomonitoring (*Pleurozium schreberi*). The authors identified a consistent decline in the concentrations of zinc, cadmium, lead and copper, which is associated with improved environmental policies and reduced industrial emissions. This provides an essential macro-ecological context for understanding the dynamics of heavy metal air pollution in the country. The study conducted by I. Grinfelde *et al.* (2024) focused on assessing the impact of industrial activity on air quality in the city of Jelgava. The authors found elevated concentrations of copper, zinc and lead near industrial zones and transport corridors, indicating the presence of local pollution sources. This research makes a significant contribution to understanding the spatial distribution of heavy metals and to improving environmental monitoring approaches in urbanised areas of Latvia.

However, despite the availability of studies on atmospheric emissions, snow cover and bottom sediments, there is no comprehensive comparison that would allow for the assessment of interrelations between different environmental media and provide an integrated picture of technogenic impacts. For Baltic cities, including Jelgava, there remains a limited understanding of the spatial patterns of pollution distribution and the mechanisms of its seasonal modulation, which restricts the effectiveness of environmental monitoring and urban environmental management. Therefore, this study aimed to provide a theoretical explanation of the mechanisms of formation and spatial organisation of technogenic pollution in the urban environment of Jelgava, taking into account the distribution patterns and dynamics of heavy metals. To achieve this aim, the following objectives were set: to analyse the spatial and temporal structure of heavy metal distribution; to identify the source-related and mechanistic foundations of technogenic pollution using geostatistical and factor analysis methods; and to assess the overall ecological state of Jelgava's urban environment by comparing it with the global context to determine regional specificity and the degree of ecological resilience.

Materials and Methods

Jelgava, situated in the central part of Latvia, is defined by its compact urban structure and extensive transportation networks, encompassing an area of approximately 60.32 km^2 and housing nearly 55,000 residents (Fig. 1). The region experiences a temperate climate with average winter temperatures around -5.5°C and annual precipitation levels ranging from 550 to 560 mm. Snowfall typically occurs from December through February, providing ideal conditions for snow sampling and air quality monitoring, crucial for assessing urban pollution dynamics.

A lichen indication approach was applied in this study, involving a comprehensive inventory conducted across 125 sampling plots, with the elaborated methodology. Furthermore, the Tube Lichen (*Hypogymnia physodes*) transplant method was employed following the description provided in prior research (Merdan *et al.*, 2025). Additionally, samples of Maritime Sunburst Lichen (*Xanthoria parietina*) were gathered from 20 designated plots, with chemical analyses conducted as outlined (Spriņģe *et al.*, 2024). Snow sampling was conducted in 20 plots in 2017 and expanded to 60 plots from 2018 to 2023. Additionally, in 2018 and 2019, snow samples were specifically collected from 18 plots located within transport corridors to evaluate the localised impacts of pollution.

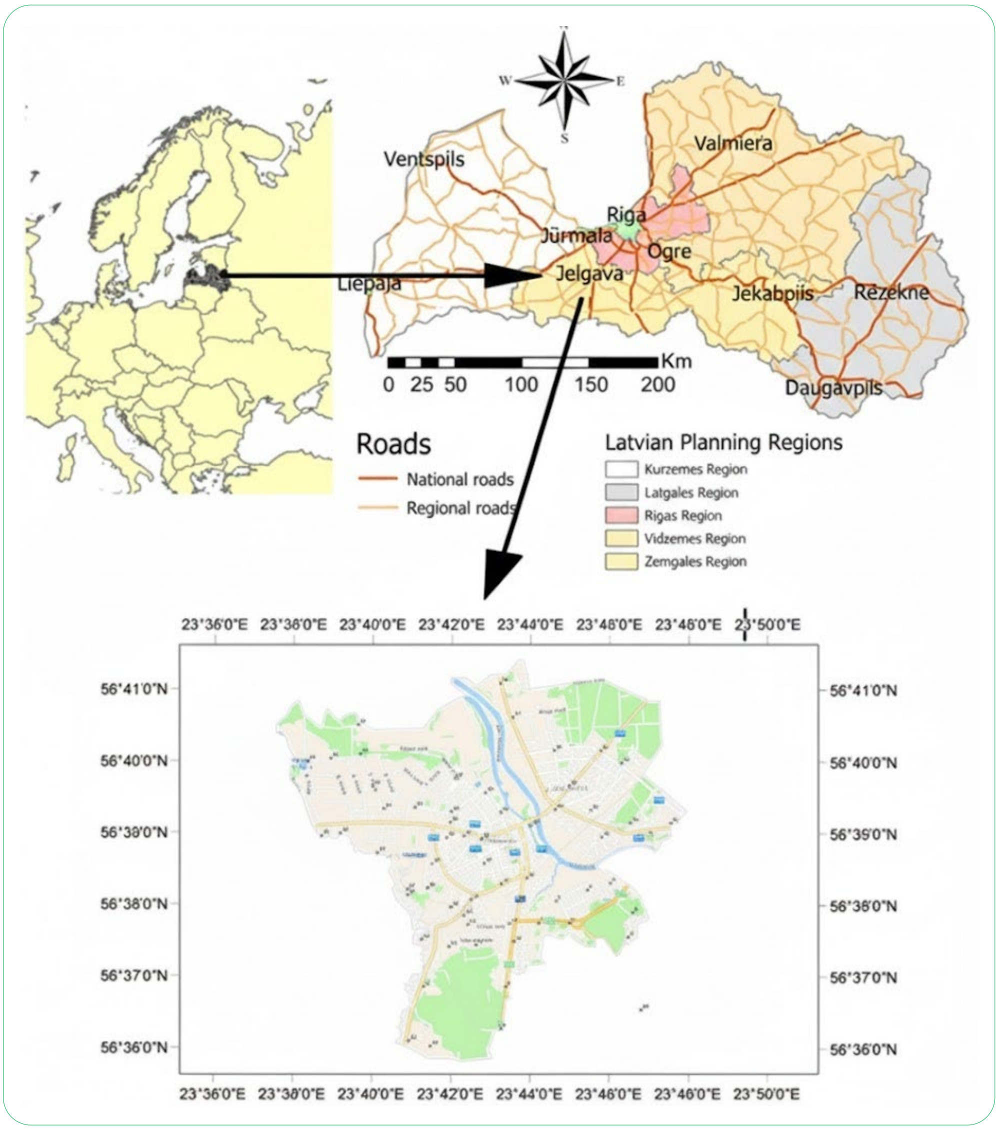

Figure 1. Location of study area with snow sampling points

Source: created by the authors

Snow sampling served as a vital method for evaluating short-term air pollution caused by chemical elements in urban areas. From 2017 to 2023, snow samples were collected annually during periods of accumulation lasting 5 to 9 days. Initially, sampling in 2017 focused on 20 plots near the city centre, supplemented by a single plot located 5 km outside the city in the Mežciem Forest Massif. By 2018, the sampling network had expanded to include 59 plots across the city and one plot outside its boundaries. To ensure comprehensive spatial coverage and accurate results, one sampling plot was designated per square kilometre, maintaining an average density of one plot per square kilometre. Each plot yielded three snow samples, with the full snow cover collected for analysis. Snow was gathered using disposable, dust-free nitrile gloves to prevent contamination. The samples were collected at a distance of 5 meters from roadways, stored in sterile plastic containers, immediately refrigerated, and then transported to the laboratory for further analysis.

For the preparation of snow samples analysed with Inductively Coupled Plasma Optical Emission Spectroscope (ICP-OES) (Thermo Fisher Scientific, United States), two distinct approaches were tested: (1) filtering the snow samples through a paper filter before acidifying them to 1% HNO_3, and (2) acidifying the samples to 1% HNO_3 first, allowing them to stabilise for three days, and then filtering them through a paper filter. Snow samples collected during 2017 and 2018 were analysed using both ICP-AES (Shimadzu Corporation, Japan) and ICP-OES spectrometers. In 2019, the analysis was exclusively conducted with ICP-OES. From 2020 to 2023, an 8900 Triple Quadrupole

Inductively Coupled Plasma Mass Spectrometer (ICP-MS) (Agilent Technologies, United States) spectrometer was employed to achieve high-resolution analysis. Additionally, Maritime Sunburst Lichen *(Xanthoria parietina)* samples underwent preparation for ICP-OES analysis, which involved drying and meticulously removing impurities such as bark and leaves.

Geographic Information Systems (GIS) provided essential capabilities for examining the spatial distribution and relationships of air pollution within urban settings. Using ArcGIS software (Environmental Systems…, 2025), the study mapped and analysed the spatial distribution of heavy metals in urban air. Spatial interpolation was performed with the inverse distance weighting technique, a built-in feature of ArcGIS. This method was selected due to its proven efficiency in analysing air quality data. Compared to alternative tools, inverse distance weighting was favoured for its simplicity and ability to produce reliable results without requiring complex data modelling or subjective assumptions. By employing this approach, the study successfully explored the spatial and temporal dynamics of heavy metal contamination, laying a foundation for targeted mitigation strategies and informed urban planning.

Results

Mechanisms of formation and factor structure of heavy metal distribution in the urban ecosystem of Jelgava

This subsection presents results from the descriptive statistical analysis of snow sample data, used to determine air pollution levels caused by heavy metals. In the Baltic States, urbanisation is accompanied by the development of a persistent technogenic background, with heavy metals serving as key indicators of anthropogenic pressure (Stankevica *et al*., 2021; Pilecka-Ulcugaceva *et al*., 2024a). Compact urban development and high traffic density contribute to the local accumulation of pollutants along major roads and in industrial zones. Bioindication using the lichen *Xanthoria parietina* and the analysis of snow samples confirm the predominance of transport-atmospheric pathways for the deposition of metals (Ni, Cu, Pb, Zn), as well as the correlation between road network configuration and accumulation zones (Pilecka-Ulcugaceva *et al*., 2024b). Bottom sediments and indoor dust in residential buildings indicate prolonged retention and secondary transfer of pollutants, linking external and internal environments. The consistency of signals across different media highlights the leading role of transport and heating during the cold season and confirms the effectiveness of a multi-matrix approach for a comprehensive assessment of technogenic pressure in the urban conditions of Jelgava (Niu *et al*., 2024).

In 2019, copper concentrations showed higher levels in samples No. 18 and No. 39, with 12.5 µg/L and 11.7 µg/L, respectively. These elevated levels were likely influenced by traffic, nearby residential developments, an adjacent rail line, and improper waste management practices. In particular, sample No. 18 highlighted significant contributions from anthropogenic activities. Most samples exhibited nickel concentrations below 0.6 µg/L, except for sample No. 2, which recorded a value of 4.4 µg/L. This anomaly was attributed to local heating practices using suboptimal fuels during winter and proximity to a high-traffic corridor.

Elevated lead concentrations were observed in sample No. 13 (11.1 µg/L) and sample No. 48 (72.3 µg/L). The high values in sample No. 48, approximately seven times greater than in other locations, were likely due to waste incineration in private residences and proximity to transportation hubs. Most vanadium concentrations were below 0.7 µg/L, with higher values near high-traffic zones and railways. Zinc concentrations exceeded 50 µg/L in samples No. 39 (53.7 µg/L), No. 46 (73.2 µg/L), and No. 48 (204.5 µg/L). The highest zinc concentrations were linked to traffic emissions and heating practices involving unsuitable fuels.

Data from 60 aluminium measurements (2018-2021) revealed significant annual variations. Average concentrations ranged from 0.08 µg/L in 2019 to 91.68 µg/L in 2020, with the highest maximum value of 1183.66 µg/L recorded in 2020. High aluminium levels were predominantly observed along major transport corridors such as Dobele Highway and Rīgas Street. The proximity to high-traffic roads played a significant role in aluminium distribution patterns. Between 2022 and 2023, tungsten concentrations ranged from 0.05 µg/L to 4.35 µg/L, with higher concentrations near transportation corridors. These findings align with trends observed in other urban studies, emphasising traffic intensity as a key driver of tungsten contamination.

Spatial analysis revealed that major streets and intersections in Jelgava were hotspots for heavy metal pollution, particularly in areas with high traffic and industrial activities. Elevated concentrations (10.9-12.5 µg/L) were detected in the city centre, particularly at the intersection of Lielā Street and Dambja Street. This is attributed to intensive traffic between Riga, Dobele, and Jelgava, and the presence of car repair shops and a gas station. Additional Cu hotspots (7.8-9.4 µg/L) were identified near Aviācijas Street, an area hosting one of Latvia's largest industrial parks. Increased concentrations in Jelgava's northwestern region correlated with logging activities and emissions from car workshops. High Pb levels were observed near Tērvetes Street and Satiksmes Street intersections, aligning with areas of frequent traffic jams. The highest Zn concentrations (153.2-204.3 µg/L) were measured in industrial zones, particularly near Aviācijas Street.

Over the study period (2018-2023), temporal fluctuations in heavy metal concentrations were evident: The highest average concentration (79.62 µg/L) was recorded in 2018, attributed to local fireworks and increased industrial activities. By 2023, Zn concentrations had declined significantly to an average of 8.88 µg/L. Annual variations were marked, with the highest concentrations (1183.66 µg/L) observed in 2020 along major transport corridors. Proximity to high-traffic areas consistently influenced Pb levels. Concentrations ranged from 0.05 µg/L to 4.35 µg/L (2018-2023), peaking near transport hubs, indicating traffic intensity as a significant contributor (Fig. 2).

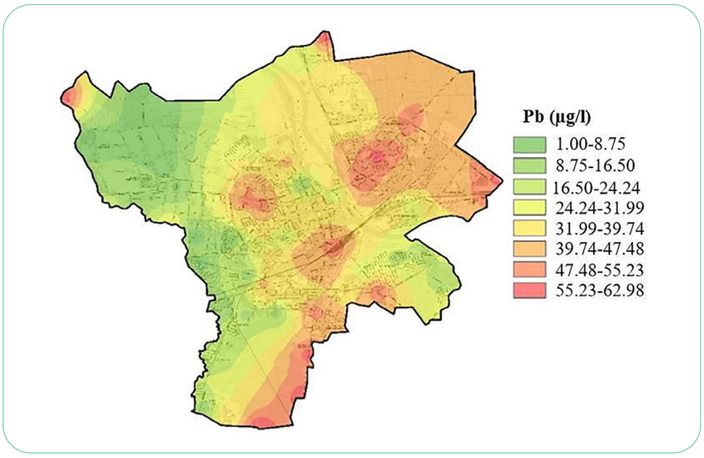

Figure 2. Spatial distribution of Lead (Pb) Concentrations in Jelgava, 2019
Source: created by the authors

These findings emphasise the need for both spatially targeted interventions (e.g., pollution mitigation in hotspots) and temporal monitoring to assess the effectiveness of policies and changes in urban activities. Analysis of the spatial distribution of heavy metals across various components of the urban environment revealed a distinct clustering of concentrations along transport corridors and near industrial zones. The distribution maps show "hotspots" of elevated Ni, Cu, Pb and Zn levels, corresponding to areas of high traffic intensity and older residential districts, where heating is primarily based on solid fuels. This spatial pattern confirms the local selectivity of pollution and indicates a combination of diffuse and point sources (Fig. 3).

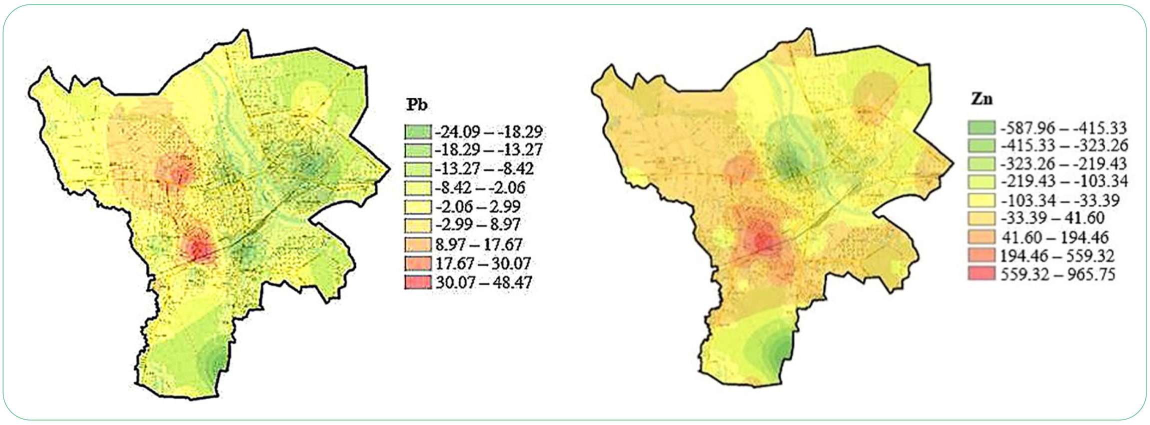

Figure 3. Spatial distribution of lead (Pb) and zinc (Zn) concentrations in the urban environment of Jelgava, 2018-2023
Source: created by the authors based on M. Stankevica *et al.* (2021), J. Pilecka-Ulcugaceva *et al.* (2024a)

Various methods are available for assessing long-term pollution, which can be categorised into chemical and biological approaches. Among the biological methods, the calculation of the Index of Atmospheric Purity (IAP) is widely used. Lichens are effective indicators for assessing areas impacted by sulfur dioxide, nitrogen oxides, and heavy metals. The accumulation of toxic elements in lichens correlates with proximity to pollution sources (Fedoniuk *et al.*, 2025). In Jelgava, the long-term air quality assessment also utilised the collection and analysis of the lichen *Xanthoria parietina*. This method complements chemical analysis techniques by examining pollutants in biological organisms and cells. Data from 125 sampling plots across Jelgava identified three pollution zones: high pollution (Group 1, IAP 0-110), moderate pollution (Group 2, IAP 111-200), and low pollution or clean air zones (Group 3, IAP > 200). High pollution zones in Jelgava in 2016 covered 1.66 km^2 (2.75% of the city's area), primarily in the city centre near wastewater treatment facilities, major road intersections, and an area adjacent to Langervaldes Forest. Moderate pollution zones accounted for 26.54 km^2 (44.0% of the city), with slight increases in area since 1996. Clean air zones covered 32.12 km^2 (53.25%), showing a significant portion of the city retained relatively low pollution levels.

Cartographic analysis identified a clear spatial concentration of heavy metals: peak Pb and Zn values coincide with densely built-up areas and zones with intensive traffic, while minimum values occur in green and peripheral districts.

This confirms the predominance of the transport-atmospheric pathway of pollution. Factor analysis (PCA/FA) identified two main sources: the transport-related source (Ni, Cu, Zn), associated with tyre and brake wear and engine emissions; and the heating-industrial source (Pb, Cd), characteristic of older housing areas and heating zones. An additional natural factor (Mn, Fe) reflects the mineral background. The consistency of distribution across different matrices (snow, lichens, bottom sediments) confirms the transit of metals from the atmosphere to the hydrosphere. Integrated indices (EF, CF, I_{geo}, PLI) showed elevated values for Ni and Cu along major roads and in industrial areas (EF > 10, CF > 6, I_{geo} = 2-3, PLI > 2), indicating a high level of technogenic risk (Pilecka-Ulcugaceva *et al.*, 2024a). Environmental hazard zoning of Jelgava identifies the following categories: high risk – transport and industrial areas; medium risk – central districts; low risk – green and suburban areas. This provides a basis for prioritising management measures such as vegetative barriers, road dust control and the restriction of solid fuel heating.

Complex dynamics and comparative analysis of heavy metal pollution in urban systems

The formation of heavy metal pollution in Jelgava represents a complex system of interconnected flows between the atmosphere, soil, water bodies and residential environments. The primary sources are emissions from vehicles and heating systems, which generate aerosols containing Ni, Cu, Zn and Pb. These particles settle on soil, vegetation and water surfaces, forming a persistent technogenic background. In winter, snow acts as a temporary depot, accumulating metals near traffic arteries; during melting, pollutants re-enter the hydrological system, intensifying secondary contamination. After deposition, metals undergo redistribution – dust is resuspended by wind and vehicle movement, returning to the atmosphere. A portion of the deposited elements enters bottom sediments via surface runoff, where they are either fixed in insoluble forms or bound to organic matter, forming a long-term reservoir of technogenic substances that can be remobilised under changing hydrochemical conditions (Glevitzky *et al.*, 2025). Thus, the migration system of metals functions as a closed technogenic cycle – emission, deposition, temporary accumulation, redistribution and remigration – which is typical of medium-industrialised cities in Northern Europe.

Within indoor environments, this cycle continues. Concentrations of Ni, Pb and Zn in indoor dust are comparable to outdoor levels, reflecting the infiltration of pollutants through ventilation systems, windows and dust particles brought in from outside. Ground floors and apartments facing major roads are particularly vulnerable, where metal concentrations exceed those in inner courtyards by 1.5-2 times (Guliyeva, 2023). Such penetration of outdoor dust creates a persistent hygienic risk, especially for children, as heavy metals are not metabolised and tend to bioaccumulate. Similar patterns have been reported in other European cities, indicating the universality of this transfer mechanism (Spriņģe *et al.*, 2024). For Baltic cities, including Jelgava, pollution is predominantly of the transport-atmospheric type with seasonal fluctuations: in winter, concentrations in snow samples almost double. This highlights the influence of climate and energy consumption structure on the chemical specificity of urban systems. Jelgava represents a typical example of a moderately developed Baltic city, where metal pollution follows general European trends but with pronounced regional and seasonal modulation (Jachimowicz *et al.*, 2025). Additionally, to assess Jelgava's position, Table 1 presents a comparative interpretation of heavy metal pollution indicators with data from other urbanised regions in Europe and worldwide.

Table 1. Comparison of heavy metal pollution indicators in Jelgava and other urbanised areas in Europe and worldwide

Country/region	Object of analysis	Main elements (mg/kg or equivalent)	Pollution level/ indices	Dominant sources	Characteristics
Jelgava, Latvia	Lichens, snow, bottom sediments, indoor dust	Ni: 20-60, Cu: 40-90, Pb: 30-70, Zn: 100-200	PLI = 1.5-2.2; I_{geo} = 1-3	Road transport, heating, dust formation	Medium-industrial pollution type; pronounced seasonality and spatial gradients
Riga, Latvia	Bottom sediments	Ni: 30-80, Cu: 70-130, Zn: 150-300	I_{geo} = 2-3	Transport, road runoff, urbanisation	Similar range to Jelgava; higher Cu and Zn levels due to population density
Kaunas, Lithuania	Wastewater sludge	Ni: 25-75, Cu: 60-110, Pb: 35-80, Zn: 150-250	PLI = 2-2.5	Municipal effluents, transport	Comparable to the Jelgava; accumulation in sludge confirms a persistent technogenic background
Berlin, Germany	Soils and road dust	Ni: 40-90, Cu: 80-180, Pb: 100-250, Zn: 250-400	PLI = 2.5-3	Transport, heating, historical industrialisation	Higher technogenic background; high persistence of soil contamination
Delhi, India	Road dust	Ni: 100-200, Cu: 200-400, Pb: 300-600, Zn: 500-1000	PLI = 4-5.5	Intense traffic, industrial emissions	Very high pollution levels; dominance of Pb and Zn due to industrial and traffic emissions

Table 1. Continued

Country/region	Object of analysis	Main elements (mg/kg or equivalent)	Pollution level/ indices	Dominant sources	Characteristics
Paris, France	Soils and atmospheric deposition	Ni: 40-80, Cu: 70-160, Pb: 120-240, Zn: 200-380	PLI = 2.2-2.8	Transport, historical urban layer	Similar levels to Jelgava; within the European range of moderate pollution
Shanghai, China	Soils and roadside sediments	Ni: 60-130, Cu: 150-280, Pb: 200-350, Zn: 400-700	PLI = 3.5-4.5	Industry, urbanisation, road transport	More pronounced industrial influence; high deposition of heavy metals

Source: created by the authors based on S. Roy *et al.* (2022), J. Pilecka-Ulcugaceva *et al.* (2024a), J. Pilecka-Ulcugaceva *et al.* (2024b), G. Spriņģe *et al.* (2024), H. Liu *et al.* (2025), P. Jachimowicz *et al.* (2025)

For cities in Northern Europe, a stable pollution pattern dominated by transport and heating emissions is typical, which is also confirmed for Jelgava. The concentrations of Ni (20-60 mg/kg), Cu (40-90 mg/kg) and Zn (100-200 mg/kg) fall within the range's characteristic of moderately urbanised regions of the Baltic zone. Unlike industrial agglomerations in East and South Asia, where Pb and Zn levels exceed European values by four to six times, Jelgava demonstrates a controlled anthropogenic load (PLI = 1.5-2.2; I_{geo} = 1-3) and pronounced spatial mosaic pollution, where concentrations decrease sharply at a distance of only 100-200 metres from emission sources. Seasonal modulation of pollution, with higher Ni and Cu levels in winter and stabilisation in summer, reflects climatic regulation of the chemical state of the environment. Jelgava may be classified as a moderately polluted urban system, where anthropogenic processes are counterbalanced by natural mechanisms of dispersion and self-purification. Consequently, in a global context, Jelgava can be regarded as a representative example of a post-industrial city in temperate latitudes, where the ecological state is determined not by the scale of emissions but by the balance between anthropogenic activity, climatic factors and self-regulating mechanisms of urban ecosystems. It occupies a stable position between cleaner Northern European models and overloaded Asian urban systems, reflecting a transition from industrial ecology to sustainable urban functioning.

Discussion

The results of the study demonstrated that transport is the primary source of heavy metal accumulation, particularly Ni, Cu, Pb and Zn. Maximum concentrations were recorded along major roads and at transport hubs, gradually decreasing with distance into residential blocks. This spatial selectivity confirms the predominance of the atmospheric pathway for particle transport, generated through tyre and brake wear and exhaust emissions. This aligns with the findings of A. Vijayan *et al.* (2024), who treated snow as a seasonal integrator of transport-related pollution. They observed identical distribution patterns in the snow cover: a sharp concentration gradient from roadways to inner areas, with Ni, Cu and Zn prevailing in regions with high traffic intensity. The consistency of Latvian and global data indicates the universality of the transport-atmospheric mechanism in urban systems and confirms that, even under differing climatic conditions, transport remains the dominant factor in shaping the technogenic background.

In the study by M.L. Messager *et al.* (2021), an innovative approach to monitoring heavy metals in urban areas was proposed, combining low-cost bioindication methods with spatial modelling. The authors integrated data on Cu, Zn, Ni and Pb concentrations from multiple media (vegetation, dust and soil) to create highly detailed pollution distribution maps. Their model showed that spatial anomalies in metal concentrations closely correlate with the configuration of the road network and building density, with transport zones serving as the primary accumulation hotspots. These results are consistent with the present study – a similar multi-matrix approach (lichens, snow, bottom sediments, indoor dust) revealed the same spatial coherence of pollution. Traffic intensity and the compactness of urban development determine the structure of the technogenic background and serve as the primary factors in heavy metal accumulation, confirming the universality of integrated bioindication methods for assessing urban pollution flows (Ilderbayeva *et al.*, 2024).

The study also showed that bottom sediments in small urban watercourses function as long-term reservoirs of technogenic metals. Elevated concentrations of Ni, Cu, Pb and Zn are recorded, reflecting both atmospheric deposition and input via surface runoff. Sediments accumulate metals over multiple seasons, creating a persistent geochemical signature and exhibiting signs of phytotoxicity (Kozyatnyk *et al.*, 2014; 2015). Similar patterns were reported by L. Fu *et al.* (2023), who analysed bottom sediments of urban rivers in China: they identified comparable Ni, Cu, Pb and Zn profiles, noted the spatial selectivity of metal accumulation, and described the role of microorganisms and resistance genes in metal redistribution. This confirms the universality of sediments as long-term pollution reservoirs and emphasises the need to account for the biogeochemical activity of sediment microbiota when assessing environmental risks in urban catchments.

The study by M. Taka *et al.* (2022) revealed pronounced spatio-temporal patterns in the distribution of copper, zinc, nickel and lead in surface runoff from urban areas in Finland. The highest metal loads were observed during the winter and spring periods, which directly aligns with the findings of the present study – winter accumulation of metals in the snow cover and their subsequent release into the hydrological system during melting. The authors confirmed the existence of a closed technogenic cycle, "atmospheric deposition – surface runoff – bottom sediments – remobilisation", similar to the processes established for Jelgava, indicating that this mechanism is typical of the Northern European model of urban pollution.

In the current study, it was established that in Jelgava's urbanised system, heavy metals circulate between the atmosphere, snow cover, surface runoff and indoor dust, forming a closed technogenic cycle with seasonal accumulation and secondary contamination. Concentrations of Ni, Cu, Pb and Zn demonstrate a stable interconnection between external and internal environments, indicating infiltration of outdoor pollutants into residential spaces and the maintenance of a persistent technogenic dust background (Kavaldzhieva, 2022; Tastemir *et al*., 2025). These patterns are consistent with the results of H. Chu *et al*. (2023), which showed a close correlation between indoor and outdoor pollution driven by transport and heating sources, as well as C. Li *et al*. (2024), who confirmed the dominance of the same elements (Cu, Zn, Ni) in urban soils and their association with transport- and energy-related emissions. This supports the universality of the closed technogenic cycle model identified for Jelgava, characteristic of moderately industrialised cities.

The study by A.J. Adewumi & O.D. Ogundele (2024) reviewed over two hundred studies on heavy metal contamination in urban soils across different regions of the world. The authors systematised the concentration ranges of Ni, Cu, Pb, Zn and Cd and established that transport, industry and solid-fuel heating are the primary global sources of technogenic load. For quantitative assessment of pollution, integrated indices such as EF, CF, I_{geo} and PLI were applied, allowing the determination of ecological risk levels and the identification of priority impact zones. This was confirmed by the results of the present study, both methodologically and substantively: the same indices were used to differentiate pollution levels and rank ecological risk. In the Latvian data, EF values greater than 10 and PLI values above 2, comparable to the ranges reported in the authors' meta-analysis, indicate a similar level of technogenic impact, demonstrating the universality of index-based methods for assessing anthropogenic pressure in urban areas.

The study in Jelgava identified two main sources of heavy metal pollution: transport and heatingindustrial. The first is characterised by high loads of Ni, Cu and Zn and spatial concentration along major roads, while the second is associated with elevated Pb and Cd levels, linked to fuel combustion and emissions from small heating plants. This factor structure demonstrates the multigenic nature of urban pollution and highlights the seasonal intensification of anthropogenic load during the cold period. This aligns with the study by M. Vashist *et al*. (2025), which confirmed the same pattern at a global scale: urban trees were used as bioindicators of metal accumulation, and statistical analysis similarly identified two principal factors – transport and heating-fuel sources. The authors noted that transport contributes dominantly to the variation in Cu, Zn and Ni concentrations, whereas Pb and Cd reflect an additional heating-related background. This indicates the global reproducibility of pollution source distribution patterns and confirms the applicability of bioindication for their identification in urban environments.

The study by V.-S. Gkoltsou *et al*. (2025) highlights two interconnected levels of urban pollution – external and internal environments. Concentrations of Ni, Cu, Pb and Zn decrease with distance from major roads, and the pollution index values correspond to the ranges observed in Jelgava in the present study, indicating a similar level of anthropogenic load. The research of S.S. Sabegh *et al*. (2023) complements these findings, showing that lead, zinc and nickel from the external environment infiltrate indoor spaces, producing comparable concentrations in household dust. Both studies, despite climatic differences, support the model identified for Jelgava of a technogenic cycle linking external pollution to the indoor environment through mechanisms of dust infiltration and seasonal accumulation. This demonstrates that heavy metals circulate between external and internal environments, confirming the closed technogenic cycle identified in Jelgava. Thus, Jelgava represents a typical example of a temperate-latitude city where anthropogenic processes form a closed cycle of pollutant transfer between the atmosphere, surfaces and the indoor environment. The patterns of heavy metal migration observed in Jelgava align with international data and reflect the universal transport-heating type of urban pollution.

Conclusions

This research highlights the fragmented nature of global studies on heavy metals and PM in urban air pollution. While existing research often focuses on specific pollution types, it fails to address the complexities of urban environments as dynamic, multi-source pollution systems. This underscores the importance of integrated and comprehensive studies like the one conducted in Jelgava. In Jelgava, a robust monitoring network was developed to assess both long-term and short-term air pollution dynamics. This network, comprising 60 sampling plots and spanning from 2018 to 2024, generated a valuable database of chemical element concentrations in snow. The spatial and temporal coverage of this network provides a detailed understanding of pollution patterns and sources.

The study revealed significant variability in heavy metal concentrations across the city, with zinc (Zn) ranging from 0.007 to 1,002.1 μg/L, copper (Cu) from 0 to 829.50 μg/L, nickel (Ni) from 0.0005 to 40.40 μg/L, lead (Pb) from 0.7 to 62.97 μg/L, manganese (Mn) from 5.9 to 1,357.0 μg/L, and aluminium from 0.01 to 1,183.66 μg/L. Transport corridors were identified as major contributors to spatial pollution patterns, highlighting the critical role of traffic in urban air quality challenges. The integration of statistical methods with GIS-based spatial analysis proved effective in identifying pollution sources. The Kruskal-Wallis test confirmed significant differences in heavy metal concentrations across distance groups ($p < 0.0001$). This methodological framework provides a replicable approach for urban air pollution assessments globally.

Future phases, involving health impact assessments, are recommended for further interdisciplinary research. Additionally, addressing high chemical concentrations remains a complex challenge due to the multitude of point and diffuse pollution sources influenced by urban structure, as well as global and local climatic factors. Continued research is vital for advancing sustainable urban development and mitigating air pollution impacts. These results are consistent with Northern European data, confirming the transport-atmospheric mechanism of metal transfer and the stable balance of technogenic and natural processes in Jelgava's urban environment. Future phases, involving health impact assessments, are recommended for further interdisciplinary research. Additionally, addressing high chemical concentrations remains a complex challenge due to the multitude of point and diffuse pollution sources influenced by urban structure, as well as global and local climatic factors. Continued research is vital for advancing sustainable urban development and mitigating air pollution impacts.

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Комплексна оцінка забруднення важкими металами в міських середовищах: приклад міста Єлгава, Латвія

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Анотація. Якість повітря в міських умовах стала критичною глобальною проблемою і очікується, що темпи урбанізації будуть продовжувати зростати. Мета цього дослідження полягала в тому, щоб на теоретичній основі визначити закономірності формування техногенного фону та просторову структуру забруднення в міському середовищі Єлгави. Методологія базувалася на систематичному та статистичному аналізі для оцінки джерел та рівнів забруднення в місті. Тривалість дослідження, від початку збору даних до завершення аналізу, охоплювало період з 2017 по 2023 рік, протягом якого щорічно проводилась вибірка та всебічний моніторинг. Концентрації важких металів у різних компонентах міської екосистеми Єлгави були в межах таких діапазонів: Ni – 20-60 мг/кг, Cu – 40-90 мг/кг, Pb – 30-70 мг/кг, Zn – 100-200 мг/кг. Ці значення відповідають помірним рівням забруднення, типовим для урбанізованих територій Північної та Центральної Європи. Найвищі концентрації були зафіксовані поблизу основних доріг та промислових зон, тоді як периферійні райони були близькими до фонових значень. Було встановлено, що інтегровані показники якості навколишнього середовища (індекс забруднення = 1,5-2,2, індекс геоакумуляції = 1-3) характеризують Єлгаву як помірно забруднену територію, яка при цьому зберігає загальну екологічну стабільність. Факторний аналіз показав, що структура забруднення формується двома основними джерелами: викидами, пов'язаними з транспортом (Ni, Cu, Zn – знос шин і гальм, вихлопи дизельних двигунів) та викидами від опалення та промисловості (Pb, Cd – спалювання палива та місцеві викиди від малих підприємств). Єлгаву можна класифікувати як помірно забруднену, але стійку міську систему, де антропогенний тиск врівноважується природними механізмами самоочищення. Практична цінність дослідження полягає в тому, що його результати можуть бути використані муніципальними органами з питань охорони навколишнього середовища та планування для оцінки ризиків та управління якістю міського середовища

Ключові слова: міська екосистема; техногенний тиск; просторові градієнти; атмосферно-сезонна динаміка; екологічна стійкість

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Hydrochemical regime of rivers in the Borzhava River basin

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Abstract. The aim of the study was to analyse the hydrochemical parameters of surface water quality in the Borzhava River basin in Zakarpattia Region. Based on the collected data, a detailed analysis of the hydrochemical indicators of water quality in the Bozhava, Irshava, Salva and other rivers was carried out. This study was preceded by a detailed analysis of the natural conditions of the Borzhava catchment area and anthropogenic factors affecting the physical and chemical parameters, main ions and mineralisation of water, content of biogenic substances, heavy metals and specific pollutants. The ratio of calculated hydrochemical concentrations to maximum permissible concentrations for water used in fisheries was considered. The content of dissolved oxygen was found to be below the maximum permissible concentration, while the content of ammonium, phosphate, total iron, manganese, copper and zinc exceeded the normative values. The role of natural conditions in the formation of the chemical composition of surface waters in the Borzhava River basin was studied: the hydrological regime of waters, changes in water sources, the geological structure of the catchment area, and the main sources of anthropogenic impact along the river course were identified – unauthorised landfills, systematic discharges of domestic wastewater, insufficient treatment of municipal wastewater, agricultural development of floodplains and coastal lands, application of fertilisers during the farming season, and slowing of the flow in the canal system in the lower reaches of the Borzhava River, the Salva River, and the Balva Canal.

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It has been determined that the waters of the upper Borzhava River are hydrocarbonate calcium, moderately fresh with average mineralisation and clear seasonal variability. The results obtained are of significant practical importance and can be used in the preparation of the Tisza River Basin Management Plan, in the justification and implementation of environmental control measures for economic entities in the upper reaches of the Tisza, as well as in the development and implementation of environmental programmes aimed at improving water quality in the river basin

Keywords: anthropogenic load; water mineralisation; biogenic substances; seasonal variability; environmental planning

Introduction

Changes in river water quality can occur as a result of various types of anthropogenic intervention: industry, municipal services, agriculture, land reclamation, fishing, recreation, forestry, etc. Being closely linked to the catchment area, the surface water bodies of the Borzhava River reflect the ecological state of the entire geosystem. Thus, determining the physical, chemical and chemical indicators of river water and studying their seasonal and long-term dynamics will allow to identify the factors that shape and influence water quality within individual sections of the river. One of the largest tributaries of the Tisza River in the Zakarpattia Region, the Borzhava River, is of great importance. The Borzhava River basin is of great ecological, economic, tourist and recreational importance. Natural conditions and anthropogenic influences within this territory determine the main features of the chemical composition of water in the basin, particularly in its lower reaches.

V. Strokal (2021) analysed the problems of pollution of Ukraine's transboundary rivers and outlined five prospects for sustainable development to achieve SDG 6. The proposed approaches were aimed at integrating EU water legislation and forming an effective water management policy. Z. Odnorih *et al.* (2020) examined the organisation of environmental monitoring of surface waters with a view to bringing them closer to European standards, analysed water sample data from 2018 in the Western Bug basin, and outlined ways to improve environmental water management. A study by P.S. Lozovitsky (2025) found that despite significant financial expenditure on water protection in Ukraine, the environmental condition of water resources remains critical. The identified imbalance between the volume of investments and actual results indicates the inefficiency of existing management mechanisms. This highlights the need to transition to an integrated water management model that combines economic instruments with environmental priorities and a transparent assessment of the impact of environmental protection measures.

The article by M. Vovkunovych *et al.* (2024) presents a geoinformation analysis of the hydrographic network of the Borzhava River basin, which identified more than 3,000 km of watercourses of various types, including permanent, temporary, canals and reclamation areas. The structure of permanent watercourses has been established, allowing for the assessment of the internal organisation of the river system, the identification of areas of erosion and flooding, and the creation of a cartographic basis for environmental monitoring and risk management. O.I. Symkanych *et al.* (2024) presented the results of mapping the spatial and seasonal distribution of natural (^{40}K, ^{238}U, ^{232}Th) and technogenic (^{137}Cs) gamma-active nuclides in the bottom sediments of the Borzhava River, which made it possible to identify areas of their accumulation and migration depending on the season. The data obtained are of practical importance for forecasting the ecological state of the territory, developing regulatory and legal acts, and managing radiation safety in mountainous regions.

Scientists L.Yu. Roman & S.Yu. Chundak (2019) carried out background monitoring of the ecological state of surface waters of the Bronka and Synyavka rivers. The aim of the study by L.Yu. Roman & S.Yu. Chundak was to identify or refute the dynamics of changes in the water quality of the Synyavka and Bronka rivers due to anthropogenic impact, which, according to the results of the study, was determined to be insignificant and legitimate. The work of V. Leta & M. Karabiniuk (2025) revealed a decrease in water intake and discharge in the Borzhava River basin in 2010-2023 and established the impact of anthropogenic factors (agriculture, lack of sewage systems, industrial discharges) on water quality. A set of measures to optimise water use and reduce environmental impact was proposed. At the same time, there is no systematic analysis of hydrochemical indicators of water quality that would provide a spatial-temporal distribution in the Borzhava River basin. Thus, the aim of this study was to conduct a comprehensive analysis of the hydrochemical regime of surface waters in the Borzhava River basin, taking into account the natural features of the territory and the impact of economic activity.

Materials and Methods

The analysis of the hydrological regime of waters and a brief hydrographic description are based on data from the Central Geophysical Observatory Named After Boris Sreznevsky (n.d.). To study the chemical composition of surface waters in the Borzhava River basin, monitoring data from four monitoring stations operated by the Tisza River Basin Water Resources Management Authority were used: Borzhava River – Velyki Komyaty Village, Borzhava River – Bene Village, Irshava River – Loza Village, Salva River – Bukove Village, as well as data from hydrochemical surveys conducted by the authors in September 2024 at 23 points (Table 1). Publicly available hydrochemical data from the Tisza River Basin Water Resources Management

Authority for a period of many years (2007-2023), as well as the results of own field studies, the correlation of which was ensured by comparing a set of water quality assessment parameters and conducting hydrochemical surveys after coordination with the Tisza River Basin Water Resources Management (n.d.) surface water monitoring programme.

Table 1. List of water sampling locations

No.	Sampling location	Geographical coordinates
1	Borzhava River – Koretsky Village	48°28’23” N; 23°13’34” E
2	Prokhidnyi Stream – Koretsky Village	48°28’20.7” N; 23°13’28.1” E
3	Borzhava River – upstream of Bereznyky Village	48°27’58.7” N; 23°13’55.8 E
4	Kushnytsia River – mouth	48°26’14” N; 23°15’14.1” E
5	Bronka River – mouth	48°24’30.1” N; 23°16’05.5” E
6	Borzhava River – downstream of Bronka Village	48°23’25.5” N; 23°17’27.1” E
7	Borzhava River – downstream of Dovhe Village	48°21’21.4” N; 23°16’24.6” E
8	Borzhava River – Lukove Village	48°19’26.5” N; 23°11’57.2” E
9	Kryvulia River – Zahattia Village	48°22’15.5” N; 22°58’32.6” E
10	Irshava River – Zahattia Village	48°22’21.7” N; 22°58’35.5” E
11	Irshava River – Dovzhnytsia Village	48°22’14.3” N; 22°59’02.1” E
12	Ilnytsia River – mouth	48°19’32.2” N;23°02’17.4” E
13	Synyavka River – mouth	48°19’32.2” N; 23°02’17.4” E
14	Borzhava River – Velyki Komyaty Village	48°14’44.1” N; 22°54’48” E
15	Irshava River – Kamyanske Village	48°15’20.5” N; 22°55’46.8” E
16	Borzhava River – Nyzhni Remety Village	48°15’04.3” N; 22°49’52.2” E
17	Borzhava River – Kvasovo Village	48°11’21.4” N; 22°46’34.9” E
18	Borzhava River – downstream of Velyka Roztoka Village	48°16’49.1” N; 29°03’58.6” E
19	Borzhava River – upstream of Velyki Komyaty Village	48°14’45.7” N22°59’35.2” E
20	Borzhava River – Nyzhni Remety Village	48°15’04.4” N; 22°49’48.3” E
21	Balva Canal	48°11’31.7” N; 22°57’12.9” E
22	Salva River – downstream of Balva Canal	48°11’32.7” N; 22°57’11.9” E
23	Salva River – mouth	48°11’09.2” N; 22°47’41.1” E

Source: compiled by the authors based on materials from Tisza River Basin Water Resources Management (n.d.)

The chemical composition of surface waters in the Borzhava River basin was analysed according to the following groups of components: physical and chemical indicators (suspended solids, pH, dissolved oxygen content, permanganate oxidisability (PO), chemical oxygen demand (COD) and BOD_5); main ions (HCO_3^-, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-) and water mineralisation (dry residue); nitrogen compounds (NH_4^+); heavy metals (Cu, Cr, Zn); specific pollutants (anionic surfactants – AS). The quality of surface waters in the upper reaches of the Tisza River was assessed according to hygienic standards for water quality in water bodies for drinking, domestic and other needs of the population, as well as requirements for fishery water bodies – maximum permissible concentrations (Order of the Ministry of Agrarian Policy of Ukraine No. 471, 2012; Order of the Ministry of Health of Ukraine No. 721, 2022).

The analysis of hydrochemical parameters was carried out in a logical sequence of actions: identification of maximum values of indicators; comparison of indicators with each other; comparison of indicators in the context of spatial and temporal variability; comparison of the results obtained with the MPC regulatory indicators; comparison of measurement results with retrospective data. Water sampling during the field stage of the study was carried out in compliance with regulatory documents, in particular DSTU ISO 5667-6:2009 (2009) and DSTU EN ISO 5667-6:2022 (2022) and the principles of representativeness, isokinetics, stratification, and traceability. The programming of surface water sampling in the Borzhava River basin included the definition of objectives (water quality control, assessment of anthropogenic impact, identification and study of trends), and the selection of sampling sites and points was carried out taking into account hydrography, accessibility, safety and mixing of flows, and the availability of an existing network of water monitoring points (Tisza River Basin…, n.d.).

During sampling, sampling devices with a rope and rod were used, as well as special containers equipped with mechanisms for opening at a specified depth and refrigeration equipment. The samples were stabilised in accordance with DSTU EN ISO 5667-3:2022 (2022), taking into account the characteristics of the components under study (dissolved gases, metals, organic substances). The samples were stored at a temperature of 1-5 °C and transported in conditions that prevented any change in their composition (no light, airtightness, cooling), and all actions were recorded in the relevant protocols. Chemical analysis of the selected water samples was carried out at the Uzhhorod Border State Control and Toxicology Laboratory (n.d.) using the following methods: spectrometric, photometric, titration, thin-layer chromatography in accordance with DSTU ISO 6332:2003 (2003), DSTU 7260:2012 (2012), DSTU 7811:2015 (2015), and DSTU ISO 18412:2017 (2017).

The results of spatial analysis were visualised using a graphical method of data representation in the form of bar charts with the help of the ArcGIS 10.8.2 software package. This method allowed for a clear comparison of quantitative indicators along the course of the studied rivers of the Borzhava basin, while maintaining spatial reference.

Results

The Borzhava River flows within the modern Khust and Berehove districts of Zakarpattia Region, covering territories that previously belonged to the Svaliava, Irshava, Vynohradiv, and Berehove districts. It is a right tributary of the Tisza and is part of the Danube drainage basin. The total length of the Borzhava is 106 km, and the area of its basin is 1,360 km^2. The source of the river is located on the slopes of Mount Stiy, which is part of the Borzhava mountain range. In its upper reaches, the Borzhava is mountainous, with a V-shaped valley ranging from 40 to 900 m in width. Further on, the river crosses the Zakarpattia lowlands. Its course is characterised by considerable sinuosity, with numerous islands and oxbow lakes in the floodplain. The width of the riverbed varies from 0.6 to 53 m, and the average slope is 13 m/km. The main tributaries of the river are the Irshava (right) and Salva (left). The hydrological regime of the Borzhava is determined by frequent floods, which provide approximately 70% of the annual runoff from March to August. Summer-autumn and winter low water levels are unstable, and flooding is possible in spring. The average water flow is 10 m^3/s, and its turbidity varies from 50 to 500 g/m^3 according to data from the Zakarpattia Regional Centre for Hydrometeorology (n.d.).

The long-term dynamics and seasonal variability of the chemical composition of river waters in the Borzhava basin have been analysed in detail, and regime characteristics have been identified for individual parameters. The hydrochemical analysis of water covered a number of parameters, among which physicochemical parameters, in particular the content of suspended solids, are of key importance. Suspended solids include sand, clay, iron hydroxides, as well as organic components: silt, microorganisms, petroleum products. In the Borzhava River basin, an increase in the concentration of suspended solids downstream from 0.58 to 29.58 mg/dm^3 was recorded, which is associated with active agriculture and increased organic content in the water. At the same time, the level of suspended solids in the upper reaches of the river also reaches 29.58 mg/dm^3, but this is due to natural processes. The concentration of suspended solids correlates with water transparency, which indicates the influence of erosion processes in the upper part of the basin and anthropogenic load in the lower part.

Among the hydrochemical indicators important for assessing the state of the environment of hydrobionts, the pH level is key. In all the rivers studied, there are slight seasonal fluctuations caused by changes in food sources, soil type and, to some extent, economic impact (Fig. 1). Summer and autumn floods contribute to water alkalisation and an increase in pH. The lowest values were recorded in the Borzhava River (6.8 units in the Velyki Komyaty Village, Bene Village) and the Salva River (6.7 units in the Bukove Village), which are close to the lower limit of the MPC for fishery waters.

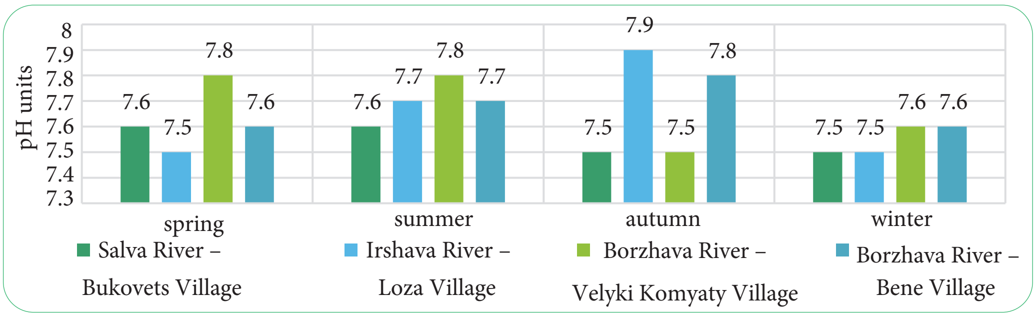

Figure 1. Seasonal fluctuations in average annual pH values
Source: compiled by the authors based on materials from Tisza River Basin Water Resources Management (n.d.)

The dissolved oxygen (O_2) content is a key indicator of water quality, as it ensures the mineralisation of organic matter in surface waters. Its level has clear seasonal fluctuations, with minimum values in the summer-autumn period. In the Borzhava basin, the average long-term seasonal values range from 7.8 to 12.2 mg/dm^3. At the same time, a decrease was recorded in Salva and the Balva Canal: in September 2021 – 5.5 mg/dm^3 (Salva), in September 2024 – 5.91 mg/dm^3 (Balva) and 3.76 mg/dm^3 (Salva mouth). This indicates water pollution and an excess of organic substances, which is environmentally hazardous at low flow rates.

A comparison of the monitoring data with the MPC of 5 mg/dm^3 revealed that the PO levels were exceeded. In particular, in September 2024, a value of 9.67 mg/dm^3 was recorded in the waters of the Salva River (mouth) and 6.7 mg/dm^3 in the Balva Canal, indicating a significant presence of hard-to-oxidise organic substances and pollutants that can accumulate in the aquatic environment downstream (Fig. 2). At the same time, the average long-term PO indicators in the waters of the Borzhava River (control point in the Bene Village) show insignificant fluctuations within the range of 2.7-2.9 mg/dm^3, which do not exceed the established MPC.

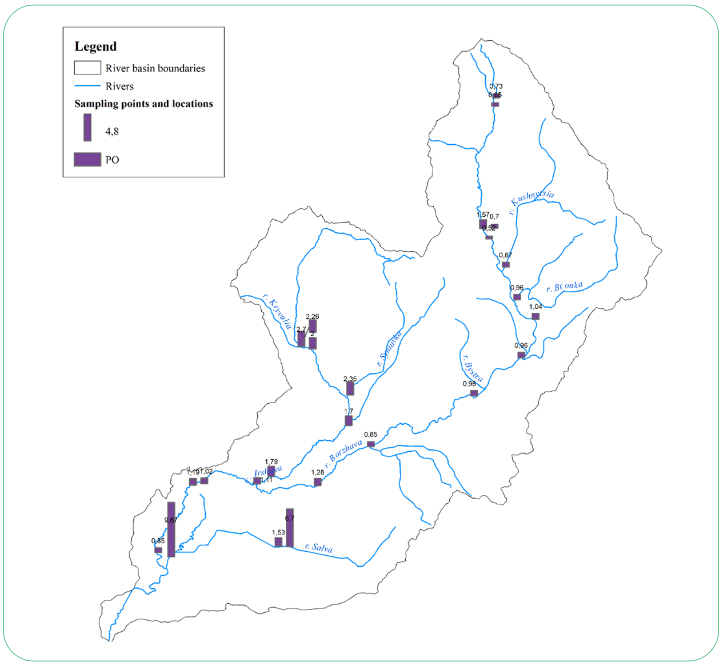

Figure 2. Cartogram of spatial distribution of PO indicators, mg/dm^3
Source: compiled by the authors based on field research materials

In most cases, the average long-term COD values of the analysed water samples from the Borzhava River basin do not exceed the MPC set at 15 mgO/dm^3. The exception is the Salva River, where, according to the diagrams below, consistently high COD values with pronounced seasonal variability are observed, confirming the previously recorded pollution. In particular, during the summer-autumn low water period, the average multi-year values are 17.5 and 22.4 mgO/dm^3. Similar concentrations were recorded during autumn sampling in 2024. In the lower reaches of both the Borzhava itself and its tributaries, the COD level rises to 9.88 mgO/dm^3. Spatial analysis of BOD in the Borzhava River basin indicates a link between the indicators and natural conditions in the upper reaches of the river and anthropogenic factors in the lower reaches of the Borzhava and Salva rivers.

Analysis of multi-year monitoring data from Tisza River Basin Water Resources Management (n.d.) indicates seasonal variability in BOD_5 values, with increases during the summer-autumn and winter low-water periods (Table 2). Seasonal fluctuations are due to higher concentrations of organic matter in the summer-autumn period due to reduced water consumption, slower flow (less turbulent movement – less oxygen), the inflow of organic matter from agricultural land (manure, fertilisers, plant residues) and its accumulation in the lower reaches. Temperature fluctuations in winter lead to a decrease in the biological activity of aquatic organisms that decompose organic matter, a slowdown in self-purification rates, and limited aeration due to ice cover.

Water mineralisation was analysed based on dry residue content. Water mineralisation is one of the key indicators for assessing the hydroecological status of water bodies. Spatial analysis shows an increase in water mineralisation downstream, indicating a growing anthropogenic impact on surface waters and, consequently, a load on the ecological environment (Fig. 3).

Table 2. Average multi-year seasonal values of BOD_5

Monitoring point	Season	Values, mgO/dm^3
Borzhava River – Velyki Komyaty Village	spring	0.9
	summer	1.5
	autumn	1.2
	winter	2.2
Borzhava River – Bene Village	spring	1.9
	summer	2.5
	autumn	2.5
	winter	1.9
Salva River – Bukove Village	spring	1.2
	summer	2.6
	autumn	2.2
	winter	2.8

Table 2. Continued

Monitoring point	Season	Values, mgO/dm^3
Irshava River – Loza Village	spring	0.9
	summer	2.4
	autumn	2
	winter	1.5

Source: compiled by the authors based on materials from Tisza River Basin Water Resources Management (n.d.)

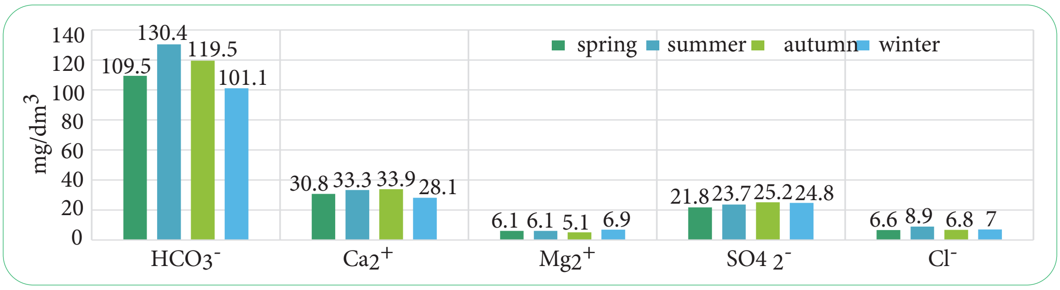

Figure 3. Seasonal fluctuations in the multi-year average values of major ion content (Borzhava River – Bene Village)
Source: compiled by the authors based on materials from Tisza River Basin Water Resources Management (n.d.)

The presence of biogenic substances in surface waters is caused by biological processes such as the metabolism of aquatic organisms, the decomposition of organic matter, and inputs from agricultural land and wastewater. Analysis of ammonium in the waters of the Borzhava basin showed seasonal variability with peak concentrations in summer (Fig. 4). The average long-term values were 0.4 mg/dm^3 (Salva River – Bukovets Village) and 0.47 mg/dm^3 (Borzhava River – Velyki Komyaty Village). During the summer-autumn low water period, concentrations approached the fishery MPC due to anthropogenic influences: farms, manure storage facilities, wastewater and recreational facilities. Exceedances of the MPC were recorded: on the Borzhava River – Velyki Komyaty Village – from 0.84 to 2.53 mg/dm^3, on the Salva River – Bukovets Village – 0.58-0.65 mg/dm^3. The data obtained during the field stage of the study indicate a growing anthropogenic impact downstream of the Borzhava and Salva rivers due to the expansion of the network of settlements, as well as an increase in the volume of wastewater and irrigation systems.

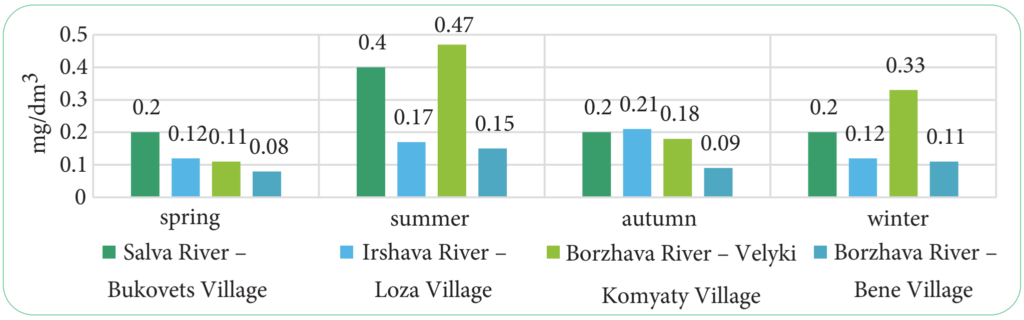

Figure 4. Seasonal fluctuations in average annual ammonium content
Source: compiled by the authors based on materials from Tisza River Basin Water Resources Management (n.d.)

During the same observation period, the nitrate content reached 8.3 mg/dm^3 in 2010 on the Borzhava River in the Bene Village. Of particular interest from the perspective of assessing anthropogenic pressures are the nitrate levels recorded in the Prokhidnyi Stream in the Keretsky Village. Although the values did not exceed the maximum permissible concentration for fisheries waters, the concentration reached 6.02 mg/dm^3. Phosphates (PO_4^{3-}) serve as an indicator of the intensity of biological activity in aquatic ecosystems. For fishery waters, the MPC for phosphates in surface waters is 0.17 mg/dm^3. Long-term monitoring data indicate a single exceedance of the MPC in the Borzhava River – Velyki Komyaty Village in December 2021 at a level of 0.37 mg/dm^3. Analysis of the results of field sampling indicates that the phosphate content is high in the waters of the Borzhava River above the Bereznyky Village (0.26 mg/dm^3), the Kushnytsia River at its mouth (0.26 mg/dm^3), the Bronka River – at the mouth (0.22 mg/dm^3) and the Borzhava River – below the Bronka Village (0.28 mg/dm^3), the Borzhava River – below the Dovhe Village (0.19 mg/dm^3), Borzhava River – Lukova Village (0.2 mg/dm^3), Kryvulia River – Zahattia Village (0.24 mg/dm^3) and Salva River – mouth (0.23 mg/dm^3).

Iron is usually present in both groundwater and surface water. Its content is determined by the geological features of the territory, the hydrological conditions of water bodies and the level of anthropogenic impact, in particular pollution by wastewater. The chronological series of monitoring the total iron content in the waters of the Borzhava basin rivers is limited to the period 2007-2018 according to data from a single point on the Borzhava River – Bene Village. Considering that this is the final monitoring point in the river basin, its data can be indicative for the entire Borzhava River. The MPC for fisheries is 0.05 mg/dm^3, and the MPC for domestic and drinking water is 0.3 mg/dm^3. The absolute values of iron content in the waters of the Borzhava range from 0.12 mg/dm^3 to 1.05 mg/dm^3, which significantly exceeds environmental standards. It has been recorded that the average long-term values for the study period are quite high and reflect dependence on natural conditions, in particular changes in water sources during the summer-autumn and winter low-water periods (Fig. 5).

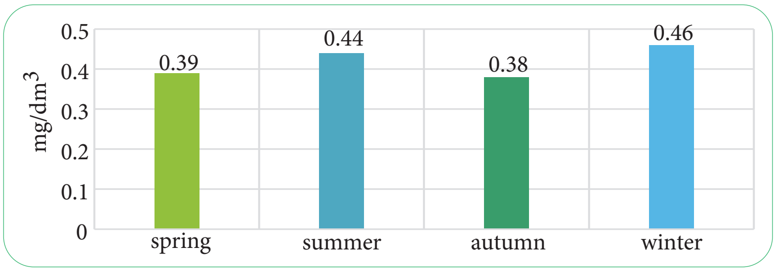

Figure 5. Seasonal fluctuations in the multi-year average values of major iron content (Borzhava River – Bene Village)
Source: compiled by the authors based on materials from Tisza River Basin Water Resources Management (n.d.)

The level of iron in water changes and reaches its highest levels during floods, when iron-containing compounds are actively washed out of the soil. In winter, when water levels are low, vegetation stops consuming iron, and due to the lack of aeration, ferrous iron is not oxidised to ferric iron, which leads to its significant accumulation in the aquatic environment. The results of the hydrochemical survey confirm a high iron content of 0.061 and 0.066 mg/dm^3 in the Borzhava River in the villages of Nyzhni Remety and Kvasovo. Spatial analysis shows a relatively uniform iron content downstream of the Borzhava, with some exceptions in the lower reaches, which may be associated with an increase in anthropogenic load, an increase in the volume of wastewater discharged into the Borzhava river system, in particular from recreational facilities.

Manganese appears in surface waters as a result of leaching of iron-manganese ores and minerals, as well as in the process of decomposition of aquatic plants. MPC for fisheries. At a level of 0.1 mg/dm^3. Absolute values of iron content range from 0.01 to 0.46 mg/dm^3, which indicates a high dependence on the hydrological regime of waters and economic use of coastal lands in the Borzhava basin. According to average annual data for 2007-2018 in the lower reaches of the Borzhava River (Bene Village), constant exceedances of the norms were recorded in the spring and summer periods, which is associated with the melting of snow and the passage of floods, resulting in increased surface runoff and, consequently, manganese content in rivers (Fig. 6).

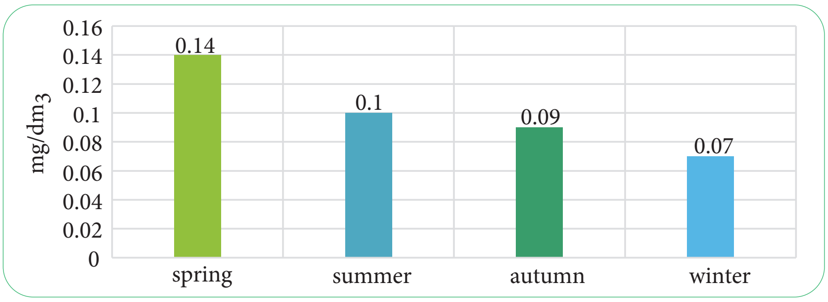

Figure 6. Seasonal fluctuations in the multi-year average values of manganese content (Borzhava River – Bene Village)
Source: compiled by the authors based on materials from Tisza River Basin Water Resources Management (n.d.)

Copper – a heavy metal that occurs naturally in rocks in the form of compounds with sulphur, silicates, carbonates and oxides. The main source of its entry into surface waters is the weathering of minerals, and among anthropogenic sources are industrial effluents from chemical and metallurgical enterprises and agricultural effluents using copper sulphate. The MPC for fishery waters is 0.001 mg/dm^3, for domestic and drinking waters – 1 mg/dm^3. According to Tisza River Basin Water Resources Management (n.d.), the concentration of copper in the summer period consistently exceeds the fishery norm by 4-5 times (Fig. 7).

Hydrochemical surveys confirmed even higher values – from 0.04 to 0.58 mg/dm^3 (Fig. 8). The reasons for this are natural weathering, ore mineralisation (the section between the villages of Bereznyky and Dovhe) and the use of copper sulphate in the middle and lower reaches.

Samples taken during economic activities showed an increase in copper concentration downstream. The exceptions are the Salva and Borzhava rivers in the Nyzhni Remety Village – 0.58 and 0.5 mg/dm³ respectively.

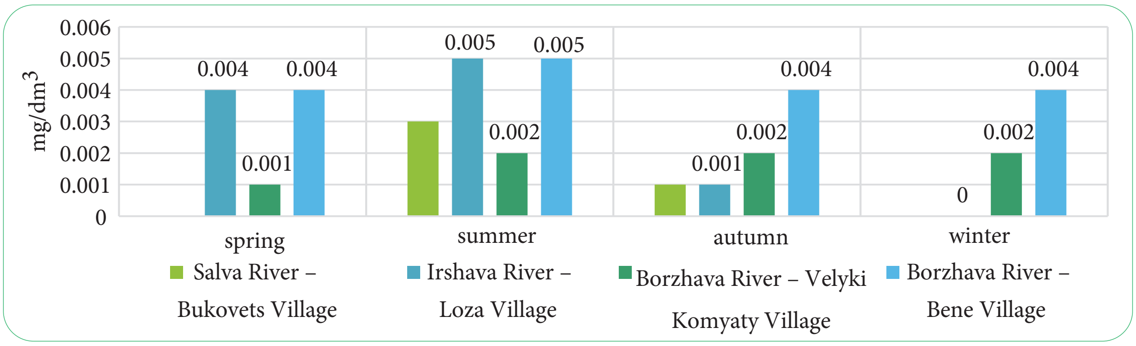

Figure 7. Seasonal fluctuations in average annual copper content
Source: compiled by the authors based on materials from Tisza River Basin Water Resources Management (n.d.)

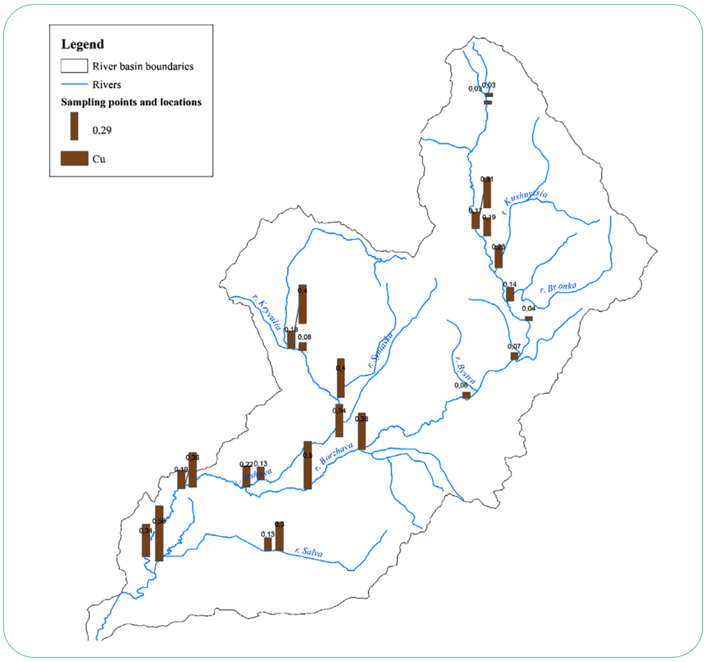

Figure 8. Cartogram of spatial distribution of copper, mg/dm³
Source: compiled by the authors based on field research materials

Chromium belongs to the group of heavy metals, and its compounds are highly toxic and have a harmful effect on surface waters. The main sources of chromium in the environment are minerals and rocks containing this element, surface runoff from mineral extraction sites, and wastewater. For waters intended for fisheries, the MPC for chromium is 0.001 mg/dm³. The increase in chromium content in surface waters is seasonal, which is explained in particular by the increase in surface runoff during periods of intense flooding in the warm season (Fig. 9).

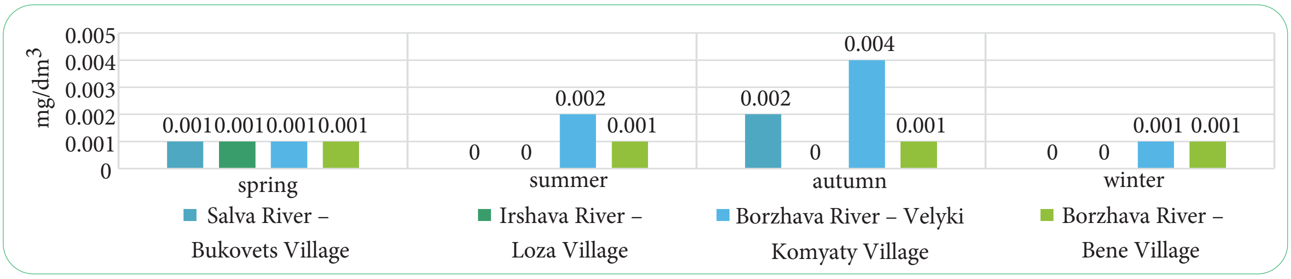

Figure 9. Seasonal fluctuations in average annual chromium content
Source: compiled by the authors based on materials from Tisza River Basin Water Resources Management (n.d.)

Zinc – a heavy metal commonly found in water and soil due to the dissolution of sphalerite. Its concentration in water varies from thousandths to tenths of a milligram per decimetre cubed, depending on the hydrological regime. The maximum permissible concentration in surface waters is 0.001 mg/dm³. In the Borzhava basin, exceedances of fishery standards are consistently recorded, mainly due to natural factors: geological structure and weathering of ore deposits (Fig. 10). Anthropogenic impact is less significant. The absence of clear seasonal dynamics confirms the dominance of natural processes in the formation of the hydrochemical regime.

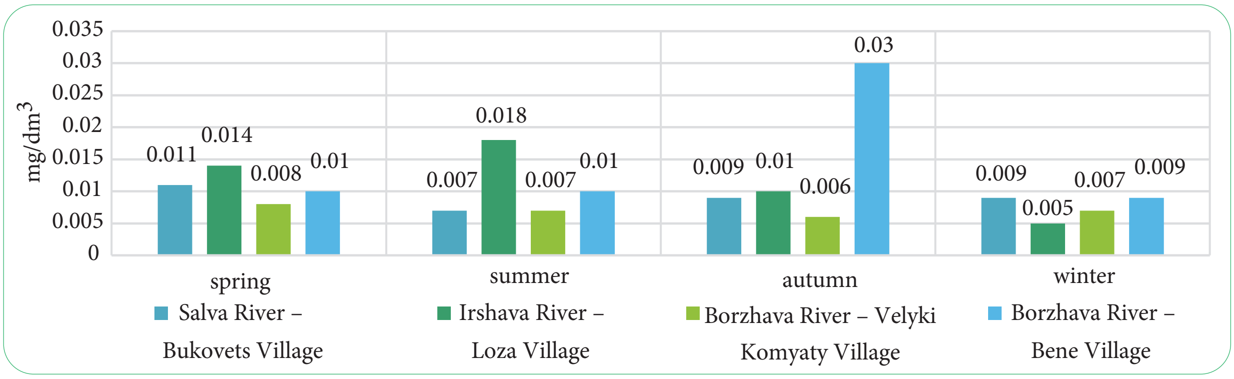

Figure 10. Seasonal fluctuations in average annual zinc content
Source: compiled by the authors based on materials from Tisza River Basin Water Resources Management (n.d.)

AS are synthetic pollutants that affect the quality of surface water. They contain organic and inorganic components and are used in cleaning agents, disinfectants, emulsifiers, and metallurgical processes. They enter the environment through wastewater and industrial emissions. The MPC for fishery waters is 0.2 mg/dm³. The results of hydrochemical surveys show insignificant fluctuations in the content of synthetic surfactants (SS) in the waters of the Borzhava basin: from 0.02 mg/dm³ to 0.11 mg/dm³. Nevertheless, spatial analysis indicates a greater load on surface waters from SS in the upper reaches of the Borzhava River from the Bereznyky Village to the Dovhe Village, which, in the absence of industrial facilities, indicates a load on the Borzhava ecosystem from municipal and domestic sewage. The absence of sewage treatment facilities in the upper reaches of the Borzhava has a negative impact on the quality of surface waters.

Discussion

As a result of a broad analysis of the literature, it should be noted that the quality of water resources is deteriorating as a result of both natural and anthropogenic factors, which complicates the identification of sources of pollution and requires interdisciplinary management. Effective environmental management of water resources requires the integration of environmental, economic and regulatory approaches. The article by N. Akhtar *et al.* (2021) summarises a wide range of natural and anthropogenic factors causing water quality degradation, with an emphasis on the complexity of identifying sources of pollution and their pathways, which is consistent with the unauthorised discharges and diffuse pollution identified in the Borzhava basin. The authors emphasise the need for an interdisciplinary approach and cross-border cooperation to ensure sustainable water management in the context of global environmental challenges.

The article by E. Lucas *et al.* (2023) reviews the impact of climate change on phosphorus losses from agricultural land as a key factor in increasing water pollution. The article by P. Ebeling *et al.* (2021) examines the seasonal dynamics of nitrate concentrations in the surface waters of 290 catchment basins in Western Europe, using a new approach to analyse long-term changes, which also correlates with the seasonal variability of hydrochemical indicators recorded in the upper reaches of the Borzhava River basin. The study revealed a complex response of water systems to nitrogen inputs and high spatial variability of seasonal patterns, highlighting the importance of hydrochemical monitoring for effective water quality management. The article by H. Huan *et al.* (2020) proposes a comprehensive approach to assessing the risk of groundwater pollution, which allows combining water flow and nitrate transport modelling in the aeration zone and aquifers. J. Liu *et al.* (2023) analysed the dynamics of nitrogen compounds in the Jianghan Plain in the context of their impact on total nitrogen (TN) export, using an empirical model to predict future scenarios. The study highlighted the critical role of accumulated nitrogen in soils and the need for integrated management strategies to effectively control pollution in agricultural regions, which is somewhat analogous to studies where phosphorus losses and nitrogen accumulation in soils are identified as key factors in surface water pollution and confirms the relevance of integrated management strategies aimed at controlling the impact of agriculture on surface water quality.

The article by Y. Gao *et al.* (2023) examines the long-term impact of nitrogen compounds on pollution in the Songhua River, with an emphasis on seasonal time lags between the reduction of nitrogen inputs and improvements in water quality. The results of the study by A. Sultana (2025) indicate seasonal variability in surface and groundwater quality parameters, highlighting the importance of long-term monitoring to assess the risks associated with the formation of disinfection by-products in conditions of variable water quality. A.B. Laniyan *et al.* (2025) investigated the seasonal influence of climatic factors on the physicochemical and microbial indicators of water quality in the Osun River basin, which revealed a significant deterioration in indicators during the wet season due to the influence of surface runoff. These studies confirm the importance of implementing and maintaining long-term monitoring, as exemplified by the Borzhava River basin, which is one of the key recommendations based on the results of the study. The article by A.O. Adeyefa (2024) assesses the physical and chemical parameters of the Ogun River water in the Abeokuta area, which is an important source of water supply for densely populated communities. Although most indicators comply with World Health Organisation standards, the calculated water quality index showed that it is unsuitable for domestic use. The study emphasises the need for regular monitoring and tighter control of sources of pollution.

The article by K.A. Bawa-Allah (2023) provides a meta-analysis of data on heavy metal pollution in Nigeria's surface freshwaters. The results showed critically high concentrations of Cd, Cr, Mn, Ni and Pb, exceeding international drinking water quality standards. The study by G. Singh *et al.* (2023) analysed the water quality of the Hindon River and found significant exceedances of MPCs for organic pollutants and heavy metals, especially in the middle reaches, where industrial and domestic effluents have an impact. The results indicate a global problem of anthropogenic pressure on aquatic ecosystems, especially in regions with insufficient control over sources of pollution, and confirm the need for urgent measures by regional authorities to restore the aquatic environment and ensure sustainable resource management. The study by A. Kadir *et al.* (2022) found that changes in land use and land cover in the coastal zone of the Surma River significantly affect water quality, especially in terms of BOD_5, electrical conductivity, TDS and TSS. In contrast, the study by M.E. Akiner *et al.* (2024) investigated the water quality of the Betwa River basin and found that the main sources of pollution are point discharges of industrial and domestic wastewater, as well as diffuse pollution from agricultural land.

The study by R. Mansour *et al.* (2024) conducted a comprehensive assessment of the water quality of the Rachine River in an urban environment, using WHO standards and multidimensional statistical analysis, which revealed seasonal fluctuations, microbial contamination and the spatial structure of sources of impact. A study by N.H. Duc *et al.* (2023) found that surface water quality in the city of Can Tho has deteriorated significantly due to intensive urbanisation, the expansion of industrial zones and agricultural impact. The results obtained are an important tool for the development of integrated water resource management strategies in the context of sustainable development. In the article by H. Allafta & C. Opp (2020), the authors studied the spatial distribution of sources of heavy metal pollution in the Shatt al-Arab River. The use of pollution indices revealed the dominance of anthropogenic factors and high levels of pollution within the studied sections of the river. W. Zhang *et al.* (2021) assessed the pollution of the Liujiang River with heavy metals using multidimensional statistical analysis, which revealed seasonal fluctuations, spatial differentiation and sources of water pollution. The above-analysed works demonstrated the effectiveness of this approach for identifying the spatial structure of pollution sources, which can be applied for further analysis of the Borzhava River basin, particularly in the context of developing a management plan for the Tisza River basin.

The article by G. Busico *et al.* (2024) implements an integrated approach to assessing water quality in the Aspio River basin. The study combines SWAT modelling, time series and statistical analysis to identify sources of pollution, which ultimately showed the dominance of urban wastewater in the formation of nitrogen load on water, and also indicates the priority of controlling urbanised areas in water protection planning. The study by V.K. Khilchevskyi *et al.* (2023) confirms that the hydrochemical regime of the upper Tisza River is formed under the influence of both natural factors (geological structure, seasonal fluctuations in water content) and anthropogenic load, and indicates the relevance of this study for regional planning, since the Borzhava is part of the Tisza catchment system. The results obtained demonstrate the need for an integrated approach to water quality management that takes into account seasonal variability of indicators and sources of anthropogenic impact. The study by K. Matiyiv *et al.* (2022) analyses the water quality of the Prut River in the Yaremche tourist cluster and its dependence on the intensity of tourist flow. The selected samples included analysis of physicochemical indicators and heavy metal concentrations determined by Sensafe membrane tests.

The article by R.L. Kravchynskyi *et al.* (2021) analysed landslides in the upper reaches of the Prut River and, based on data from Google Earth, Landsat and field observations, established a link between the spread of exogenous processes and the characteristics of the river network. The article by O. Dzham *et al.* (2021) provides an ecological assessment of the quality of surface waters of the Prudnyk River based on hydrochemical indicators and an integral pollution index. The results of the study confirm the need for regular monitoring and implementation of environmental protection measures to stabilise the ecological state of the watercourse. In a similar study on this topic, X. Zhao *et al.* (2024) found that the hydrochemical composition of the Minyong River water is formed mainly as a result of the weathering of carbonate rocks, which is confirmed by the dominance of , Ca^{2+}, Mg^{2+} and ions, which echoes the conclusions of the present study and confirms the need for a systematic study of the factors that shape and influence the ecological condition of surface waters, in particular under the influence of the geological structure of the river basin.

It has been determined that the main sources of surface water pollution are industrial effluents, urbanisation, irrational or improper land use, and agriculture within floodplains. Hydrochemical studies of river basins also show the influence of geology, tourism and exogenous processes on the chemical composition of water, which requires local monitoring and adaptive management. On the other hand, analysis of hydrological processes indicates a link with nitrogen, phosphorus and nitrate content, which in turn also justifies the need for their long-term monitoring and modelling.

Conclusions

In summary of the conducted research, a wide spatio-temporal overview of the surface water quality in the Borzhava River basin was obtained, based on a set of hydrochemical indicators sourced from both the archival materials of the Tisza River Basin Water Resources Management and the results of the conducted field investigations. The river waters of the Borzhava basin are characterised by a hydrocarbonate-calcium type with average mineralisation, corresponding to moderately fresh conditions. A clear seasonal variability in chemical composition, in particular dry residue, was found, which correlates with the hydrological regime. The spring-summer period is accompanied by an increase in the concentration of nitrogen-containing compounds caused by the active decomposition of organic matter coming from domestic wastewater and surface runoff from agricultural land. Significant exceedances of MPCs for a number of indicators have been recorded. In particular, the concentration of total iron reached 1.05 mg/dm^3 with a standard of 0.3 mg/dm^3, which is 3.5 times higher than the standard. The copper content ranged from 0.04 to 0.58 mg/dm^3 with a standard of 0.01 mg/dm^3, i.e. the excess reached 58 times. Excessive levels of manganese (up to 0.46 mg/dm^3), chromium (up to 0.004 mg/dm^3) and zinc (up to 0.03 mg/dm^3) were also detected. The main factors that shape or influence the ecological state of surface waters in the Borzhava basin are the geological structure of the territory, which causes the natural entry of iron, copper, chromium and zinc metals into the aquatic environment, and the discharge of spent mineral waters from balneological resorts, in particular "Borzhava" in the Dovhe Village. It is also worth noting the impact of a significant number of existing unauthorised landfills (the villages of Keretsky, Dunkovytsia, Velyki Komyaty, and Nyzhni Remety) and insufficiently treated municipal wastewater within the Kamianske, Bilky, Dovhe, Irshava, and Keretsky territorial communities, as well as agricultural activities, in particular through the application of mineral fertilisers and the economic development of floodplains, particularly in the Salva River sub-basin. Prospects for further research are related to the expansion of spatial and temporal monitoring of the hydroecological state, the improvement of methods for assessing the impact of anthropogenic factors on water resources, and the development of innovative approaches to rational nature management and the restoration of the ecological balance of aquatic ecosystems.

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None.

Conflict of Interest

None.

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Гідрохімічний режим вод річок басейну Боржави

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Анотація. Мета дослідження полягала в аналізі гідрохімічних параметрів якості поверхневих вод басейну річки Боржава в Закарпатській області. На основі зібраних матеріалів здійснено детальний аналіз гідрохімічних показників якості вод річок Божава, Іршава, Сальва та інших. Даному дослідженню передував детальний аналіз природних умов водозбору Боржави та факторів антропогенного впливу на значення фізико-хімічних параметрів, головних йонів та мінералізацію води, вмісту біогенних речовин, важких металів та специфічних забруднювальних речовин. Розглянуто співвідношення розрахункових концентрацій гідрохімічних до гранично допустимих концентрацій для вод рибогосподарського використання. Зафіксовано менший за норму гранично допустимої концентрації вміст розчиненого кисню, перевищення нормативних значень за вмістом амонію, фосфату, заліза загального, марганцю, міді та цинку. Вивчено роль природних умов формування хімічного складу поверхневих вод у басейні річки Боржава: гідрологічний режим вод, зміна джерел живлення, геологічна будова водозбірної території, а також вказано основні джерела антропогенного впливу вздовж течії – несанкціоновані сміттєзвалища, систематичні скиди побутових стічних вод, недостатній рівень очистки комунальних стічних вод, сільськогосподарське освоєння заплав та прибережних земель, внесення добрив у період ведення господарства, уповільнення течії в системі каналів у нижній течії річки Боржава, річки Сальва, каналу Бальва. Визначено, що води верхів'я річки Боржава є гідрокарбонатними кальцієвими, помірно прісними з середньою мінералізацією та чіткою сезонною мінливістю. Отримані результати мають вагоме прикладне значення та можуть бути використані під час підготовки Плану управління басейном річки Тиса, обґрунтуванні та реалізації заходів екологічного контролю діяльності суб'єктів господарювання у верхів'ях Тиси, а також у процесі розроблення та впровадження екологічних програм, спрямованих на покращення якості вод у басейні річки

Ключові слова: антропогенне навантаження; мінералізація води; біогенні речовини; сезонна мінливість; екологічне планування

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Evaluation of the assimilation capacity and self-cleaning ability of biogeoecosystems along the Caspian Sea coastal zone

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Abstract. The purpose of this study was to determine the level of ability of the Caspian coastal soils to neutralise anthropogenic load based on the assessment of their assimilation and self-purification characteristics. The research methodology was based on a comparative analysis of the soils of the Absheron-Khizi and Guba-Khachmaz regions of Azerbaijan, where samples were taken from the 0-20 cm horizon, after which different levels of oil load were reproduced under model conditions and microbiological, biochemical, and bioindicative parameters were assessed to determine the self-purification capacity of ecosystems. The greatest resistance was demonstrated by meadow-forest soils, which had a neutral reaction of the environment (pH 7.1-7.4), high humus reserves (70-240 t/ha) and increased biological activity, which was confirmed by the carbon dioxide content of 0.65%. Their ability to decompose hydrocarbons was 1.12 ± 0.08 mg per gram of soil per day, and the mineralisation factor reached 0.52 ± 0.03. Meadow soils with humus of 35-60 t/ha and a share of oil-degrading microorganisms of 18-22% had lower biodegradation – 0.78 ± 0.05 mg/g×day with a mineralisation factor of 0.31 ± 0.02. The most vulnerable soils were grey-brown soils with a minimum organic matter stock (24-38 t/ha) and a low proportion of destructors (8-12%); the assimilation capacity did not exceed 0.34 ± 0.04 mg/g×day with a mineralisation factor of 0.12 ± 0.01. Bioindication tests showed a drop-in germination of watercress and alfalfa to 40-45% and a 50% reduction in biomass under conditions of 10% oil contamination. The results confirmed that meadow-forest soils were the most resistant, meadow soils were in an intermediate position, while grey-brown soils were the most vulnerable to oil pollution. The practical significance of the findings lies in their potential to be used by environmental services and agricultural research centres to monitor soil conditions and develop bioremediation strategies in the Caspian Sea regions

Keywords: bioindication; oil products; toxic effects; biodegradation; sustainability; pollutant; microbial communities

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Introduction

The soils of the Caspian Sea coastal zone play a key role in maintaining biogeoecological balance, as they ensure the accumulation and transformation of organic matter, regulate the quality of surface and groundwater, and create conditions for biodiversity conservation. Their assimilation capacity and self-purification ability determine the resilience of ecosystems to external stress and form a natural barrier against anthropogenic pollution. At the same time, the long-term impact of hydrocarbon production and transportation, the development of industrial facilities, and urbanisation processes have led to the accumulation of oil products, heavy metals, and other xenobiotics in soils. This was accompanied by a change in their physical and chemical parameters, a decrease in the activity of microbial communities, and a slowdown in mineralisation processes. Such changes limit the natural potential of soils to maintain the stability of biogeoecosystems and counteract external anthropogenic pressure.

The study of the Caspian Sea coastal soils has gradually shifted from general descriptions to quantitative analysis of their properties. M.P. Babaev *et al.* (2020) proposed to determine the maximum permissible concentrations (MPC) of oil products using indicators of the soil assimilation potential. The researchers showed that this approach helped to adapt the standards to concrete soil types, but its universalisation proved impossible due to regional specifics. N. Ismailov *et al.* (2020) substantiated the concept of including assimilation capacity in soil and landscape passports, which helped to comprehensively consider physicochemical and microbiological indicators. Therewith, scientists noted the lack of unified field validation methods, which limited the practical application of this approach. The current state of the soil cover of the coastal strip was analysed by N.T. Aliyeva *et al.* (2023), who revealed the impact of a combination of climatic and anthropogenic factors on degradation processes. The greatest changes were recorded in areas with intensive economic use, where the ability of soils to recover decreased. M. Ahmadov *et al.* (2020) conducted a spatial analysis of the content of heavy metals in the coastal sediments of the western Caspian Sea. The results confirmed that background levels were exceeded even in areas remote from industrial centres, indicating a large-scale nature of the anthropogenic impact.

The study of biological mechanisms of soil restoration after oil pollution showed that microorganisms and associated plant communities play a leading role in stabilising degradation processes (Islamzade *et al.*, 2025). Q. Duan *et al.* (2023) proved that petroleum hydrocarbon pollution disrupted growth and gas exchange in sea buckthorn plants, while reducing the level of antioxidant defence. The researchers emphasised that such changes not only reduced bioproductivity but also limited the potential of plants to take part in natural soil self-purification. The analysis conducted by G. Yerulker *et al.* (2023) demonstrated differences in the structure of microbial communities in areas with different degrees of oil contamination. The researchers demonstrated that under conditions of high hydrocarbon content, microbial communities lost their functional diversity, which complicated the degradation of organic matter. X. Sui *et al.* (2021) covered the prospects of microbial and combined bioremediation methods, studying the effectiveness of combining microbial consortia with phytotechnology. The results revealed that integrated approaches accelerated the decomposition of hydrocarbons and reduced the toxicity of the soil environment. The accumulated data were summarised by B. Mekonnen *et al.* (2024), who systematised the principles and mechanisms of microbial degradation of petroleum compounds. This review noted that the key factor in the effectiveness of bioremediation was the adaptability of microbial communities to specific environmental conditions.

The problems of the functioning of the Caspian coastal soils should be considered in the context of broader environmental challenges that determine the prospects for sustainable development of the region. S. Xenarios *et al.* (2025) conducted a comprehensive review of current threats, including oil hydrocarbon pollution, degradation of coastal ecosystems, and the effects of sea level fluctuations. The results showed that the integration of local soil research into the regional policy system is a prerequisite for the development of balanced scenarios for natural resource management. B. Iskakov *et al.* (2024) covered the practical aspect of environmental safety, assessing the sensitivity and vulnerability of the coast to oil spills. The study found that the consideration of the soil cover characteristics increased the accuracy of environmental risk assessment and enabled more informed planning of response measures.

Despite the existence of some regional and international studies, there are still no comprehensive studies that integrate physicochemical and biological criteria for assessing the resilience of Caspian coastal soils to anthropogenic stress. The purpose of the present study was to quantify the assimilation capacity and self-purification potential of the soils of the Caspian Sea coastal zone. For this, it was necessary to solve the following tasks: to analyse the composition and properties of soils in the area affected by anthropogenic factors; to assess the level of assimilation capacity and self-purification capacity; to compare the results between individual sections of the coast to identify spatial differences.

Materials and Methods

The area and period of the study

The study was conducted within the soil cover of two economically significant regions of Azerbaijan – Absheron-Khizi and Guba-Khachmaz. These areas were characterised by a prominent level of anthropogenic pressure due to the development of the Siazan oil fields, the proximity of industrial facilities in the Absheron Region, and the passage of the Northern Export Pipeline. The soil cover of the territories had a different structure: the Guba-Khachmaz Region was characterised by meadow-forest and partially meadow soils, while the Absheron-Khizin Region was represented mainly by grey-brown soils with an admixture of meadow soils. Hydrocarbons were chosen as the key indicator of pollution, as their presence in the soil causes toxic effects on living organisms and leads to substantial changes in the biogeochemical cycle. Considering the absence of MPC standards for oil and oil products in Azerbaijani soils, their content was determined as a percentage of mass, considering the range of 0.5-10%. The study was conducted in 2023-2024, covering the spring (March-May) and autumn (September-November) periods, which ensured representative sampling under different moisture and microbial activity conditions.

Ethical norms

Experimental studies using cultivated and wild plants, including the collection of plant material, were conducted following institutional, national, and international guidelines in the field of bioethics and nature protection. Particular attention was paid to ensuring that sampling did not harm natural populations or disturb the ecological balance in the study regions. The study followed the requirements of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992), which guaranteed the legality and environmental safety of the experiments.

Soil sampling and preparation

Soil samples were taken at key points along the 0-20 cm horizons, which reflect the most active processes of pollutant transformation. The sampling scheme followed the principle of uniform coverage of the territory using a 200×200 m grid. The samples were collected using the "envelope" method, resulting in a total weight of 1 kg, which was placed in sterile bags and transported to the laboratory. There, they were distributed in plastic containers to which the required doses of a hydrocarbon pollutant, n-hexadecane (a saturated alkane with C16 (16 carbon atoms), were added, the choice of which as a model substrate ensured reproducibility and controllability of the experimental conditions. A total of 60 soil samples were collected, 30 from each site (Absheron-Khizin and Guba-Khachmaz). The sampling was performed in three replications, which minimised random errors and enabled the calculation of mean values and standard deviations for each indicator.

Physicochemical and biotic parameters

A comprehensive assessment of the assimilation capacity of soils included the determination of both physicochemical and biological characteristics. The acid reaction of the medium (pH) was measured in an aqueous soil-water suspension (1:2.5) using a Hanna Instruments HI 2211 pH meter (Italy). Soil moisture content was determined according to the gravimetric method after drying the samples to a constant weight at 105°C in a Memmert UF55 drying oven (Germany). Climatic parameters included both precipitation and temperature characteristics. Annual precipitation (mm/year) and air temperature data were obtained from local meteorological stations equipped with automatic Vaisala MAWS201 systems (Finland). The sum of active temperatures above +10°C (°C×day/year) was calculated by summing mean daily air temperatures exceeding the +10°C threshold over the annual cycle. This indicator was used to characterise the thermal and energy potential of the soil-climate system and its influence on biological activity.

The adsorption capacity of soils with respect to organic pollutants was determined under laboratory conditions using a batch equilibrium method. Air-dried soil samples (10 g, sieved through a 2-mm mesh) were equilibrated with a model hydrocarbon solution based on n-hexadecane at a known initial concentration. The soil-solution suspensions were shaken for 24h at 20 ± 2°C to achieve adsorption equilibrium. After centrifugation, the residual hydrocarbon concentration in the supernatant was measured spectrophotometrically using a Shimadzu UV-VIS UV-1800 spectrophotometer (Japan). Adsorption of organic pollutants (%) was calculated as the proportion of hydrocarbons removed from the solution relative to the initial concentration. The biological component included determination of the number of microorganisms capable of assimilating petroleum hydrocarbons, performed using the method of limiting dilutions on selective media, with incubation in a Binder BD 56 thermostat (Germany). The combined analysis of physicochemical, climatic, and microbiological indicators enabled an integrated characterisation of soil assimilation capacity.

Microbiological and biochemical methods

The total number of soil microorganisms was determined according to the method of limiting dilutions of soil suspensions, which were sown on meat-peptone agar and incubated at 28-30°C for 5-7 days. Accounting was conducted at the beginning of the experiment, as well as on the Days 5 and 15 after the introduction of hydrocarbon pollutants. Uncontaminated samples were considered control samples, the number of microorganisms in which was taken as 100%, while in experimental samples the result was expressed as a percentage of the control. The destructive potential of microorganisms was assessed by the photocolourimetric method: a suspension of *Bacillus* and *Pseudomonas* strains was introduced into M9 medium (a mineral minimal medium containing inorganic salts and used for cultivation of bacteria in the presence of a single carbon source) with the addition of 250 mg/l n-hexadecane, after which changes in the substrate concentration were recorded spectrophotometrically. For assessing biological activity, soil respiration was quantified as the rate of CO_2 release, which served as an integrated indicator of microbial metabolic intensity. CO_2 released during microbial respiration was absorbed by 0.1 n potassium hydroxide (KOH), after which the remaining alkali was titrated with HCl to determine the amount of CO_2 fixed in the alkaline solution. This method is considered reliable, as it enables a direct assessment of the intensity of microbial respiration as one of the key integrated indicators of soil biological activity.

Bioindication experiments

To evaluate the phytotoxicity of soils, the test plants watercress (*Lepidium sativum* L., variety Vita, seeds from Agrosel, Romania) and seed alfalfa (*Medicago sativa* L., variety Vega 87, seeds from Eurograss, Germany) were used. In model vessels with a soil weight of 1 kg, 30 seedlings were sown, maintaining humidity at 60% of the highest moisture capacity (HC) and a temperature of 22-24°C under natural light. Within 30 days, the key indicators of plant viability were considered in three replications: seed germination (%) and biomass accumulation (g per 30 seedlings), which were determined after drying in a Memmert UF55 drying oven (Germany). Background soils served as a control, while a decrease in germination or biomass relative to the control was interpreted as an indicator of phytotoxicity. The yield indicator (t/ha) represents an integral indicator of aboveground biomass productivity of natural and semi-natural vegetation typical of the studied soil types. These values were derived by extrapolating experimentally measured biomass data using standard conversion coefficients and validated against regional statistical reference data.

Calculation of the assimilation capacity and mineralisation factor

The assimilation capacity of soils was assessed by the level of bacterial biodegradation of hydrocarbons, which was determined according to the following formula:

$$B = N \times K, \tag{1}$$

where B is the level of hydrocarbon biodegradation; N is the number of oil-degrading bacteria (colony forming units (CFU) per 1 g of soil), and K is the amount of hydrocarbons oxidised by one cell per day (3.76×10^{-8} mg/cell/day). The calculations were performed in three replications, and the results were expressed in mg of hydrocarbons per gram of soil per day. Additionally, the mineralisation coefficient (K_m) was used, which was defined as the ratio of the intensity of CO_2 formation absorbed by a 0.1-normal KOH solution to the intensity of oxygen consumption (O_2) by soil microorganisms. The measurements were performed using a Shimadzu UV-VIS UV-1800 spectrophotometer (Japan) and a Testo 310 gas analyser (Germany), which helped to establish not only the ability of microbial communities to decompose hydrocarbons, but also the degree of completion of the process to complete mineralisation of the organic substrate.

Results

Spatial differences in the physical and chemical characteristics of coastal soils

The study of the soil cover of the Caspian Sea coastal areas showed substantial differences between the key soil types -meadow-forest, meadow, and grey-brown soils, which are widespread in the Absheron-Khizin and Guba-Khachmaz regions. For a comprehensive analysis, a series of key physical and chemical parameters were considered that determine the ability of soils to assimilate pollutants and maintain the stability of biogeocoenosystems. The results are summarised in Table 1.

Table 1. Key physical and chemical properties of soils in the study area (average for the spring and autumn period of 2023-2024)

Soil type	pH	Humus reserves (t/ha)	Humus content (%)	Moisture coefficient	Water retention capacity (mg/cm²)	Adsorption of organic pollutants (%)	Precipitation (mm/year)	Sum of active temperatures >10°C (°C-day/year)	Soil density (%)	Yield (t/ha)	CO_2 content (%)
Meadow-forest	7.1-7.4	70-240	2.2-6.15	1.0-1.5	20-30	46.6	570-950	3,600-4,000	29-35	70-75	0.65
Meadow	7.7-8.0	35-60	1.5-2.3	0.4-1.25	20-25	37.6	232-300	3,900-4,600	16-20	60-70	0.18-0.22
Grey-brown	7.7-8.7	24-38	1.0-1.3	0.3-0.5	15.5	30.5	150-300	4,000-4,500	8-18	5-18	0.15-0.19

Note: the sum of active temperatures means the number of degree-days with an average daily temperature above +10°*C per year, which determines the heat and energy potential of the soil and climate system*

Source: compiled by the authors

The acidity level ranged within 7.1-8.7. The most favourable conditions were in meadow-forest soils with indicators of 7.1-7.4, which corresponded to an almost neutral environment. It is in this interval that most groups of soil microorganisms function optimally, and enzymatic reactions and hydrolysis of organic compounds are activated. In contrast, meadow and grey-brown soils were characterised by distinctly alkaline pH values (7.7-8.7). In an alkaline environment, the activity of acid-dependent enzymes was inhibited, the mineralisation of organic matter slowed down, and, accordingly, the level of natural detoxification decreased. This explains why hydrocarbon degradation processes in grey-brown soils were much slower, while in meadow-forest soils, pollutants decomposed more intensively. Acidity was one of the basic parameters that determined the differences between the territories: neutral soils in the Guba-Khachmaz Region had an advantage over alkaline soils in the Absheron-Khizin Region.

The analysis of humus stocks showed a sharp differentiation between soil types. In meadow-forest soils, the humus content was 2.2-6.15% (70-240 t/ha), indicating intensive accumulation of organic residues and a well-established cycle of matter. In meadow soils, this indicator was twice lower – 1.5-2.3% (35-60 t/ha), while in grey-brown soils it stayed at a minimum level – 1.0-1.3% (24-38 t/ha). Such dynamics directly influenced the pollution resistance: soils with a high humus content can bind pollutants, provide microbial communities with energy sources, and maintain their numbers. The degraded grey-brown soils with low humus content were virtually devoid of buffering properties, making them the most vulnerable to oil loading.

The moisture coefficient reflected the balance between the amount of precipitation and evaporation rate. In meadow-forest soils, it reached 1.0-1.5, reflecting relatively stable moisture conditions. In meadow soils, the indicators decreased to 0.4-1.25, and in grey-brown soils – to critical 0.3-0.5, which confirmed a constant moisture deficit. Analogous trends were observed in the water-holding capacity: from 20-30 mg/cm^2 in meadow-forest soils to only 15.5 mg/cm^2 in grey-brown soils. This meant that biodegradation processes in soils with low moisture content were much slower, as water is the medium for most biochemical reactions. Thus, the moisture deficit in the Absheron-Khizin Region created further barriers to the self-purification of soils from hydrocarbons (Guliyev *et al*., 2024).

The ability of soils to adsorb organic pollutants varied substantially: in meadow-forest soils it was 46.6%, in meadow soils – 37.6%, and in grey-brown soils – only 30.5%. This meant that in areas with grey-brown soils, oil hydrocarbons had increased mobility and could migrate more quickly to deeper horizons, entering aquifers. Due to their high sorption capacity, meadow-forest soils actually "localised" the pollution in the upper layers, where it became available for microbial degradation. The distribution of climatic indicators confirmed these differences. In the Guba-Khachmaz Region, the average annual precipitation was 570-950 mm, which created a relatively favourable water balance. In Absheron-Khizin, this figure did not exceed 150-300 mm against the background of evaporation of 1,000-1,200 mm. Another criterion was the total heat resource: in meadow-forest soils it ranged within 3,600-4,000°C×day/year, while in grey-brown soils it exceeded 4,000-4,500°C×day/year. Excessive heat in conditions of moisture deficit did not stimulate the activity of the microbiota, but only intensified degradation processes. This confirmed that it was the water regime, not the temperature, which was the primary limiting factor for soil self-purification.

The soil CO_2 content as an integral indicator of microbial respiration showed a clear gradation: 0.65% in meadow-forest, 0.18-0.22% in meadow, and only 0.15-0.19% in grey-brown. This meant that the greatest intensity of biological processes was provided by soils with a high humus reserve and sufficient moisture. In grey-brown soils, where moisture and organic matter deficits were combined, the activity of microbial communities was almost minimal. Thus, even in the presence of potential oil-degrading bacteria, environmental conditions did not allow them to fulfil their metabolic potential. The physical structure of the soils confirmed the general pattern. The density of the meadow-forest soils was 29-35%, the density of the meadow soils was 16-20%, while the density of the grey-brown soils was only 8-18%. Low density combined with a lack of humus formed a loose structure that could not effectively retain moisture. At the same time, the yield as an integral indicator of environmental sustainability ranged within 70-75 t/ha in meadow-forest to 60-70 t/ha in meadow and only 5-18 t/ha in grey-brown. This once again confirmed that the degradation of physicochemical parameters was directly transformed into a loss of productivity.

Generalisation of all parameters allows forming a hierarchy of the assimilation capacity of the soils of the studied area: meadow-forest>meadow>grey-brown. Due to their neutral pH, high humus reserves, favourable water balance, and considerable bioactivity, meadow-forest soils showed the greatest resistance to oil pollution. Meadowlands occupied an intermediate position: their ability to self-purify was less stable due to a lack of moisture and lower organic content. The most vulnerable were grey-brown soils, where the combination of alkalinity, low organic reserves, and limited water-holding capacity contributed to the accumulation of hydrocarbons and slowed their mineralisation. The data obtained confirm that spatial differences in physicochemical and biological parameters directly determine the ability of soils to self-purify under conditions of anthropogenic load on the Caspian coast.

Biological reactions of soils to oil load

The obtained experimental data showed differences in the reactions of soil biota, which is reflected in the generalised indicators of the number and proportion of oil-degrading crops in Table 2.

Table 2. Dynamics of the number of microorganisms and the share of oil-degrading crops in soils (CFU×106/g, %)

Soil type	Start of the experiment (0 days)	Day 5	Day 15	Share of oil-degradable crops (%)
Meadow-forest	2.1 ± 0.12	2.8 ± 0.15	3.4 ± 0.18	30-35
Meadow	1.5 ± 0.09	1.8 ± 0.11	2.0 ± 0.12	18-22
Grey-brown	0.9 ± 0.07	0.8 ± 0.06	0.6 ± 0.05	8-12

Source: compiled by the authors

The number of heterotrophs in meadow-forest soils increased from 2.1×10^6 CFU/g to 3.4×10^6 CFU/g (≈1.6-fold increase in 15 days), while the share of oil-degrading cultures reached 30-35%. This meant that the microbial community not only stayed viable under the influence of the pollutant, but also structurally transformed towards consortia with a pronounced destructive potential. In meadow soils, the growth was more modest (1.5×10^6 CFU/g→2.0×10^6 CFU/g; ≈1.3-fold), and the proportion of oil-degradable forms stabilised at 18-22%, i.e. adaptation occurred, but more slowly and less completely. In grey-brown soils, a consistent decrease in the total number was recorded (0.9×10^6 CFU/g→0.6×10^6 CFU/g), with a minimum proportion of destructors (8-12%), reflecting inhibition of microbial activity and low capacity for hydrocarbon mineralisation.

The synchronous analysis of time slices showed that already on Day 5, meadow-forest soils had a positive trend (2.8×10^6 CFU/g), while meadow soils were just beginning to recover (1.8×10^6 CFU/g), and grey-brown soils showed a decline (0.8×10^6 CFU/g). This discrepancy was consistent with the previously identified physicochemical determinants: greater humus reserves, better moisture conditions, and closer to neutral pH in meadow-forest soils supported greater growth rates and catabolic activity of microbial consortia; while alkalinity, lack of organic matter, and moisture in grey-brown soils limited hydrolytic and oxidative processes. Accordingly, in meadow-forest soils, biodegradation managed to move to the mineralisation stage, while in grey-brown soils, intermediate (partially oxidised) products accumulated. The dynamics of the number of microorganisms in soils of different types revealed clear spatial and temporal differences. Within 15 days of observation, meadow-forest soils showed a stable increase in populations, while meadow soils showed a moderate increase, and grey-brown soils showed a gradual decrease (Fig. 1). This allows tracing the dependence of biological activity on the physical and chemical characteristics of the environment.

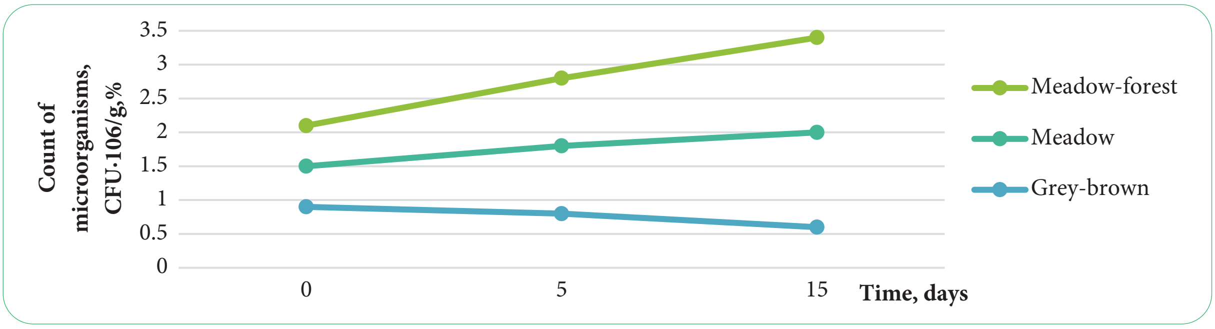

Figure 1. Dynamics of the number of microorganisms in the soil
Source: compiled by the authors

The greatest biotic potential was preserved in meadow-forest soils, where the number of microorganisms increased from 2.1×10^6 CFU/g to 3.4×10^6 CFU/g. The meadow soils had a more restrained dynamics, reaching only 2.0×10^6 CFU/g on Day 15, reflecting a limited ability to self-purification. In grey-brown soils, the number of bacteria decreased from 0.9×10^6 CFU/g to 0.6×10^6 CFU/g, which showed their extremely low resistance to oil pollution. This distribution confirmed the key role of organic matter and moisture regime in the development of assimilation capacity (Kozyatnyk *et al.*, 2015; 2017).

The bioindication experiments showed a clear dependence of the growth parameters of watercress and alfalfa on the concentration of oil pollutants in the soil. In the control samples, plants maintained high germination and biomass rates, while a gradual suppression of these characteristics was observed with increasing pollution levels. Particularly pronounced changes were recorded at a concentration of 5-10%, when the viability and productivity of both species were markedly reduced. Comparison of the two crops showed that watercress was somewhat more resistant to the toxic load, while alfalfa showed a faster biomass decline (Table 3).

Table 3. Results of bioindication experiments with test plants

Concentration, %	Germination rate of watercress (%)	Watercress biomass (g/30 seedlings)	Alfalfa germination rate (%)	Alfalfa biomass (g/30 seedlings)
0 (control)	95 ± 2	12.5 ± 0.6	93 ± 3	15.2 ± 0.7
0.5	90 ± 2	11.8 ± 0.5	89 ± 2	14.6 ± 0.6
5.0	70 ± 3	8.9 ± 0.4	65 ± 3	10.2 ± 0.5
10.0	45 ± 4	6.1 ± 0.3	40 ± 4	7.8 ± 0.3

Source: compiled by the authors

Bioindication tests showed that the impact of oil load on plants was clearly dose-dependent. Already at a minimum concentration of 0.5%, a slight inhibition of seed germination of both crops was observed (a decrease of 5-7 percentage points), while the weight of seedlings stayed almost unchanged. This indicated a certain resistance of the initial growth processes to a mild toxic effect, probably due to the buffering properties of the soil and compensatory mechanisms of the seeds. At a concentration of 5%, substantial deviations from the control values were already detected. For watercress, germination decreased by a quarter (from 95% to 70%) and biomass by almost a third (from 12.5 g to 8.9 g), indicating inhibition of both germination and further growth. For alfalfa, the effect was even more pronounced: a 28 percentage point drop in germination (from 93% to 65%) and a one-third decrease in biomass (15.2 g→10.2 g). These results emphasise that alfalfa is a more sensitive crop to the toxicity of petroleum products, which can be explained by the specifics of its root system and the need for a greater amount of available nutrients. The maximum load (10%) had a sharply inhibitory effect on both crops. In watercress, germination was more than halved (from 95% to 45%), and biomass decreased by 51% (12.5 g→6.1 g). In alfalfa, the decline was even more critical: germination dropped to 40% (57% below the control), and biomass decreased by 48.7% (15.2 g→7.8 g). These dynamics indicated that under conditions of high oil pollution, the soil had lost its ability to ensure normal plant development even in the short term (De Carolis *et al.*, 2013). Comparison between the crops showed that watercress demonstrated relatively higher resistance: at 10%, it maintained greater germination and biomass than alfalfa. At the same time, alfalfa proved to be more indicative of toxicity, as its response to medium doses (5%) was more acute. This allows recommending the combined use of both crops in bioindication tests: watercress as a more tolerant species, reflecting the overall stability of the system, and alfalfa as a sensitive bioindicator of early negative changes (Peruzzo *et al.*, 2018; Fedoniuk *et al.*, 2022).

Comparison of the data in Table 1 and Table 2 showed that the level of phytotoxicity was closely related to the proportion of oil-degrading microorganisms: in meadow-forest soils with high microbial activity, the negative effects were much weaker, while in grey-brown soils with a low proportion of degraders, even moderate concentrations caused a sharp decrease in germination and biomass. This confirmed the key role of microbial communities as the principal regulator of soil assimilation capacity and a determining factor of ecological resistance to oil load (Armenio *et al.*, 2019).

The regional context complemented the interpretation: the spatial contrasts established earlier (meadow-forest soils typical of the wetter Guba-Khachmaz sector were contrasted with the aridised grey-brown soils of the Absheron-Khizin area) explained why the same oil concentrations had different biotic responses. In the first case, the microbiota operated under better moisture and substrate conditions, and therefore the restructuring in favour of oil-degrading consortia was faster, and phytotoxicity was recorded at a lower level. In the second case, alkalinity, moisture deficit, and low humus stock limited both bacterial and plant subsystems, which increased the toxic effect. Thus, meadow-forest soils had a complete increase in the total number of microorganisms and a high proportion of destructors, which correlated with a milder phytoreaction; meadow soils had intermediate values for both blocks; grey-brown soils had a degradation trend in the microbiota and maximum inhibition of test cultures. From a practical standpoint, this meant that in the planning of bioremediation measures, microbial indicators (CFU dynamics and the proportion of destructors), together with phytoindicators, should be used as early and valid criteria for operational monitoring of effectiveness.

Integral indicators of assimilation capacity and self-cleaning ability

The integral characteristics of soils were essential for determining their ability to counteract oil pollution. While the previous parameters (pH, moisture, humus content, number of microorganisms) helped to characterise individual properties of the soil system, the integral coefficients reflected the generalised response of the soil to the complex impact of pollutants. In the present study, the key criteria were the level of bacterial biodegradation of hydrocarbons and the mineralisation coefficient, which helped to quantify the intensity of microbial decomposition and the degree to which the process was brought to complete mineralisation of organic substrates (Table 4).

Table 4. Integral indicators of soil assimilation capacity and mineralisation (mean values ± SD)

Soil type	Assimilation capacity (mg of hydrocarbons/g×day)	Mineralisation coefficient (K_m)
Forest-meadow	1.12 ± 0.08	0.52 ± 0.03
Meadow	0.78 ± 0.05	0.31 ± 0.02
Grey-brown	0.34 ± 0.04	0.12 ± 0.01

Source: compiled by the authors

The results showed that the assimilation capacity varied substantially depending on the soil type. The greatest values were recorded in meadow-forest soils (1.12 mg/g×day), which corresponded to their favourable structure, high humus content, and neutral acidity. This provided microbial communities with sufficient energy and nutrient substrates for active hydrocarbon oxidation. In meadow soils, the integrated index was almost one and a half times lower (0.78 mg/g×day), which was consistent with the data on lower humus reserves and moisture deficit. The lowest level of assimilative capacity was demonstrated by grey-brown soils (0.34 mg/g×day), where a combination of alkaline environment, low organic saturation, and unfavourable hydrothermal conditions limited the catabolic potential of microbial communities.

Comparison of mineralisation coefficients (K_m) confirmed the general trend but helped to draw additional conclusions. In the meadow-forest soils, the K_m was 0.52, which indicated the ability of microbial communities not only to decompose petroleum hydrocarbons but also to bring the process to the formation of the final mineralisation products – CO_2 and H_2O (water). In meadow soils, this coefficient was twice as low (0.31), reflecting incomplete mineralisation: some hydrocarbons accumulated in the form of intermediate metabolites that can have a toxic effect on soil biota and vegetation. In the grey-brown soils, the K_m was only 0.12, which actually meant inhibition of microbial processes and retention of the bulk of pollutants in the soil matrix without substantial biochemical decomposition.

The analysis of integral indicators revealed spatial differences between the study areas. In the Guba-Khachmaz Region, where climatic conditions provided a relatively better balance between precipitation and evaporation, the B and K_m values were consistently greater, especially in meadow-forest soils. Here, hydrocarbon biodegradation reached 1.15 mg/g×day, and the mineralisation coefficient exceeded 0.5, reflecting effective self-purification of ecosystems. In contrast, in the Absheron-Khizinsky district, due to moisture deficit and high levels of anthropogenic load, a decrease in both integral indicators was observed: the assimilation capacity ranged within 0.28-0.92 mg/g×day, and the K_m did not exceed 0.3. This confirmed the greater vulnerability of this region to oil pollution and the limited possibilities for natural soil recovery.

A comparison of the results with previous analyses showed their internal logic. Where high humus reserves, favourable water regime, and activity of microbial communities were previously recorded (meadow-forest soils of the Guba-Khachmaz district), the integral coefficients confirmed maximum resistance to anthropogenic load. In contrast, in the grey-brown soils of the Absheron-Khizin district, which were characterised by a deficit of organic matter, high alkalinity, and low moisture, the values of B and K_m were minimal, which was consistent with their inability to effectively self-purify. The mineralisation coefficient reflected not only the overall intensity of hydrocarbon destruction, but also the quality of this process. In soils with a low K_m, decomposition occurred mainly to intermediate organic products that could accumulate and reduce environmental safety. On the contrary, at high K_m values, mineralisation was reduced to final stable compounds, which reduced the risk of secondary pollution. Thus, the integral indicators helped not only to quantify the level of self-cleaning, but also to draw conclusions about its effectiveness and completeness.

The total interpretation helped to build a hierarchy of soil stability based on integral parameters: Meadow-forest>Meadow>Grey-brown. This gradation confirmed the previous data and demonstrated that it was the combination of physical, chemical, and biotic properties that determined the ability of soils to withstand oil load. In terms of practical environmental conclusions, this meant that additional bioremediation measures were needed in the Absheron-Khizin Region, while in the Guba-Khachmaz Region the natural potential of the soils was still relatively high.

Discussion

The results showed that the assimilation capacity of soils varied substantially between regions. Bioindication experiments confirmed a concentration-dependent drop in germination and biomass of test plants. The comprehensive assessment showed that meadow-forest soils had the greatest assimilation capacity due to their y neutral pH (7.1-7.4), high humus reserves (70-240 t/ha), and increased biological activity (biogenicity) (CO_2 0.65%). Grey-brown soils, on the other hand, were characterised by alkalinity (pH 7.7-8.7), minimal humus (24-38 t/ha), and a low proportion of oil-degrading microorganisms (8-12%), which substantially reduced their ability to self-purify. Analogous spatial contrasts were discussed by K. Pachikin *et al.* (2021), who showed that soil degradation on the northern Caspian coast was accompanied by loss of humus, profile compaction, and a decrease in buffering capacity.

Meadow soils occupied an intermediate position between meadow-forest and grey-brown soils in terms of assimilation capacity. With an alkaline reaction (pH 7.7-8.0) and average humus reserves (35-60 t/ha), they showed a share of oil-degrading microorganisms of only 18-22%, which ensured a relative ability to self-purification, but under conditions of moisture deficit (coefficient 0.4-1.25), their biological activity was limited. Such sensitivity of soil systems to fluctuations in the water regime shows that that even an average level of organic buffering did not guarantee stable microbial functioning. A. Mamataeva *et al.* (2024) showed that the accumulation of oil products in medium-buffered environments contributed to the formation of toxic metabolites that reduced the overall assimilation capacity of ecosystems. Meadow soils have only a partial potential for self-purification: their effectiveness was determined by the balance between average humus levels and limited bioactivity in conditions of moisture deficit.

Thus, the results obtained confirm that the combination of abiotic and biotic characteristics is a key factor in the formation of the assimilation potential of soils under anthropogenic stress. Bioindicator tests showed that even 0.5% oil caused the first signs of inhibition, while at 5-10%, there was a sharp drop in germination and biomass of both crops: germination dropped to 70% and 45% for watercress and 65% and 40% for alfalfa, while biomass was almost halved. These differences reflected a clear concentration-dependent dynamic of phytotoxicity. The obtained patterns are consistent with the data of X. Zhang *et al.* (2025), who showed that hydrocarbon pollution caused a decrease in the activity of soil enzymes and a restructuring of microbial communities, which indirectly limited crop growth in phytoremediation systems. A.A. Akinsemolu & H.N. Onyeaka (2025) found analogous effects, focusing on the inhibition of the growth of sensitive plant species in coastal ecosystems with high organic load. M. Butu *et al.* (2021) noted a drop-in biomass on degraded soils with long-term anthropogenic impact, emphasising the direct link between chronic pollution and the productivity of phytoremediation. The findings of the study confirm the conclusions of P. Baltrėnas & E. Baltrėnaitė (2020), who proved the species-specificity of the reactions: different crops reacted differently to analogous concentrations of hydrocarbons, which explains the sharper decrease in germination of alfalfa compared to watercress. The phytotoxic effect was not only dependent on the concentration of the pollutant, but also on the biological characteristics of the test crops, which is key to predicting the environmental consequences of oil loading (Hussain *et al.*, 2022).

The assimilation capacity was 1.12 ± 0.08 mg of hydrocarbons/g×day in meadow-forest soils, 0.78 ± 0.05 mg/g×day in meadow soils, and only 0.34 ± 0.04 mg/g×day in grey-brown soils, while the mineralisation coefficient ranged from 0.52 ± 0.03 to 0.12 ± 0.01. The data obtained revealed a clear gradation of ecosystems' resistance to oil loading. A comparison with the literature showed analogous patterns. The high efficiency of biodegradation under conditions of balanced pH and sufficient humus fund was confirmed by V. Ghisman *et al.* (2025), emphasising that it is the combination of physicochemical and biotic factors that ensures maximum resistance to anthropogenic impact. The findings of W. Jin *et al.* (2025) showed that in coastal industrial areas, hydrocarbon risks were reduced precisely where the rate of microbial mineralisation was higher, which is consistent with the maximum values of K_m in meadow-forest soils. E. Chapman *et al.* (2020) emphasised the vulnerability of ecosystems functioning on the edge of climatic and anthropogenic stresses and pointed to the increased effects of degradation with a decrease in microbial activity – an analogous situation was observed in grey-brown soils. Quantitative models by K. Fennel *et al.* (2022) proved that mineralisation parameters can be considered as key predictors of environmental stability, which confirms the value of the K_m coefficient in this study. Additionally, D.A. Hutchins & D.G. Capone (2022) emphasised the role of the nitrogen cycle as a limiting factor in bioremediation, which partially explains the reduced efficiency in grey-brown soils, where the biogenic potential was minimal.

In the Guba-Khachmaz Region, the level of self-purification processes was the greatest, as evidenced by the biodegradation of hydrocarbons in meadow-forest soils at 1.15 mg/g×day and a mineralisation coefficient of more than 0.5. In contrast, in the Absheron-Khizin district, the assimilation capacity was only 0.28-0.92 mg/g×day with a K_m below 0.3, reflecting a high vulnerability of these soils to oil loading. The obtained results were consistent with the findings of A. Vaksmaa *et al.* (2023), who proved that microbial communities demonstrate markedly greater degradation activity in wet ecosystems, while in dry conditions, the decomposition efficiency was sharply reduced. The risk analysis conducted by P.O. Iniaghe & E.D. Kpomah (2023) showed that a low mineralisation factor was directly related to elevated levels of polycyclic aromatic hydrocarbons in soils, which confirmed the value of the data obtained for hazard assessment. M. Dehghani Darmian *et al.* (2020) demonstrated an analogous approach, considering the assimilative capacity as a key criterion in controlling pollution in aquatic ecosystems. The use of spatial geographic information system technologies, as described by Y. Wang (2023), helped to reasonably map risks and identify the most vulnerable areas, which is especially significant for areas with moisture deficit. Finally, the generalisation by Y.M. Youssef *et al.* (2021) emphasised that the combination of natural and anthropogenic factors always determines the scale of degradation processes in coastal regions, which was fully reflected in the comparison of the two study areas.

A generalisation of the results showed that the soils differed substantially in terms of their assimilation capacity and resistance to oil load. The most favourable characteristics were recorded in meadow-forest soils with a high humus reserve, sufficient moisture, and considerable biological activity. The meadow soils had an intermediate level of self-cleaning, but their efficiency was limited by moisture deficit. The grey soils were the most vulnerable, as low humus and alkalinity contributed to the accumulation of pollutants. Spatial differences between the Guba-Khachmaz and Absheron-Khizin districts confirmed the decisive influence of climatic and anthropogenic factors.

Conclusions

The analysis of physicochemical characteristics showed that meadow-forest soils had the greatest level of environmental sustainability. The neutral pH of 7.1-7.4, high humus reserves of 70-240 t/ha, moisture content of 1.0-1.5, and CO_2 content of 0.65% ensured active mineralisation and recovery processes. In meadow soils, the conditions were mediocre: pH 7.7-8.0, humus 35-60 t/ha, moisture content 0.4-1.25, CO_2 0.18-0.22%, which limited the assimilation capacity in case of moisture deficit. The worst parameters were found in grey-brown soils: pH 7.7-8.7, humus 24-38 t/ha, moisture coefficient 0.3-0.5, CO_2 0.15-0.19%. This indicated a low level of self-cleaning due to a lack of organic matter and moisture. Microbiological observations confirmed these differences. In the meadow-forest soils, the number of microorganisms increased from 2.1×10^6 CFU/g to 3.4×10^6 CFU/g in 15 days, and the share of oil-degrading crops was 30-35%, which reflected a high potential for destruction. In meadow soils, the growth was more modest – from 1.5×10^6 CFU/g to 2.0×10^6 CFU/g with a share of 18-22%. Grey-brown soils showed a regression: the number decreased from 0.9×10^6 CFU/g to 0.6×10^6 CFU/g, and the proportion of destructors did not exceed 8-12%. This confirmed that even in the presence of bacteria, the potential of their functioning depends on the organic matter reserves and water regime.

The results of bioindication tests showed a high sensitivity of plants to oil load. At a concentration of 5%, germination of watercress decreased from 95% to 70%, and alfalfa – from 93% to 65%, biomass decreased from 12.5 g to 8.9 g and from 15.2 g to 10.2 g, respectively. At 10% oil, germination dropped to 45% in watercress and 40% in alfalfa, and biomass almost halved to 6.1 g and 7.8 g. This demonstrated that even relatively resistant plant species are unable to withstand elevated levels of pollution, making natural recovery impossible without additional interventions. Integral indicators confirmed the general trend. The assimilation capacity in meadow-forest soils was 1.12 ± 0.08 mg/g×day with a mineralisation coefficient of 0.52 ± 0.03, which indicated that the process had reached stable end products. In meadow soils, the corresponding values were 0.78 ± 0.05 and 0.31 ± 0.02, and in grey-brown soils – only 0.34 ± 0.04 and 0.12 ± 0.01. This proved that soils with a neutral pH and high humus content provide the most effective self-purification, while alkaline soils with a lack of organic matter stay the most vulnerable.

A limitation of this study is not only the lack of long-term observations, which restricts assessment of the long-term dynamics of soil self-purification, but also the simplified experimental model of oil contamination. Laboratory experiments used n-hexadecane as a model saturated alkane, which ensured reproducibility but did not fully reflect the complexity and toxicity of real crude oil containing surfactants, resins, asphaltenes, and other persistent components. Therefore, the obtained assimilation and biodegradation indicators should be interpreted as responses to a simplified hydrocarbon load rather than to actual oil pollution. Future studies should incorporate complex petroleum mixtures and long-term field monitoring to more accurately evaluate the self-purification potential of Caspian coastal soils under realistic contamination conditions.

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Оцінка асиміляційної здатності та самоочисної спроможності біогеоекосистем прибережної зони Каспійського моря

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Анотація. Метою цього дослідження було визначення рівня здатності прибережних ґрунтів Каспійського моря нейтралізувати антропогенне навантаження на основі оцінки їхніх асиміляційних і самоочисних характеристик. Методологія дослідження ґрунтувалася на порівняльному аналізі ґрунтів Апшерон-Хизинського та Губа-Хачмазького регіонів Азербайджану, де відбір зразків здійснювали з горизонту 0-20 см, після чого в модельних умовах відтворювали різні рівні нафтового навантаження та оцінювали мікробіологічні, біохімічні й біоіндикативні показники з метою визначення самоочисної здатності екосистем. Найвищу стійкість продемонстрували лучно-лісові ґрунти, які характеризувалися нейтральною реакцією середовища (pH 7,1-7,4), високими запасами гумусу (70-240 т/га) та підвищеною біологічною активністю, що підтверджувалося вмістом вуглекислого газу на рівні 0,65 %. Їхня здатність до розкладання вуглеводнів становила 1,12 ± 0,08 мг на грам ґрунту за добу, а коефіцієнт мінералізації досягав 0,52 ± 0,03. Лучні ґрунти з вмістом гумусу 35-60 т/га та часткою нафторуйнівних мікроорганізмів 18-22 % характеризувалися нижчим рівнем біодеградації – 0,78 ± 0,05 мг/г×добу при коефіцієнті мінералізації 0,31 ± 0,02. Найбільш уразливими виявилися сіроземно-бурі ґрунти з мінімальним запасом органічної речовини (24-38 т/га) та низькою часткою деструкторів (8-12 %); у цих ґрунтах асиміляційна здатність не перевищувала 0,34 ± 0,04 мг/г×добу при коефіцієнті мінералізації 0,12 ± 0,01. Біоіндикативні тести засвідчили зниження схожості насіння крес-салату та люцерни до 40-45 % і зменшення біомаси на 50 % за умов 10 % нафтового забруднення. Отримані результати підтвердили, що лучно-лісові ґрунти є найбільш стійкими, лучні ґрунти займають проміжне положення, тоді як сіроземно-бурі ґрунти є найбільш уразливими до нафтового забруднення. Практична значущість результатів полягає в можливості їх використання екологічними службами та аграрними науково-дослідними центрами для моніторингу стану ґрунтів і розроблення стратегій біоремедіації в регіонах Каспійського моря

Ключові слова: біоіндикація; нафтопродукти; токсичний вплив; біодеградація; стійкість; забруднювач; мікробні угруповання

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Assessment of heavy metal and pesticide contamination in organic crops using *Allium cepa*

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Abstract. Increasing requirements for the environmental safety of agricultural systems necessitate reliable bioindicative methods for assessing the toxicity of soil contaminants to plants. This study aimed to compare the phyto-, cyto-, and genotoxic effects of binary combinations of heavy metals (Cd+Pb, Cu+Zn) and glyphosate using the *Allium cepa* test system. A controlled laboratory experiment with 20 onion bulbs per group, five repetitions, and one control and three experimental treatments was conducted. Morphometric analysis of root growth (root length and fresh weight), visual evaluation of morphological damage, cytogenetic analysis of apical meristem cells (mitotic index and chromosomal aberration frequency and spectrum), and Student's t test were used to assess. EC50 was calculated using nonlinear regression, and compared to maximum permissible concentration standards. The highest phytotoxicity was observed for the Cd+Pb combination, which reduced root growth by 55.1%, followed by Cu+Zn (47.2%), while glyphosate showed the lowest effect (39.0%). Cytogenetic analysis revealed significant inhibition of mitotic activity (54.2%, 38.5%, and 26.3%, respectively) and increased chromosomal aberrations, with heavy metals showing predominantly clastogenic effects and

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glyphosate characterised by a higher proportion of chromosomal bridges. Experimentally determined EC50 values for Cu, Zn, Pb, and Cd were 3-25 times lower than current maximum permissible concentrations, indicating biologically significant effects at concentrations considered permissible. The results demonstrated the high sensitivity of the *Allium cepa* test system and indicated that existing environmental standards for heavy metals may underestimate risks to plant organisms, particularly in agricultural systems where copper-containing products are permitted

Keywords: phytotoxicity; genotoxicity; cytotoxicity; cytogenetic analysis; apical meristem

Introduction

Against the backdrop of the increasing demands for soil quality and environmental safety in agriculture, the problem of toxic contamination is becoming acute. Human activity leads to the accumulation of persistent heavy metals and pesticides in the soil, which inhibit cellular processes and cause disease. Bioindication, a method of assessing the state of the environment using living organisms, is used to identify these threats. Various biological objects have been used in studies of soil toxicity bioindication. D.S. Gangwar (2024) analysed current trends in the development of biosensor technologies for monitoring pollutants in agricultural systems. The potential of biosensors for the accurate determination of toxic substances, including pesticides, organic pollutants and heavy metals, has been established. The results justified the need to integrate biosensor technologies into environmental monitoring systems for agricultural soils. P. Osyczka *et al.* (2023) investigated the suitability of measuring peroxidation of membrane lipids in *Cladonia rei* lichen as a biomarker for predicting elevated levels of toxic trace elements in soil. It was found that the level of peroxidation did not increase linearly with the pollution index value, indicating the activation of protective mechanisms in lichens. The data obtained confirmed the effectiveness of using physiological indicators of lichens to assess the ecological state of soil ecosystems.

Microbial communities as indicators of soil quality were studied by N. Malik *et al.* (2023), who conducted a comparative analysis of soil toxicity in organic and conventional farm fields. The results showed that alternative soil management practices reduced heavy metal toxicity and supported the microbial population. The differences in microbial composition between different farming systems indicated the sensitivity of microorganisms to soil cultivation methods. The long-term impact of sustainable soil management practices on heavy metal concentrations was assessed by Y. Chen *et al.* (2025). Organically managed soils contained 10.8-73.7% less heavy metals than conventional systems and were characterised by lower geoaccumulation indices. Microbial sequencing revealed increased richness and diversity of bacteria and fungi in organic soils, demonstrating the positive impact of organic practices on soil biota. Vertebrates as bioindicators of the ecological status of agroecosystems were studied by M. Verderame & R. Scudiero (2019), who analysed the health status of the *Podarcis siculus* lizard from agriculturally managed areas. A comparison with populations from non-anthropogenic areas showed that lizards from organic farms had lower levels of toxic heavy metal accumulation in their tissues. The differences observed confirmed that less intensive agricultural management systems created a less toxic environment for wildlife compared to conventional farming methods.

The variability and succession of microbial communities under conditions of persistent heavy metal pollution were analysed by M. Shuaib *et al.* (2021). It was found that heavy metals (copper, lead, mercury, nickel, cadmium, zinc, and arsenic) caused significant changes in the composition of microbial communities and activated specific mechanisms of microorganism survival. The adaptive processes identified revealed the role of microbes in the biogeochemical cycles of polluted ecosystems and the mechanisms of their tolerance to toxic stress.

The biogeochemical characteristics of heavy metals in the agroecosystems of the Forest-Steppe zone of Ukraine were studied by I. Shumyhai *et al.* (2022). It was found that a significant amount of chemical elements entered the soil with mineral and organic fertilisers, negatively affecting its physical and chemical properties. The results justified the need to control the quality of fertilisers and develop measures to reduce the anthropogenic load on regional agroecosystems. The effectiveness of exogenously applied melatonin in increasing pepper tolerance to chromium stress was investigated by M. Rizwan *et al.* (2024). It was found that melatonin improved photosynthetic parameters and antioxidant enzyme activity in plants under chromium stress conditions. The recorded effects demonstrated the promise of using natural bioregulators to increase plant resistance to the toxic effects of heavy metals in agricultural production. The interaction of heavy metals and pesticides in the soil environment was studied by W. Jiang *et al.* (2021), who analysed the effect of cadmium and lead ions on the enantioselective degradation of α-cypermethrin. The results showed that heavy metals significantly inhibited the degradation of the pesticide, increasing its half-life and suppressing the activity of key soil enzymes.

The combined negative effect of pollutants on biochemical processes in the soil is important for understanding the fate of pesticides in contaminated agroecosystems (Khassanova *et al.*, 2024). The mechanisms of combined soil contamination with heavy metals, microplastics and pesticides were analysed by S. Fang *et al.* (2025). Complex synergistic interactions between pollutants through electrostatic adsorption, surface complexation and physical absorption were identified. The established changes in the bioavailability and toxicity of individual components when they interact emphasised the need to take into account the multicomponent nature of pollution when assessing environmental risks. A systematic analysis of the toxic effects of heavy metals and pesticides on agricultural soils and plants was carried out by A. Alengebawy *et al*. (2021). The mechanisms of pollutant accumulation in plant tissues and their impact on plant physiological parameters, including photosynthesis, water exchange and growth, were analysed. The summarised data substantiated the need to develop comprehensive strategies for monitoring and reducing the negative impact of pollutants on the productivity and safety of agricultural products.

Despite the achievements, there is a lack of long-term and comprehensive assessments of the impact of pollutants on ecosystems, as well as standardised methods of biodiagnostics. In addition, there is a need for in-depth study of the mechanisms of interaction between different stressors and the development of innovative monitoring technologies. The identified gaps necessitated the current study. The aim of the study was to conduct a comprehensive bioindicative assessment of the toxic effects of different types of pollutants on agroecosystems – binary combinations of heavy metals and glyphosate – on the morphophysiological and cytogenetic in dicators of the test organism *Allium cepa* to establish their relative danger and mechanisms of toxic action.

Materials and Methods

The present work was an experimental laboratory study conducted between September and November 2024. Data collection was carried out under controlled laboratory conditions. *Allium cepa* L. bulbs of the "Stuttgart Riesen" variety were used as biological test objects. *Allium cepa* was selected due to its high sensitivity to genotoxic and cytotoxic effects, large chromosomes (2n = 16) facilitating cytogenetic analysis, extensive validation in the scientific literature for assessing heavy metal and pesticide toxicity, simple cultivation protocol, and demonstrated correlation with other biological test systems. The sample was selected deliberately, using clear inclusion criteria: only healthy bulbs of the same size (diameter 3.5 ± 0.5 cm) without mechanical damage, signs of sprouting or disease were used. Bulbs that did not meet these criteria were excluded from the study. The experimental design included one control and three experimental groups, each consisting of 20 bulbs in five replicates. Analytically pure chemical reagents were used for the model solutions: cadmium chloride ($CdCl_2$), lead nitrate ($Pb(NO_3)_2$), copper sulphate ($CuSO_4 \cdot 5H_2O$), zinc sulphate ($ZnSO_4 \cdot 7H_2O$) and a commercial glyphosate preparation (in the form of isopropylamine salt, 360 g/l). Specifically, the Cd + Pb solution contained cadmium and lead at a 1:1 molar ratio, and the Cu + Zn solution contained copper and zinc at a 1:1 molar ratio.

The bulbs were germinated in individual 200 mL glass containers containing 100 mL of the corresponding test solution at a temperature of 22 ± 2 °C and a 12-hour photoperiod. Bulbs were placed with the basal plate facing downward so that only the basal part was immersed (~3-5 mm) and were fixed at the container mouth using a cardboard/foam support ring (no substrate was used). Aqueous exposure was necessary to achieve the study objectives: direct comparison of toxic effects between pollutants requires identical exposure conditions and precise concentration control, which is unattainable in soil systems where complex sorption, precipitation, and microbial processes create variable and unpredictable bioavailability.

This method enabled accurate determination of EC_{50} values – quantitative parameters essential for comparing experimentally observed toxicity with established regulatory maximum permissible concentration (MPC) standards for soils, including DSanPiN 2.2.7.029-99 (1999) for heavy metals and Regulation of the European Parliament and of the Council No. 396/2005 (2005) for pesticide residues. Furthermore, direct solution contact provided optimal conditions for cytogenetic analysis by ensuring sufficient pollutant uptake to root meristem cells, allowing detection of chromosomal aberrations and differentiation between clastogenic and aneugenic mechanisms. The experimental design prioritized mechanistic understanding and relative toxicity ranking over field simulation, providing fundamental data on intrinsic toxic potency independent of site-specific soil characteristics. For quantitative assessment of phytotoxicity at the macroscopic level, the length of all roots of each bulb was measured using a millimetre ruler and the wet weight of the root bundle was determined on Sartorius CPA225D analytical scales (Germany) (accuracy ±0.1 mg). Based on these data, the phytotoxic effect (PE) was calculated using formula (1):

$$PE = ((L_c - L_e) / L_c) \times 100\%, \quad (1)$$

where L_c – the average root length in the control group; and L_e – the average root length in the experimental group. A visual analysis of morphological changes was also carried out, recording changes in colour, turgor, and the presence of necrosis and deformations. This comprehensive approach made it possible to obtain data on general growth inhibition and specific external manifestations of toxicity.

Cytogenetic analysis methods were used to elucidate the cellular mechanisms of toxicity. Root tips were fixed in Clark's fixative (ethanol : acetic acid, 3:1), after which temporary pressure preparations were prepared by acid hydrolysis in 1N HCl and staining with 2% aceto-orsenine. The preparations were analysed using a Leica DM500 light microscope (Leica Microsystems, Germany). Cytotoxicity was assessed by calculating the mitotic index (MI) as the proportion of cells in mitosis per 1,000 cells analysed. Genotoxicity was determined by the frequency and spectrum of chromosomal aberrations (bridges, fragments, lagging chromosomes, C-mitoses) in the anaphase and telophase stages, analysing at least 200 anaphases and telophases for each group. These methods allowed to differentiate the effect of pollutants on cell division processes and the integrity of the chromosome apparatus.

The interpretation of the results was based on statistical data processing in the R software environment (version

4.2.1). To compare the mean values between groups, the two-sample Student's t test was used, and differences were considered statistically significant at a level of $p < 0.05$. Quantitative assessment of toxicity was performed by determining the effective concentration (EC_{50}). EC_{50} values were estimated by fitting a nonlinear regression, which accounts for the lower and upper asymptotes, slope, and inflection point of the dose-response relationship. The EC_{50} value was derived as the inflection point of the fitted curve corresponding to 50% growth inhibition. The experimentally determined EC_{50} values were compared with the regulatory MPC (DSanPiN 2.2.7.029-99, 1999; Regulation of the European Parliament and of the Council No. 396/2005, 2005) allowed to assess the adequacy of existing environmental standards.

Analysis of macroscopic indicators allowed the level of phytotoxicity of the studied pollutants to be established and compared. Cytogenetic analysis revealed the cellular mechanisms of this toxicity, differentiating between cytotoxic and genotoxic effects. The calculation of EC_{50} and its comparison with MPC provided a quantitative basis for assessing the environmental risks associated with soil contamination in agricultural systems. Thus, the consistent application of these methods provided a comprehensive bioindicative assessment of the impact of heavy metals and glyphosate on plant organisms.

Results

The effect of heavy metals and glyphosate on the growth processes of the test object *Allium cepa* L. was assessed by analysing morphometric parameters and visual morphological changes in the root system. Quantitative and qualitative results characterising the phytotoxic effect are presented in Table 1.

Table 1. The effect of heavy metals and glyphosate on macroscopic indicators of the root system of *Allium cepa* L

Test group	Average root length, mm ($M \pm SD$)	Phytotoxic effect (PE), %	Average root wet weight, mg ($M \pm SD$)	Ratio to control, %	Visual morphological changes
Group 1 (Cd+Pb)	8.12 ± 0.45	55.1	315 ± 25	56.3	Necrosis of tips (dark brown colour), thickening, brittleness, deformities
Group 2 (Cu+Zn)	9.55 ± 0.61	47.2	380 ± 31	67.9	Browning of tips, loss of turgor, curvature, reduction in root hairs
Group 3 (Glyphosate)	11.03 ± 0.52	39.0	442 ± 28	78.9	Retention of white colour, reduction in diameter, general growth inhibition without local necrosis
Control	18.08 ± 1.15	-	560 ± 42	100	Elastic, white roots with a well-developed root hair zone

Note: M – mean value; SD – standard deviation; PE was calculated using the root growth inhibition formula

Source: compiled by the authors

Analysis of the data obtained demonstrates statistically significant ($p < 0.001$) inhibition of growth processes in all experimental groups compared to the control. This confirms the phytotoxic effect of the studied combinations of heavy metals and glyphosate at the given concentrations. The most pronounced inhibitory effect was recorded in Group 1 (Cd + Pb). The average root length in this group was 8.12 ± 0.45 mm, which corresponds to the maximum PE calculated by formula (1) at 55.1%. This reduction in length was accompanied by a proportional decrease in the average raw weight of the roots to 315 ± 25 mg, which is only 56.3% of the control value. Qualitative analysis confirmed high toxicity: intense necrotic processes were observed at the tips of the roots (darkening to dark brown), their thickening and increased brittleness, indicating deep structural damage to the tissues.

In Group 2 (Cu + Zn), the phytotoxic effect was slightly lower but remained at a high level (F = 47.2%). The reduction in root length to 9.55 ± 0.61 mm correlated with a decrease in root mass to 380 ± 31 mg (67.9% of the control). The morphological changes in this group were different in nature compared to Group 1: instead of pronounced necrosis, browning of the tips and a noticeable loss of turgor were observed, indicating a disturbance in the water balance of the cells and the initial stages of damage. A decrease in the number of root hairs was also noted.

Group 3 (Glyphosate) showed the lowest level of phytotoxicity among the experimental groups (PE = 39.0%). Growth inhibition to 1,103 ± 0.52 mm was statistically significant, but visual damage was minimal. The roots retained their normal white colour and showed no signs of necrosis or deformation. The main effect was manifested in general growth inhibition and a decrease in root diameter, which may indicate a systemic rather than a local mechanism of toxic action directed at the biochemical processes of growth. In the control group, active growth of the root system was observed to an average length of 18.08 ± 1.15 mm. The roots were elastic, white in colour, with a well-developed zone of root hairs, indicating optimal conditions for growth and the absence of toxic stress.

Analysis of the variability of indicators (SD) indicates the highest homogeneity of response in Group 1 (SD = 0.45), which may be due to the strong and universal inhibitory effect of the Cd+Pb combination. Conversely, the greatest variability in the control group (SD = 1.15) reflects the natural variability of biological processes in the absence of stress factors. Thus, the analysis of macroscopic indicators allowed to establish a clear gradation of phytotoxicity of the studied pollutants: (Cd+Pb) > (Cu+Zn) > Glyphosate. The morphological changes detected indicate different mechanisms of damage. For a deeper understanding of these mechanisms at the cellular level, cytogenetic analysis was performed. To elucidate the cellular mechanisms underlying macroscopic growth inhibition, cytogenetic analysis of apical meristem cells was performed. Detailed results are presented in Table 2.

Table 2. Cytotoxic and genotoxic effects in cells of the apical meristem of *Allium cepa* L

Indicator	Group 1 (Cd+Pb)	Group 2 (Cu+Zn)	Group 3 (Glyphosate)	Control
MI, %	48.5 ± 3.1	65.2 ± 4.0	78.1 ± 3.5	106.0 ± 5.8
MI inhibition, %	54.2	38.5	26.3	-
Total frequency of aberrations, %	12.4 ± 1.5	8.9 ± 1.1	5.1 ± 0.9	1.2 ± 0.4
Spectrum of aberrations, % of total number:				
Chromosome fragments	62.9	58.4	49.0	66.7
Chromosome bridges	37.1	41.6	51.0	33.3
Lagging chromosomes	3.2	2.1	1.5	0.5
C-mitosis	1.8	0.9	0.2	0

Note: several types of aberrations could be observed simultaneously in one cell, therefore the total percentage exceeds 100%
Source: compiled by the authors

The results of cytogenetic analysis revealed disturbances in cell division processes and structural damage to chromosomes in all experimental groups. The cytotoxic effect, assessed by changes in the MI, directly correlates with the data of macroscopic analysis. Group 1 (Cd+Pb) showed the most profound suppression of mitotic activity: the intensity of cell division decreased by more than half (54.2% inhibition) compared to the control. This indicates the cytotoxic effect of the combination of cadmium and lead, which blocks the transition of cells to mitosis or stops it in the early stages. In Group 2 (Cu+Zn), MI inhibition was less pronounced but still significant, reaching 38.5%. Glyphosate (Group 3) showed the least cytotoxic effect, with a 26.3% reduction in MI. Thus, in terms of cytotoxicity, the studied pollutants are ranked in the same order as in terms of phytotoxicity.

The genotoxic effect, characterised by the frequency and spectrum of chromosomal aberrations, also shows a clear dependence on the type of pollutant. The overall frequency of aberrations in Group 1 exceeded the control level by more than 10 times, indicating the high mutagenic potential of the Cd+Pb combination. Analysis of the spectrum of abnormalities in this group showed that almost two-thirds (62.9%) of all aberrations were chromosomal fragments. This dominance indicates a predominantly clastogenic (chromosome-fragile) mechanism of action. In Group 2, the frequency of aberrations exceeded the control by 7.4 times. The spectrum of abnormalities was similar to Group 1, with a predominance of fragments (58.4%), indicating a similar, albeit less intense, clastogenic mechanism of action of the Cu+Zn pair.

Group 3, which includes glyphosate, was identified within the study. Although the overall frequency of aberrations here was the lowest among the experimental groups (4.2 times higher than the control), the spectrum of disorders was different. This group had the highest relative proportion of chromosomal bridges (51.0%), which even exceeded the proportion of fragments. A mechanism of genotoxicity was established, covering not only chromosome breaks but also disturbances in the functioning of the apparatus of their separation. Additional evidence of the specificity of heavy metal action is the detection of C-mitoses, a marker of spindle dysfunction. This type of aberration was most pronounced in the heavy metal groups (Group 1 – 1.8% and Group 2 – 0.9%), while glyphosate showed a minimal level of C-mitoses (0.2%), indicating a significantly higher aneugenic potential of heavy metals compared to glyphosate at the concentrations studied. Thus, microscopic analysis not only confirmed the toxicity gradation established at the macro level, but also revealed differences in the mechanisms of toxic action of the studied pollutants. Heavy metals demonstrate a powerful clastogenic and aneugenic effect, while the genotoxicity of glyphosate is associated with other cellular targets. The results of calculating p values for key macroscopic and microscopic indicators are summarised in Table 3.

Table 3. Summary table of p values for comparison of experimental groups

Comparable groups	Root length	Root weight	MI	Frequency of aberrations
Control vs Group 1	< 0.001	< 0.001	< 0.001	< 0.001
Control vs Group 2	< 0.001	< 0.001	< 0.001	< 0.001
Control vs Group 3	< 0.001	< 0.01	< 0.01	< 0.01
Group 1 vs Group 2	< 0.05	< 0.05	< 0.01	< 0.05
Group 1 vs Group 3	< 0.001	< 0.001	< 0.001	< 0.001
Group 2 vs Group 3	< 0.01	< 0.05	< 0.05	< 0.01

Source: compiled by the authors

The data presented in Table 3 provide quantitative statistical confirmation of the observed effects and allow for an objective assessment of the reliability of the differences identified between the groups. Analysis of *p* values is key to moving from qualitative observations to scientifically sound conclusions. The results of the analysis clearly demonstrate that the impact of all pollutants studied led to statistically significant changes compared to the control group. For Group 1 (Cd+Pb) and Group 2 (Cu+Zn), the highest level of statistical significance ($p < 0.001$) was recorded for all four indicators: root length and mass, MI, and frequency of chromosomal aberrations. Such a low *p* value indicates that the probability of such large differences occurring by chance is extremely low (less than 0.1%). This is evidence of the strong and indisputable phyto- and genotoxic effects of both combinations of heavy metals.

For Group 3 (Glyphosate), the differences from the control are also statistically significant, but with a slightly higher p-value for some parameters. While root length inhibition remains highly significant ($p < 0.001$), the *p* value for root mass, MI and aberration frequency is < 0.01. This is consistent with the data in the previous tables, which showed a less pronounced toxic effect of glyphosate. Nevertheless, a significance level of $p < 0.01$ is still considered highly reliable in biological studies and leaves no doubt about the presence of a toxic effect. A key result that highlights the informative nature of the study is the presence of statistically significant differences not only relative to the control, but also between the experimental groups themselves. This allows not only to state toxicity, but also to compare its level.

A comparison of Group 1 (Cd+Pb) and Group 2 (Cu+Zn) revealed significant differences in all analysed parameters. The most significant difference was observed in the MI ($p < 0.01$), indicating a significantly stronger cytotoxic potential of the Cd+Pb pair. The differences in macroscopic indicators (length, weight) and the frequency of aberrations were also significant ($p < 0.05$). This allows to make a reasonable conclusion that, under the conditions studied, the combination of cadmium and lead is more toxic than the combination of copper and zinc. Similarly, a comparison of both groups with heavy metals (Group 1 and Group 2) with Group 3 (Glyphosate) revealed highly significant differences ($p < 0.01$ or $p < 0.001$) in all indicators. This statistically confirms that the toxicity of both combinations of heavy metals is significantly higher than that of glyphosate. Thus, the results of statistical analysis allow to establish a clear, scientifically based hierarchy of toxicity of the pollutants under study. The toxicity gradation is as follows: (Cd+Pb) > (Cu+Zn) > Glyphosate. The presence of reliable differences between all groups indicates not only different levels of toxicity, but also the high sensitivity and differential ability of the *Allium cepa* test system used, which makes it an effective tool for the comparative assessment of the toxicity of various chemical compounds and their combinations.

To provide a quantitative reference for toxicity assessment and regulatory comparison, EC_{50} were calculated for individual components of the studied pollutants. It should be noted that, except for glyphosate, the experimental exposure was conducted using binary mixtures (Cd+Pb and Cu+Zn). Therefore, the obtained EC_{50} values do not represent the intrinsic toxicity of the experimental mixtures as such, but rather serve as comparative indicators reflecting the relative sensitivity of the *Allium cepa* test system and allowing alignment with existing regulatory MPC. The values shown in Table 4 were compiled by integrating the experimentally obtained EC_{50} values from the present dose-response analysis with the corresponding MPC values extracted from applicable regulatory documents, followed by calculation of the MPC/EC_{50} ratios for comparative assessment.

Table 4. Comparison of experimentally determined EC50 values with regulatory MPC values

Pollutant	MPC of mobile forms in soil, mg/kg	Experimental EC_{50}, mg/l	MPC/EC_{50} ratio
Cadmium (Cd)	0.7	0.45	1.6
Lead (Pb)	6.0	2.10	2.9
Copper (Cu)	3.0	0.12	25.0
Zinc (Zn)	23.0	2.55	9.0
Glyphosate	0.1	0.22	0.45

Source: compiled by the authors based on DSanPiN 2.2.7.029-99 (1999), Regulation of the European Parliament and of the Council No. 396/2005 (2005)

A comparative analysis of experimentally determined toxic concentrations and regulatory indicators revealed a systemic discrepancy for a group of heavy metals. This indicates that biologically significant negative effects at the level of primary producers in the agroecosystem may occur at concentrations that are considered acceptable according to current regulations. The most critical discrepancy, demonstrating the potential inconsistency of existing standards with biological effects, was recorded for copper (Cu). The experimentally determined EC_{50} of 0.12 mg/L was 25 times lower than the MPC standard (3.0 mg/kg). Such a significant discrepancy indicates a potentially high environmental risk associated with copper contamination of soils, which may be underestimated when using a regulatory approach alone. In certain agricultural management systems, copper-containing fungicides are widely used plant protection products, which leads to the gradual accumulation of copper in the soil to concentrations that, although not exceeding the MPC, may have a phytotoxic effect (Shahini *et al.*, 2023).

A similar, albeit less pronounced, trend can be observed for other metals studied. For zinc (Zn), the MPC exceeds the EC_{50} by nine times, and for lead (Pb) by almost three times. This confirms that the problem of non-compliance of standards with biological effects is not unique to copper, but is systemic for the group of heavy metals. For cadmium (Cd), a different relationship was observed. Despite its known high toxicity and one of the lowest MPC standards, the experimentally determined EC_{50} was still 36% lower than the standard. This indicates that even for the most dangerous pollutants, existing standards may not have a sufficient safety factor to protect plant organisms from chronic exposure.

A fundamentally different picture is observed for glyphosate. Its experimental EC_{50} (0.22 mg/l) was 2.2 times higher than the MPC standard adopted in the European Union (EU) countries (0.1 mg/kg). This may indicate that: a) the standard for glyphosate has been set with a significant safety margin specifically for acute phytotoxicity to higher plants; b) the *Allium cepa* test system may be less sensitive to this herbicide than other biological objects (e.g., soil microorganisms, aquatic invertebrates), the risks to which were also taken into account when developing the MPC.

Summarising the data obtained, it can be stated that the results of the study cast reasonable doubt on the adequacy of existing MPC standards for heavy metals, especially for copper and zinc, in the context of protecting plant components of agroecosystems. The identified discrepancies, where biologically significant effects occur at concentrations significantly lower than the permissible limits, justify the need to review and possibly tighten environmental standards, which is particularly relevant for ensuring the environmental sustainability and productivity of agricultural systems.

Discussion

The current study evaluated the toxicity of heavy metals and glyphosate using morphometric growth indicators and cytogenetic changes in *Allium cepa*. The most toxic effect was observed with Cd+Pb exposure, accompanied by a significant reduction in root length and mass, inhibition of mitotic activity by more than 50%, and a high frequency of chromosomal aberrations, especially fragmentation. A systemic discrepancy between biologically active concentrations of toxicants and current standards was recorded, which makes it necessary to review the MPC in organic production soils. In a study by T. Da Silva Martins *et al.* (2024), soil toxicity was bioindicated using enzyme activity (arylsulfatase, urease) under conditions of prolonged pesticide exposure. It was found that increased concentrations of Cd, Cu, and Zn in soils lead to a decrease in enzyme activity, indicating a decline in soil quality. Although the study confirms the negative impact of heavy metals, the methodology is based not on phytotests but on microbiological indicators. Unlike the results with *Allium cepa*, the authors do not analyse genotoxicity and do not question the current standards. The discrepancy in the conclusions may be explained by the lower sensitivity of microbiological indicators to sublethal concentrations or by a different biological object of analysis.

In the experiment, the cadmium-lead combination caused the most severe morphological changes, including intense necrotic processes at the root tips (darkening to dark brown), their thickening and increased brittleness, indicating profound structural tissue damage and a maximum phytotoxic effect of 55.1%. M. Bożym & J. Rybak (2024) established a completely different toxicity hierarchy using *Lepidium sativum*: Se > As > Hg > Sb > Mo > Cd > Co > Zn > Ni. Lead showed stimulating effects at low concentrations instead of high toxicity, and zinc took the place of cadmium as less toxic, fundamentally contrasting with the results found in the current study on serious phytotoxicity. The discrepancies can be explained by the species-specific sensitivity of different plant test objects and concentration effects (Mustafayeva *et al.*, 2011; Lyubchyk *et al.*, 2019).

In the experiments conducted, glyphosate showed the lowest level of phytotoxicity among all groups, with growth inhibition of up to 11.03 ± 0.52 mm with minimal visual damage. The main effect was manifested in general growth inhibition and a decrease in root diameter without signs of necrosis or deformation, which was interpreted as a systemic mechanism of toxic action directed at the biochemical processes of growth. E. Yalçin & K. Çavuşoğlu (2022) documented severe chromosomal aberrations and genotoxicity in *Allium cepa* at a concentration of 500 mg/L, showing direct interactions between deoxyribonucleic acid (DNA) and glyphosate through spectral analysis. The study found an increase in the formation of micronuclei, chromosome fragments, sticky chromosomes, and bridges, along with severe cell damage, including damage to epidermal and cortical cells and irregular vascular tissue. The discrepancies are explained by the use of different concentrations of glyphosate and different focuses on morphological versus cytogenetic effects.

Cytogenetic analysis showed that in the glyphosate group, the highest relative proportion of chromosomal bridges (51.0%) even exceeded the proportion of fragments, indicating a distinct mechanism of genotoxicity associated not only with chromosome breaks but also with disruption of the apparatus of their separation, unlike the potent clastogenic and aneugenic effects of heavy metals. C. Benbrook *et al.* (2023) conducted a meta-analysis of 94 genotoxicity tests, showing that 73% of studies of technical glyphosate and 95% of studies of glyphosate formulations were positive for genotoxicity. Seven positive *in vivo* human studies reported DNA damage, oxidative stress, and chromosomal aberrations, providing strong evidence of clastogenic and aneugenic effects (Ilderbayeva *et al.*, 2024). This contradicts the conclusion of the current study that glyphosate has no clastogenic potential. In cytogenetic analysis, C-mitoses – a marker of spindle dysfunction – were only observed in the heavy metal groups (Group 1 and Group 2), indicating their aneugenic potential, which is absent in glyphosate at the concentrations studied. R. Mesnage *et al.* (2022) demonstrated that glyphosate-based herbicides activated DNA damage response pathways using ToxTracker tests, revealing mechanisms of oxidative stress and protein unfolding.

Results of the statistical analysis allowed for the establishment of a clear, scientifically grounded hierarchy of toxicity for the studied pollutants, with the gradation (Cd+Pb) > (Cu+Zn) > Glyphosate. The presence of significant differences between all groups indicated not only different levels of toxicity but also the high sensitivity and differential capability of the *Allium cepa* test system used. V.I. Domínguez-Rodríguez *et al*. (2020) presented a modified Organisation for Economic Co-operation and Development (OECD) protocol using biotests with earthworms, which showed different sensitivity patterns compared to plant tests. For oil drilling waste, soil extracts showed 0% mortality, while direct soil contact showed 100% mortality. However, after treatment, mortality dropped to acceptable OECD ranges (3-13%), indicating that methodological approaches significantly influence conclusions about toxicity. The discrepancies are explained by the different sensitivities of the test organisms and methodological peculiarities.

The study's results demonstrate clear gradations of phytotoxicity for the studied pollutants with a progressive increase in toxic effects, confirmed by statistically significant inhibition of growth processes in all experimental groups compared to the control, with the most pronounced inhibitory effect at the highest concentrations. C. Wei *et al*. (2022) demonstrated clear hormesis dose-effect relationships, where low concentrations of zinc (15-30 mg/L) improved wheat growth and the activity of antioxidant enzymes. The maximum stimulatory response occurred at 15 mg/L for root growth, with improved photosynthetic ability and antioxidant enzyme activity, completely contradicting linear dose-effect models of toxicity. The discrepancies are explained by non-linear biological reactions and the essential nature of some metals at low concentrations.

Glyphosate demonstrated a statistically significant growth inhibition to 11.03 ± 0.52 mm, which was interpreted as evidence of a toxic effect and a potential danger to agroecosystems, especially in contexts where its use is restricted but contamination from neighbouring agricultural plots can occur. M. Hagner *et al*. (2019) found that applying Roundup at maximally allowed doses (3 kg/ha of glyphosate) had only minor and temporary effects on soil fauna and functioning, with no glyphosate residues detected at the end of the experiment. The effects on soil functioning were minimal compared to mechanical weed removal, challenging assumptions about glyphosate's persistence and toxicity. The discrepancies may be explained by different doses, environmental conditions, and exposure times.

The study's results treated all investigated heavy metals exclusively as toxicants that cause damage to plant tissues and inhibit growth processes, without considering the possible positive biological roles of some of these elements at low concentrations. Y. Wan *et al*. (2024) provided comprehensive documentation of over 9,000 hormesis models, showing patterns of low-dose stimulation and high-dose inhibition for trace elements and heavy metals in multiple biological systems, demonstrating that environmental pollutants can act as biological regulators rather than exclusively toxic agents. This changes the understanding of the role of metals in biological systems and the need to consider hormetic effects in toxicological assessments.

In the context of alternative agricultural management practices, attention was focused on external contamination by heavy metals and pesticides, without a detailed consideration of potential sources of contamination that may come from the organic materials themselves used in such farming systems. J.O. Olowoyo & L.L. Mugivhisa (2019) demonstrated that organic materials used in farming can contain toxic pollutants that bioaccumulate in plant tissues. Manure contained varying concentrations of arsenic, cadmium, and lead, with higher concentrations in pig manure compared to cow manure, challenging assumptions about the safety of organic fertilisers regarding heavy metal contamination. The discrepancies are explained by the underestimation of internal sources of contamination in organic systems.

The organic farming system was considered an environment with minimal use of synthetic pesticides, where the main sources of contamination are external or associated with the previous conventional use of land, with the expectation of gradual remediation following conversion to organic methods (Zakharchuk *et al*., 2019; Shuvar *et al*., 2022). A. Benzing *et al*. (2025) showed that 21 out of 90 chemicals may potentially leave residues in organic food even after two years of conversion, with food residues linked to residual contamination in soil. The research was based exclusively on the results of bio-testing with *Allium cepa* to establish a hierarchy of pollutant toxicity and draw conclusions about the adequacy of regulatory standards. The high sensitivity and differential ability of this test system were seen as an advantage for environmental assessment. Nevertheless, D. Kim *et al*. (2021) demonstrated that the choice of test species at the screening level of ecological risk assessments is critical, as different species can show opposite reactions to the same substances. This indicates the limitations of conclusions based on a single test organism, even one as sensitive as *Allium cepa*.

The problem identified in the current study is the significant phytotoxic and genotoxic effect of heavy metals (Cd+Pb, Cu+Zn) and glyphosate on the growth and structure of the *Allium cepa* L. root system, manifested by growth inhibition, morphological damage, and cellular aberrations. This points to a high ecological risk of soil contamination, especially considering the discrepancy between toxic concentrations and existing standards. One study, namely P. Ziarati *et al*. (2020), examined the bioadsorption of heavy metals from contaminated soils and water using food and agricultural wastes. This research proposes an alternative approach to limiting soil heavy metal toxicity through immobilisation and reduced plant availability, which does not contradict the phytotoxic effects observed in the present study but opens discussion on potential mitigation strategies. Another study, V.O. Velychko (2020), analysed physiological and ecological monitoring of xenobiotics, including heavy metals, within the food-livestock system, emphasising the systemic effects of heavy metals on living organisms through food chains. The conclusions stress the importance of controlling the migration of toxic elements and accounting for them across different trophic levels, thereby broadening the context of the present research, which is focused mainly on a plant-based test system.

A.O. Splodytel (2019) focused on the distribution and mobility of heavy metals (Cd, Cu, Pb) in national park territories and their seasonal migration with water flow. The detected exceedances of metal threshold levels in water underscore the environmental danger and confirm the need for monitoring not only soil, as in the current study, but also issues of multi-component detoxification and contamination dynamics. O.V. Shabatura *et al*. (2023) determined the change in the long-term content of Cu, Pb, Zn, Cd, and other elements in the air, which correlates with the influence of industrial and agricultural pollution sources. Such data support the broader ecological context of the current research while offering an alternative, atmospheric bio-indication, that complements the assessment of soil toxicity.

According to the present results, the EC_{50} values for copper (0.12 mg/L), zinc (2.55 mg/L) and other metals showed that biologically significant effects occur at concentrations 3-25 times lower than the current MPCs. This suggests that existing regulatory standards for soil contamination, specifically the MPCs for heavy metals established in national sanitary regulations (DSanPiN 2.2.7.029-99) and their alignment with European regulatory approaches governing permitted agricultural inputs, may underestimate ecological risks. This is particularly relevant for for agricultural management systems in which the use of copper-based fungicides is permitted under European regulatory frameworks, leading to the gradual accumulation of copper in soils at concentrations that do not exceed MPC values but may still exert phytotoxic and genotoxic effects on primary producers (Hutorov *et al*., 2021; Hussain *et al*., 2022). In the publication by T. Odunjo & E. Thomas (2021), it was found that in soil samples from organic farms, the content of heavy metals (Pb, Cr, Ni) was predominantly in forms with low bioavailability to plants (reserve and reducible fractions). The authors concluded that risks of metal uptake by plants in organic systems are minimal. This contradicts the findings of the present study, where toxicity was observed even at low concentrations. Possible explanations for these discrepancies include differences in assessment methods (fractional analysis versus phytotesting), the use of different test systems, and variation in soil types.

In the course of the present study, glyphosate was found to suppress *Allium cepa* growth, reduce the MI by 26.3%, and increase the frequency of chromosomal bridges. Although these effects were less pronounced than in the Cd+Pb group, they were statistically significant. The experimental EC_{50} exceeded the regulatory MPC by a factor of 2.2, which may suggest an overestimation of risk or limited sensitivity of the test object. The work of J.L. Gallego & J. Olivero-Verbel (2021) offered an alternative perspective by studying the cytogenetic toxicity of glyphosate and mixtures of heavy metals in soils from organic and conventional crops. It was found that in organic soils, glyphosate did not reach levels that produced marked toxicity, and pesticide contents were below detection limits. By contrast, conventional samples showed an increased frequency of cytogenetic abnormalities. Thus, unlike the present study, this research confirmed the ecological safety of organic systems with respect to glyphosate, which may be explained by lower actual pesticide concentrations under field conditions.

The conducted study therefore established a clear hierarchy of phyto- and genotoxicity for the pollutants under investigation; however, comparative analysis with other scientific works reveals substantial variability and contextual dependence of such results. The established toxicity ranking is not universal and may shift significantly depending on the choice of test organism, specific interactions between metals (e.g. antagonism), and substance concentration. Interpretation of toxicity is further complicated by nonlinear dose response relationships, particularly hormesis, where low concentrations of some metals may have a stimulatory rather than inhibitory effect. Moreover, conclusions about pollutant mechanisms of action, especially glyphosate, remain contentious, as macroscopic manifestations may not fully reflect the spectrum of cytogenetic damage, while broader meta-analyses point to more complex mechanisms of genotoxicity. Assumptions regarding the ecological purity of certain agricultural management practices are also called into question, since the literature indicates prolonged persistence of pesticides in soil and the possibility of contamination via organic fertilisers themselves. Thus, while the findings obtained are valid within the scope of the present experiment, they should be interpreted in light of these factors, underscoring the need for a comprehensive, multisystem approach in ecotoxicological assessments that accounts for the broader ecological context, including pollutant migration pathways and possibilities for bioremediation.

Conclusions

A comprehensive comparative assessment of the phyto- and genotoxic effects of various types of agroecosystem pollutants was carried out, combining macroscopic morphometric analysis and cytogenetic research. A quantitative hierarchy of toxicity of the studied pollutants was established with statistically significant differences ($p < 0.001$): the cadmium-lead combination caused maximum inhibition of root system growth to 8.12 ± 0.45 mm with a phytotoxic effect of 55.1% and a decrease in mass to 56.3% of the control values, while the copper-zinc pair caused less pronounced inhibition to 9.55 ± 0.61 mm (47.2%), and glyphosate showed the weakest effect with a reduction in length to 11.03 ± 0.52 mm (39.0%). Specific morphological damage was identified for each type of contaminant: dark brown necrosis and thickening for the cadmium-lead combination, browning of the tips with loss of turgor for the copper-zinc pair, and general inhibition without local necrosis for glyphosate.

Cytogenetic analysis revealed the mechanisms of toxic action at the cellular level through the assessment of the MI and the spectrum of chromosomal aberrations. The most profound inhibition of cell division was recorded in the cadmium-lead group with a decrease in the MI to 48.5 ± 3.1% (54.2% inhibition) and a tenfold increase in the frequency of aberrations to 12.4 ± 1.5% compared to the control (1.2 ± 0.4%). Statistical analysis confirmed the reliability of the differences found both between the experimental groups and the control ($p < 0.001$-0.01) and between the experimental groups themselves ($p < 0.001$-0.05). A predominantly clastogenic mechanism of action of heavy metals was established, with a predominance of chromosomal fragments (62.9% for cadmium-lead and 58.4% for copper-zinc combinations), while glyphosate was characterised by a different spectrum with a prevalence of chromosomal bridges (51.0%). A comparison of experimentally determined EC_{50} values with MPC standards revealed critical discrepancies for heavy metals: copper showed a 25-fold, zinc a 9-fold, and lead a 2.9-fold exceedance of MPCs over biologically significant concentrations. The data obtained justify a review of existing environmental standards for heavy metals in the direction of tightening, especially in the context of agricultural systems. Further research should focus on studying the chronic effects of subtoxic concentrations and synergistic interactions of pollutants in field conditions. A limitation of the study was the use of a single test system, which requires verification on additional model organisms.

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Conflict of Interest

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Оцінка забруднення сільськогосподарських культур важкими металами та пестицидами з використанням *Allium cepa*

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Анотація. Зростання вимог до екологічної безпеки аграрних систем зумовлює необхідність застосування надійних біоіндикаторних методів для оцінювання токсичності ґрунтових забруднювачів для рослин. Метою цього дослідження було порівняння фіто-, цито- та генотоксичних ефектів бінарних комбінацій важких металів (Cd+Pb, Cu+Zn) і гліфосату з використанням тест-системи *Allium cepa*. Проведено контрольований лабораторний експеримент із 20 цибулинами в кожній групі, п'ятьма повтореннями, а також однією контрольною та трьома дослідними групами. Для оцінювання застосовано морфометричний аналіз росту коренів (довжина коренів і свіжа маса), візуальну оцінку морфологічних ушкоджень, цитогенетичний аналіз клітин апікальної меристеми (мітотичний індекс і частота та спектр хромосомних аберацій), а також t критерій Стьюдента. Значення EC50 обчислювали за допомогою нелінійної регресії, та порівнювали з нормативами гранично допустимих концентрацій. Найвищу фітотоксичність виявлено для комбінації Cd+Pb, яка зменшувала ріст коренів на 55,1 %, далі – Cu+Zn (47,2 %), тоді як гліфосат проявляв найнижчий ефект (39,0 %). Цитогенетичний аналіз показав суттєве пригнічення мітотичної активності (відповідно 54,2 %, 38,5 % і 26,3 %) та зростання частоти хромосомних аберацій, причому важкі метали переважно проявляли кластогенну дію, а гліфосат характеризувався вищою часткою хромосомних містків. Експериментально визначені значення EC50 для Cu, Zn, Pb і Cd були у 3-25 разів нижчими за чинні гранично допустимі концентрації, що свідчить про біологічно значущі ефекти за концентрацій, які вважаються допустимими. Отримані результати демонструють високу чутливість тест-системи *Allium cepa* та вказують на те, що наявні екологічні нормативи щодо важких металів можуть недооцінювати ризики для рослинних організмів, особливо в аграрних системах, де дозволене застосування мідьвмісних препаратів

Ключові слова: фітотоксичність; генотоксичність; цитотоксичність; цитогенетичний аналіз; апікальна меристема

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Methodological approaches to assessing the impact of threats on environmental safety

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Abstract. The aim of this study was to conduct a comprehensive analysis of methodological approaches for assessing the impact of anthropogenic threats on environmental safety, particularly under urban conditions in Ukraine and Germany. The study was based on the integration of quantitative methods – including geoinformation modelling of the spatial distribution of pollutants and statistical analysis of long-term data – with qualitative approaches such as SWOT analysis of environmental management systems and expert evaluations. The results revealed critical differences between the regions studied: in Poltava (Ukraine), consistently high levels of air pollution were recorded (particulate matter (PM)2.5 – 45 μg/m3, NO2 – 50 μg/m3), significantly exceeding both the indicators for Leipzig (Germany) (18 μg/m3 and 25 μg/m3, respectively) and European standards. The situation in Kryvyi Rih was particularly acute, with 40% of the city's territory showing signs of soil degradation, and concentrations of heavy metals in water resources exceeding permissible levels by two to three times. The study also quantified the socio-economic consequences of environmental issues; in particular, annual losses in Poltava are estimated at USD 2-3 million due to the treatment of respiratory diseases. The data obtained confirmed the effectiveness of an integrated approach to environmental risk management, which considers both technical aspects of monitoring and social factors. The study's conclusions underscored the necessity of developing standardised indicators of environmental safety, implementing modern real-time monitoring systems on a wide scale, and enhancing international cooperation to adapt European experience to the context of Ukrainian cities

Keywords: anthropogenic impact; air quality monitoring; land reclamation; environmental risk management; urban ecology

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Introduction

Modern challenges to global ecological security are driven by the increasing technogenic load, climate change, degradation of natural resources, and the insufficient effectiveness of environmental management in many regions of the world. Ukraine is no exception to this trend. The problem of preserving ecological security has become particularly urgent due to the growing intensity of industrial pollution, uncontrolled deforestation, soil degradation, water resource contamination, and the consequences of military operations in the country. In this context, the issue of improving methodological approaches to assessing the impact of threats on ecological security is becoming critical both for the formation of state policy and for the development of practical solutions at the regional and enterprise levels.

Despite the considerable number of scientific studies devoted to ecological security, a significant proportion focus primarily on individual aspects of the problem, such as monitoring atmospheric air pollution, the condition of water bodies, or land resources. Forecasting the dangers of unchecked deforestation in Ukraine was the main topic of O. Korystin *et al.* (2024). By highlighting the critical areas at risk and the importance of predictive modelling in developing efficient forestry management plans, they emphasised the pressing need to address the environmental damage brought on by deforestation. A systematic assessment of scenario-based methods for evaluating soil ecosystem services and hazards in agroecosystems was carried out by O. Scammacca *et al.* (2025). In order to better comprehend future soil concerns, their research synthesised a large number of papers on soil degradation and changes in ecosystem services, highlighting the significance of scenario-based modelling. However, a comprehensive approach to assessing the cumulative impact of multidirectional threats on environmental security, as well as the development of a unified methodology for their analysis, remains insufficiently elaborated.

With an emphasis on ecological security, F.M. Sabil *et al.* (2025) investigated technical methods for handling ecological red-line issues. To achieve long-term sustainability, they emphasised the necessity of integrating technical solutions within more comprehensive ecological security frameworks. The use of nature-based approaches to water security was investigated by M.D.C. da Costa *et al.* (2025), who emphasised how they may enhance sustainable water management. They classified various nature-based alternatives and evaluated how well they worked to reduce pollution and water scarcity. The authors concluded that integrating these fixes into national water management plans might greatly improve water security in areas that are at risk.

With an emphasis on changes in agricultural intensity in Europe, V. Diogo *et al.* (2022) created context-specific frameworks for integrated sustainability evaluation. The authors concluded that managing agricultural developments in a way that supports long-term sustainability in the European setting required including environmental, economic, and social factors into the evaluation process. Using a crowdsensing paradigm to collect real-time data, P. Diviacco *et al.* (2022) investigated the usage of vehicle sensor networks (VSN) in urban areas to monitor air quality. Their research showed that by utilising extensive vehicle data collecting, VSNs might offer insightful information on air quality.

However, significant gaps remain in the standardisation of threat assessment methodologies, which hinders the provision of comprehensive risk analysis across different sectors of the economy. The importance of long-term monitoring to follow changes in the ocean's chemistry in response to increased carbon emissions was emphasised in an editorial by A.E.R. Hassoun *et al.* (2025) that focused on time-series observations of ocean acidification. Their study made clear how important it is to keep gathering data in order to comprehend how ocean acidification is developing and how it affects marine ecosystems.

In the analysis of Ukraine's strategic directions for boosting innovation and investment potential, M.M. Panchenko (2024) emphasised the need of focused investments in technology and research to increase economic competitiveness. The author concluded that, especially in light of the global economic issues, Ukraine's long-term success depended on promoting innovation. Similarly, L.S. Franko (2024) investigated how state innovation policy fuelled Ukraine's economic expansion, emphasising how concerted policy initiatives may develop technology and boost the nation's competitiveness. Although both studies emphasise the necessity for innovation-focused initiatives, there is still a lack of knowledge regarding how these policies can be successfully linked with the objectives of social and environmental sustainability.

In order to increase the precision and effectiveness of environmental impact assessments in industrial processes, J.D. Chea *et al.* (2025) investigated the use of automated tracking systems in life cycle assessments (LCA). According to their research, automating the tracking of chemical emissions and usage over the course of a product's life cycle could improve the accuracy of LCA and expedite data collecting. In a similar vein, A.E. Igharo *et al.* (2024) looked at how low-carbon and green economies affected food security in Africa, emphasising how environmental sustainability programs may increase food security by encouraging sustainable farming methods and minimising environmental damage. Although the significance of incorporating sustainability practices is emphasised in both studies, little is known about how these techniques might be used to provide scalable, sustainable results in various regional and industrial contexts.

Existing theoretical approaches to assessing the impact of threats on environmental security include the principle of risk prevention, the concept of integrated risk management, and the model of sustainable development, which emphasises a balance between environmental, economic, and social factors. Nonetheless, the comprehensive integration of these approaches into practical assessment methodologies remains an unresolved issue. This study aimed to analyse a range of methodological approaches for assessing the consequences of anthropogenic threats to environmental security, particularly in the context of urban areas. The hypothesis of the study was that the integration of modern quantitative analysis and risk modelling methods would significantly enhance the validity of management decisions in the field of environmental security.

Materials and Methods

The study was based on a comprehensive analysis of scientific papers published in international peer-reviewed journals, as well as the application of a multi-level assessment of environmental safety, which includes quantitative and qualitative methods, spatial analysis, and risk modelling. The research focused on three cities – Poltava and Kryvyi Rih (Ukraine), and Leipzig (Germany) – selected for comparative analysis due to their contrasting environmental profiles. Poltava is mainly characterised by transport-related pollution sources, Kryvyi Rih by a significant technogenic load resulting from mining and metallurgical industries, while Leipzig represents a successful ecological transformation of the urban environment within a post-industrial development context. Particular attention was given to the development of methods for risk forecasting and assessing the effectiveness of environmental measures at local and regional levels.

The data sources encompassed a wide range of official, academic, and public initiatives. In Ukraine, state statistical reports from the State Statistics Service of Ukraine (2023), the Ministry of Environmental Protection and Natural Resources of Ukraine (2025), the Ukrainian Hydrometeorological Centre (2025), municipal databases, and independent monitoring by public organisations were utilised. In Germany, data were obtained from the Federal Environmental Protection Agency, the European Environment Agency (2023), and academic research. In addition, global databases such as NASA's Earth Observation System Data and Information System, Landsat, and Copernicus were used, enabling the construction of dynamic pollution models that accounted for spatio-temporal changes.

Geospatial analysis was conducted using geographic information systems (QGIS, ArcGIS, Google Earth Engine) and computational models. Multi-criteria evaluation techniques (Analytic Hierarchy Process (AHP), Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE)) were employed. The AHP method was used to derive the relative weights of different environmental factors influencing pollution levels, while PROMETHEE was employed to rank these factors based on their importance. The study systematically analysed the three cities – Poltava, Kryvyi Rih (Ukraine), and Leipzig (Germany) – each with distinct environmental characteristics. Poltava is primarily affected by transport emissions, Kryvyi Rih by complex technogenic impacts due to mining and metallurgical activities, and Leipzig serves as an example of a city with a comprehensively implemented environmental modernisation system. All three cities were examined both within the methodological framework and in the empirical findings of the study. Spatial pollution analysis was performed using machine learning algorithms (Random Forest, XGBoost) to predict the dynamics of pollutant concentration changes.

The indicators of pollution levels were chosen to include significant environmental elements that affect urban ecological safety. Air quality indicators including particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) were added due to their well-known impacts on public health and the environment. Heavy metal concentrations were used to assess local water contamination, a major issue in industrial locations. To assess land use sustainability and ecosystem impact, soil deterioration was included. These indicators provide a holistic view of urban environmental issues, enabling focused management and mitigation.

Quantitative methods included regression and correlation analysis, machine learning, and probabilistic approaches for assessing pollution risks and forecasting consequences. Bayesian methods and Mean Squared Error (MSE) were applied to evaluate uncertainties. The study conducted statistical modelling of environmental risks, considering various pollution sources, their interrelations, and potential scenarios for future developments. Qualitative methods encompassed expert assessments, and SWOT analysis. For statistical analysis, tools, such as Excel, R, and Python, were used.

To give professional assessments of environmental risks, a total of 45 experts were chosen, including ecologists, urban planners, and environmental managers. These specialists were picked due to their broad backgrounds in urban ecology and environmental management, as well as their participation in local or regional risk assessment frameworks and policy creation. A systematic questionnaire was used for the expert assessment, and participants were asked to rate different environmental risks on a five-point scale (1 = very little risk, 5 = very high danger). The degree of soil deterioration, water contamination, air pollution, and the socioeconomic effects of environmental harm were the main evaluation criteria. The average scores for each category of environmental concern were determined by combining and analysing all of the expert evaluation data using statistical tools.

In order to gauge environmental awareness and engagement, an online survey was used to analyse public opinion. To guarantee demographic representation, including variables like age, gender, educational attainment, and geographic area, respondents were chosen by stratified random sampling. The survey contained open-ended questions for qualitative insights after multiple-choice and Likert-scale questions. In order to facilitate segment analysis, demographic information was gathered at the start of the survey. Descriptive statistics (frequencies, averages, and standard deviations) were used to analyse quantitative data, and thematic coding was used to process qualitative responses in order to find recurrent themes and patterns pertaining to public attitudes and actions about environmental issues.

Results

The study made it possible to obtain a number of key results that highlight the effectiveness of various methodological approaches to assessing the impact of threats on environmental safety. Particular attention was given to the analysis of quantitative and qualitative methods, their integration within composite approaches, and their adaptation to regional conditions. Quantitative methods demonstrated high accuracy in measuring pollution levels. The average annual concentration of fine particulate matter ($PM_{2.5}$) in Poltava was 35 μg/m³, which is 40% higher than the standard limit (25 μg/m³). In Leipzig, this indicator was significantly lower – 18 μg/m³ – indicating the effectiveness of strict environmental standards and the innovative purification technologies being actively implemented in Germany. The dynamics of $PM_{2.5}$ concentrations, as presented in the graph, show seasonal peaks during winter in Ukraine, associated with the use of coal for heating. In contrast, such fluctuations in Leipzig are minimal due to the widespread use of alternative energy sources. Table 1 presents the average annual levels of air, water, and soil pollution in the three cities.

Below, there is a Table 2, which illustrates the seasonal dynamics of $PM_{2.5}$ concentrations in Poltava and Leipzig.

Fluctuations in $PM_{2.5}$ concentrations in the air by month during 2024 in the cities of Poltava, Kryvyi Rih, and Leipzig are presented in Figure 1.

Table 1. Average annual levels of air, water, and soil pollution in Poltava, Kryvyi Rih, and Leipzig

Indicator	Poltava	Kryvyi Rih	Leipzig
$PM_{2.5}$ (μg/m³)	45	48	18
NO_2 (μg/m³)	50	55	25
Heavy metals in water (mg/l)	0.12	0.26	0.05
Soil degradation (%)	15	40	5

Source: compiled by the authors based on Ministry of Environmental Protection and Natural Resources of Ukraine (2025), Ukrainian Hydrometeorological Centre (2025), Air quality data access and tools (2025), A. Grachev (2025)

Table 2. Seasonal dynamics of PM2.5 concentrations in Poltava, Kryvyi Rih, and Leipzig

City	Average annual concentration (μg/m³)	Winter peak level (μg/m³)	Summer minimum (μg/m³)	Deviations from the EU norm (%)
Poltava	35	45	25	+40%
Leipzig	20	22	18	-20%
Kryvyi Rih	50	55	45	+100%

Source: compiled by the authors based on Ukrainian Hydrometeorological Centre (2025), Air quality data access and tools (2025)

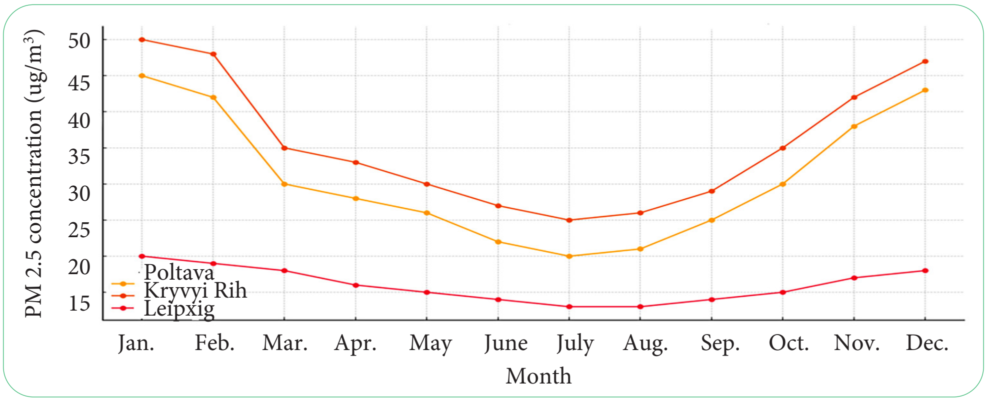

Figure 1. Seasonal fluctuations in PM2.5 concentrations in the air during 2024 in Poltava, Kryvyi Rih, Leipzig
Source: compiled by the authors based on Ukrainian Hydrometeorological Centre (2025), Air quality data access and tools (2025)

Geographic information modelling (GIS) has proven critical for identifying spatial patterns of pollution. In the study by Y. Golik *et al.* (2020), data from 20 monitoring stations in Poltava were integrated into a GIS platform, enabling the creation of a detailed map showing the distribution of NO_2. The resulting cartographic data include the geographic coordinates of each station, allowing for the precise identification of local "hot spots" with high pollutant concentrations. The data were classified according to pollution sources – industrial emissions, transport flows, and local emissions resulting from the use of outdated heating systems. In addition, the map contains supplementary geospatial layers reflecting city infrastructure, including industrial zones, transport networks, and green spaces.

Analysis of the cartographic data also facilitated the identification of the main pollution sources. In Poltava, industrial emissions account for approximately 70% of total pollution levels, while transport emissions contribute around 25%. These findings provided the basis for developing recommendations to establish green zones, which, according to forecasts, could reduce NO_2 levels by 15% within five years. A comparative analysis between Poltava and

Leipzig underscores the need to revise transport policy and modernise industrial facilities in Poltava and Kryvyi Rih in order to mitigate the impact of local pollution sources.

Mathematical risk modelling, as demonstrated in the study by T. Koptieva & I. Levchenko (2024), was used to assess the long-term consequences of anthropogenic impacts, such as soil degradation from mining, which is essential for predicting future environmental risks and informing effective mitigation strategies. The researchers focused on Kryvyi Rih and found that 40% of the city's territory exhibits signs of soil degradation due to mining activities. The forecasting model indicated that heavy metal concentrations in water resources exceed permissible limits by two to three times, directly affecting the health of 60% of the population in industrial areas. These data were corroborated by sociological surveys, which revealed a high prevalence of respiratory diseases among local residents.

Qualitative methods, such as SWOT analysis and expert assessments, complemented quantitative data by enabling consideration of the socio-economic context. A SWOT analysis of environmental management systems in Kryvyi Rih identified critical weaknesses, including the absence of soil monitoring infrastructure and outdated wastewater treatment systems. The main environmental threats identified for Ukraine were water pollution (reported by 45% of respondents) and soil degradation (30%). Experts also emphasised the importance of integrating social factors – such as population migration due to health-related issues – into risk assessment models. For example, in industrial regions, the escalation of environmental problems is often accompanied by a decline in the number of qualified personnel, complicating the implementation of effective environmental measures (Dyomin *et al.*, 2020; 2021).

Integrated approaches that combine environmental, economic, and social data have proven to be the most effective for comprehensive threat assessment (Bulatov, 2025). In Kryvyi Rih, the integration of geographic information systems with sociological surveys enabled the development of a land reclamation strategy involving the use of phytoremediation for soil decontamination and the creation of "green corridors" to restore biodiversity. Machine learning models, such as Random Forest and XGBoost, through their high predictive accuracy, were integral in assessing the reduction of pollutant concentrations and ensuring the robustness of the strategy. The modelling assumes a gradual reduction in pollution levels by 25% over the three-year period from 2022 to 2024. In the first year, following the implementation of initial environmental measures (e.g., equipment modernisation, optimisation of production processes, and improvements to wastewater treatment systems), pollutant concentrations decreased to approximately 92 units. This reflects the initial impact of emission reduction technologies. The second year shows a more substantial decline, with levels falling to 83 units. At this stage, further measures were introduced, including enhancement of monitoring and control infrastructure, expansion of environmental programmes (e.g., transition to cleaner fuels, installation of additional filtration systems, and greening of industrial areas).

The greatest cumulative effect is observed in the third year, when pollution indicators decrease to 75 units. This corresponds to a total reduction of 25% compared to the initial level. Achieving this result involves the completion of the main set of measures: full modernisation of production processes, the transition of a significant proportion of enterprises to less energy-intensive technologies, substantial expansion of green zones, and the introduction of regular environmental monitoring systems. This illustrates not only the gradual decrease in the concentration of toxic substances in soils and water, but also enables the tracking of the effectiveness of each stage in the implementation of environmental measures. A total reduction of 25% over three years demonstrates the effectiveness of an integrated approach that combines technological, managerial, and environmental solutions.

The uncertainty in the model's predictions was measured using Bayesian techniques, which provide a probabilistic framework for evaluating the output's confidence. The Bayesian method made it possible to incorporate past knowledge and update forecasts in response to new information. The MSE was used to assess the Bayesian model's performance, and it came out to be 0.04. The Bayesian model is successful in capturing the underlying patterns in pollution levels while taking uncertainty into account, as evidenced by the low MSE value, which shows a strong fit between the model's predictions and the observed environmental data. In addition to predictions, the application of Bayesian approaches improved the data' interpretability and aided in environmental risk management decision-making by providing insight into the confidence ranges.

A comparative analysis of Poltava and Leipzig revealed that Ukraine's technological lag results in higher pollution levels. For example, in Poltava, the absence of automated real-time monitoring systems leads to delayed responses to environmental threats, whereas in Leipzig, similar systems reduce risks by 40%. This disparity underscores the need for investment in modern technologies and the adaptation of European standards to Ukrainian conditions (Maksiuta & Golik, 2020). Practical recommendations developed on the basis of the study's findings include the implementation of sensor networks for monitoring $PM_{2.5}$ and NO_2, the establishment of green zones in urban areas, and the engagement of local communities in planning environmental initiatives. For instance, in Poltava, it is proposed to install air quality sensors in the most polluted areas to enable real-time data collection and timely intervention. In Kryvyi Rih, the focus is on land reclamation using phytoremediation, which not only decontaminates the soil but also creates additional green zones to enhance the quality of life for residents.

The hypothesis of regional disparities between Ukraine and the EU was also confirmed: insufficient funding, technological backwardness, and weak monitoring infrastructure in Ukraine contribute to higher pollution levels compared to European cities. For example, in Poltava, the absence of modern filtration systems at industrial facilities leads to emissions that would be unacceptable in the EU. Studies demonstrate that effective assessment of environmental threats requires the integration of diverse methodologies, consideration of regional contexts, and active participation of local communities. In Kryvyi Rih, for example, the combination of technical interventions (reclamation) and social initiatives (public monitoring) enabled the development of a comprehensive strategy that addresses both environmental and socio-economic factors. A similar approach could be adapted for other industrial regions where anthropogenic pressure on the environment is particularly acute.

A map of Kryvyi Rih indicating soil degradation zones visualises the scale of the problem, while a graph depicting the reduction of NO_2 concentrations in Poltava highlights the potential benefits of establishing green zones (Grachev, 2025). These visual elements not only enhance data comprehension but also make the research findings more compelling for informing management decisions. The study conducted by T. Koptieva & I. Levchenko (2024) identified key aspects of environmental risk management in Poltava. As shown in Table 3, the SWOT analysis of the city's environmental management system revealed significant strengths and weaknesses that influence the effectiveness of efforts to mitigate environmental threats.

Table 3. SWOT analysis of environmental management in Poltava

Category	Characteristic
Strengths	Availability of land reclamation programs, including a project to restore territories after the closure of quarries; access to international funding through EU programs.
Weaknesses	Lack of systematic soil monitoring in active mining areas; outdated wastewater treatment infrastructure, leading to pollution of the Ingulets River.
Opportunities	Implementing Internet of Things (IoT) sensors to automate pollution data collection; collaborating with European experts to develop adaptive strategies.
Threats	The growth of mining activity, which exacerbates land degradation; migration of qualified environmental personnel abroad due to low salaries.

Source: compiled by the authors based on T. Koptieva & I. Levchenko (2024)

The system's strengths include active participation in international projects. For example, a reclamation programme funded by the European Bank for Reconstruction and Development has restored 120 hectares of land previously used for iron ore mining. However, weaknesses – such as the lack of modern soil analysis equipment – limit the capacity to respond swiftly to emerging threats (Hussain *et al.*, 2022b). Soil monitoring is conducted only once every three to five years, which is insufficient for dynamic industrial regions. Opportunities for improvement are linked to technological innovation. The introduction of IoT sensors in quarry areas would enable real-time monitoring of heavy metal concentrations, while collaboration with European organisations could provide access to advanced reclamation techniques (Zhao *et al.*, 2025). Threats such as the increase in mining volumes have a direct impact on the region's ecological condition. Notably, over 2022-2024, the area of degraded land has expanded by 18%, attributed to intensified activity by mining companies. Using AHP, based on the experts' survey, the average score for each category was as follows: water pollution: 8.7/10 (45% of experts identified this as the main threat); soil degradation: 7.9/10 (30% of experts); biodiversity loss: 6.5/10 (25% of experts). Table 4 below presents the results of the expert assessment of priority environmental threats.

Table 4. Assessment of priority environmental threats

Category	Average score	% of experts who named the main threat
Water pollution	8.7/10	45%
Soil degradation	7.9/10	30%
Biodiversity loss	6.5/10	25%

Source: compiled by the authors based on T. Koptieva & I. Levchenko (2024)

Table 4 provides a clear comparison of risk assessments across different categories and helps to identify priority areas for the development of measures aimed at minimising environmental threats. Experts highlighted that water pollution in industrial regions such as Poltava is linked not only to mining activities but also to deteriorating drainage infrastructure. For example, in 2023, an accident at the city's treatment facilities resulted in the discharge of 500 tonnes of untreated wastewater into the river, causing a mass die-off of fish (Death of aquatic bioresources…, 2023). Soil degradation, according to expert opinion, is further complicated by the fact that 60% of the land requiring reclamation has not yet been included in state programmes.

Special attention is also paid to the integration of social factors. Experts noted that environmental issues are often accompanied by social tensions. For instance, in areas with polluted water bodies, there has been an increase in disease among children, prompting families to migrate to other regions (Hussain *et al.*, 2022a). This places additional pressure on local authorities, which frequently lack the resources to respond promptly to these challenges. The survey results also revealed that the majority of experts (75%) consider the state's efforts in environmental education to be insufficient. The absence of public information campaigns means that local communities remain unaware of the scale of environmental threats, hindering their engagement in ecological initiatives (Guliyev *et al*., 2024). After that, the cities were ranked according to how well they managed these environmental hazards using the PROMETHEE technique. The rating was determined by comparing each city's performance to the environmental parameters that were found. The decision matrix used in the PROMETHEE method, with the corresponding weighting coefficients, is shown in Table 5.

Table 5. Weighting and ranking of environmental threats

City	Air pollution ($PM_{2.5}$)	Water contamination	Soil degradation	Total score
Poltava	0.45	0.35	0.20	0.40
Kryvyi Rih	0.48	0.26	0.40	0.39
Leipzig	0.18	0.05	0.05	0.13

Source: compiled by the authors

According to the PROMETHEE results, Leipzig exhibited the best performance in mitigating environmental threats, followed by Poltava and Kryvyi Rih. These rankings are a reflection of Leipzig's sophisticated environmental management systems, which include efficient regulatory frameworks and real-time monitoring. Poltava and Kryvyi Rih, on the other hand, received worse scores because of antiquated monitoring methods and increased pollution, especially in industrial areas. The SWOT analysis and expert assessments underscored that effective environmental risk management requires not only technical solutions but also consideration of the socio-economic context. For example, land reclamation programmes in Poltava can succeed only if adequate funding, skilled personnel, and the active participation of local residents are secured. Experts further emphasised the need for the creation of a unified database to monitor environmental indicators, which would facilitate timely responses to emerging challenges.

A comparative analysis, presented in Table 6, of Poltava and Leipzig revealed significant differences in approaches to environmental risk management, rooted in disparities in technological advancement, financial capacity, and legislative frameworks. In Leipzig, a member city of the European Union, automated air quality monitoring systems have been deployed across the urban area. These systems include a network of over 50 sensors that monitor concentrations of $PM_{2.5}$, NO_2, SO_2, and other pollutants in real time. As a result, the city has reduced environmental risks by 40% over 2020-2024, particularly through the timely introduction of traffic restrictions in areas with elevated pollution levels and by informing the public via mobile applications. In contrast, in Poltava, air quality monitoring is still largely based on manual measurements conducted once or twice a month. This prevents the timely detection of peak pollution levels, especially during winter months, when coal-based heating significantly raises $PM_{2.5}$ concentrations. For example, in January 2023, $PM_{2.5}$ levels in the city centre reached 75 μg/m^3 (with the regulatory norm set at 25 μg/m^3), but the data were processed only three weeks later, making a prompt response impossible.

Table 6. Comparative characteristics of air quality monitoring systems in Poltava, Kryvyi Rih, and Leipzig

Parameter	Poltava (as of 2024)	Leipzig (as of 2024)	Kryvyi Rih (as of 2024)
Number of sensors	5 (manual measurements)	50 (automated systems)	8 (manual measurements)
Measurement frequency	1-2 times per month	Real-time data	1-2 times per month
Average $PM_{2.5}$ level	45 μg/m^3	18 μg/m^3	55 μg/m^3
Average NO_2 level	50 μg/m^3	25 μg/m^3	60 μg/m^3

Source: compiled by the authors based on S. Kessinger *et al.* (2024), V.V. Lesyuk (2025), Report on the implementation in 2024 of the measures of the City Program for Solving Environmental Problems of Kryvbas and Improving the Environmental Condition for 2016-2025 (2025)

For Poltava, it is critically important to implement comprehensive measures aimed at improving environmental safety. The first step should involve the establishment of a network of 30 automated sensors strategically positioned across the city, including industrial zones, major transport routes, and residential areas. The application of IoT technologies will enable real-time transmission of data on $PM_{2.5}$, NO_2, and other pollutants to a central platform, providing interactive map-based visualisations (World Health Organization, 2021). This system will allow for the prompt identification of "hot spots" and the implementation of targeted interventions, such as temporary traffic restrictions or optimisation of industrial operations. Integration with European standards requires the introduction of a public warning system via SMS and mobile applications, following the example of Leipzig. For instance, if $PM_{2.5}$ levels exceed 35 μg/m^3, residents would receive alerts with recommendations to minimise outdoor exposure. Simultaneously, the creation of "low-emission zones" is necessary, where truck traffic is restricted during periods of peak pollution (Chernyshev *et al*., 2020). Such zones could encompass city centres or areas near schools and hospitals.

Funding for these initiatives can be secured through participation in European Commission (2021) programmes, such as Horizon Europe, and through partnerships with German twin cities that have experience in implementing similar systems. Cooperation with local businesses is also essential: companies could provide infrastructure for sensor installation or co-finance part of the implementation in exchange for access to environmental analytics that may help optimise their own production processes (Raupov, 2024). To enhance effectiveness, it is recommended to establish an interagency working group comprising city officials, environmental experts, healthcare professionals, and IT specialists to coordinate project implementation and facilitate international cooperation.

In Leipzig, an automated air quality monitoring system has become a central instrument in managing environmental risks (Tõnisson *et al*., 2021). A network of 50 sensors – located in industrial zones, along transport corridors, and within residential districts – continuously transmits data on $PM_{2.5}$, NO_2, SO_2, and other pollutants to a centralised platform. This information is processed in real time using artificial intelligence, which predicts pollution trends and automatically generates recommendations for city authorities. One of the most effective practices has been the implementation of "low-emission zones". Additionally, residents receive personalised recommendations via SMS, such as avoiding walks in parks during periods of elevated ozone levels.

From 2024 to 2025, the number of hospitalisations due to asthma exacerbations in Leipzig has decreased by 25%, and the economic cost of treating respiratory diseases has been reduced by EUR 1.5 million annually. A study conducted by a local university revealed that 40% of residents changed their behaviour – such as switching to public transport – after gaining access to real-time pollution data (Tõnisson *et al*., 2021). For Poltava, a similar approach could represent a transformative breakthrough. According to experts, the implementation of 30 automated sensors with real-time monitoring functionality could reduce the average annual $PM_{2.5}$ concentration by 20-25% through the prompt introduction of mitigation measures and prevent 500-700 hospitalisations from respiratory diseases each year.

Poltava's technological lag in environmental monitoring is not an insurmountable obstacle. Leipzig's experience demonstrates that modern monitoring systems are not only essential tools for environmental control but also serve as powerful mechanisms for socio-economic stabilisation. For Poltava, this approach is especially promising given the affordability of the technology: the cost of a single IoT sensor for measuring $PM_{2.5}$ is only USD 200-300, making the system scalable even in cities with limited budgets. A crucial factor is the availability of international support: EU programmes such as Clean Air for Ukraine and Horizon Europe can fund up to 70% of the project's cost. Additionally, twin cities such as Dresden have expressed readiness to provide technical documentation, training for specialists, and data-sharing cooperation.

For successful implementation, it is advisable to establish an interagency working group comprising representatives of city authorities, environmental specialists, healthcare professionals, and IT experts. A pilot project should be launched with the installation of 10 sensors in the most polluted areas – such as near the "Poltavagaz" site – accompanied by public engagement through webinars and community discussions. In the long term, if Poltava succeeds in implementing even half of the proposed measures, it could achieve EU-compliant air quality levels by 2030, save USD 1-1.5 million annually in medical expenses, and serve as a model for other Ukrainian cities such as Dnipro and Kharkiv.

Thus, technological modernisation should not be viewed as an expense, but rather as an investment in the future. It creates a foundation for improving quality of life, reducing the economic burden, and facilitating Ukraine's integration into the European environmental space. This study has provided clear answers to key questions regarding the assessment of environmental threats, regional differences, and practical solutions. Each conclusion is grounded in data analysis, international comparisons, and specific examples drawn from Ukrainian cities. Quantitative methods, such as GIS and statistical analysis, ensure precision and objectivity. GIS enabled visualisation of areas where lead concentrations exceeded permissible levels by a factor of 4.5 and cadmium by 3.2. Statistical analysis further showed that the average annual concentration of NO_2 in Poltava is 50 $\mu g/m^3$ – well above the norm of 40 $\mu g/m^3$ – primarily due to heavy traffic and emissions from industrial enterprises.

A survey of 45 experts highlighted water pollution as the most critical environmental threat, with 45% of respondents identifying it as the top priority. These qualitative tools allow consideration of not only technical issues but also social and economic dimensions, such as population migration linked to deteriorating public health. The hypothesis regarding regional differences was fully confirmed. A comparison of Poltava and Kryvyi Rih (Ukraine) and Leipzig (Germany) revealed substantial disparities in environmental management approaches. In Leipzig, a network of over 50 automated monitoring sensors provides real-time data, allowing rapid response measures. When $PM_{2.5}$ concentrations exceed 35 $\mu g/m^3$, truck access to the city centre is restricted and residents are notified via mobile applications. As a result, over the past five years, the city has achieved a 40% reduction in emissions and a 25% decrease in asthma-related hospitalisations.

The average annual $PM_{2.5}$ concentration in Poltava (45 $\mu g/m^3$) is more than twice as high as in Leipzig (18 $\mu g/m^3$). The primary reasons for these disparities are technological backwardness, insufficient funding (0.7% of GDP compared to 2.1% in Germany), and a weak legislative framework that lacks strict sanctions for violations of environmental standards. Automated monitoring would require the deployment of 30 IoT sensors in Poltava to measure $PM_{2.5}$, NO_2, and SO_2 in real time. This would enable the creation of interactive pollution maps and the timely implementation of mitigation measures, such as temporary closure of industrial facilities or rerouting of traffic. The development of a mobile application for the public would ensure access to up-to-date air quality information, which is particularly vital for individuals with chronic health conditions.

Land reclamation efforts in Poltava should incorporate phytoremediation – a technology whereby hyperaccumulator plants (e.g., white mustard) absorb heavy metals from contaminated soils. This method is already being used successfully in Europe; cultivating specific crops in polluted areas has been shown to restore up to 50% of degraded land within 5-10 years. For water resources, plans are in place to modernise the treatment facilities along the Inhulets River, thereby reducing the inflow of toxins into underground water sources. Community integration is to be facilitated through the creation of an "Eco-Patrol" platform, allowing residents to report illegal emissions via photo and video evidence. This approach has already been implemented in Lviv, where environmental activists assist authorities in identifying violations. Additionally, annual training sessions are planned for local residents, focusing on the fundamentals of environmental auditing and the use of portable air quality sensors.

The study has demonstrated that effective responses to environmental threats require a systemic approach that integrates innovation, financing, and active community participation. The implementation of automated monitoring systems, land reclamation strategies, and the involvement of local residents are not merely technical challenges, but long-term investments in the health and well-being of future generations. The experience of Leipzig illustrates that even limited resources can be utilised effectively by adapting European practices to local conditions. The next steps should focus on the development of national environmental standards, the strengthening of international cooperation, and the establishment of a transparent environmental management system accessible to all citizens.

The findings of the study confirm that an integrated approach – combining quantitative and qualitative methods – is optimal for a comprehensive assessment of environmental threats. Quantitative techniques, such as geo-information modelling and statistical analysis, provide accuracy and objectivity, enabling the measurement of pollution levels, the identification of "hot spots", and the prediction of environmental trends (Fedoniuk *et al.*, 2025). For example, in Kryvyi Rih, GIS technologies revealed that 40% of the city's territory was affected by soil degradation due to mining activities, while in Poltava, statistical data showed that NO_2 concentrations exceeded regulatory limits by 1.5 times. However, the effectiveness of these methods is contingent on the availability of infrastructure: automated sensors, laboratory equipment, and qualified personnel are essential for generating reliable results.

Based on the results of the study – which employed statistical tools such as Excel, R, and Python – a detailed analysis of environmental pollution was conducted. Statistical processing enabled the determination of average pollution values, standard deviations, and correlation coefficients between various parameters. For instance, in relation to air pollution, it was found that the average $PM_{2.5}$ concentration in Poltava was 35 μg/m^3, with a standard deviation of approximately 7 μg/m^3, while the correlation coefficient between $PM_{2.5}$ and NO_2 levels was 0.78, indicating a strong relationship between these pollutants. Similarly, expert assessments of water resources produced an average score of 8.7/10 with a standard deviation of 1.2/10. Correlation analysis between water pollution levels and soil degradation produced a coefficient of 0.65. To facilitate a comparative analysis of the effectiveness of different research approaches that consider the socio-economic context – including SWOT analysis, expert assessments, and statistical analysis – Table 7 was developed. This table outlines the characteristics of each method and provides conclusions regarding their respective effectiveness.

Table 7. Characteristics of the applied methods for assessing environmental threats

Method	Characteristic	Conclusions on effectiveness
SWOT analysis	Identifies the region's strengths and weaknesses, opportunities and threats	Identified the lack of modern monitoring systems (e.g., in Kryvyi Rih) as a key weakness
Expert assessments	Rating on a scale of 1 to 10, taking into account local socio-economic characteristics	They emphasised the priority of combating water pollution
Statistical analysis	Calculating averages, standard deviations, correlation coefficients using Excel, R, Python	Provided a quantitative assessment of the state of the environment and identified relationships between individual pollution indicators

Source: compiled by the authors based on Ministry of Environmental Protection and Natural Resources of Ukraine (2025)

This combination of methods enabled the analysis to go beyond "pure" data, taking into account local characteristics such as migration trends, regional economic priorities, and the level of public trust in authorities. The results of statistical analysis complemented qualitative approaches by providing an objective, quantitative assessment of the environmental situation and validating conclusions derived from SWOT analysis and expert evaluations. A critical factor in the successful implementation of such approaches is their regional adaptation. The experience of Leipzig – where automated monitoring systems led to a 40% reduction in pollution – demonstrates that European practices must be tailored to Ukrainian realities. In the case of Poltava, for example, the introduction of similar technologies should be accompanied by the development of local standards that reflect the specific nature of pollution sources (e.g., coal-based heating) and existing budgetary limitations. Integration with European standards may proceed in phases, starting with the creation of "low-emission zones" and eventually expanding to the full deployment of IoT sensor networks.

International cooperation is also a key element. Sharing expertise with twin cities (e.g., Dresden for Lviv, or Leipzig for Poltava), participation in EU initiatives such as Horizon Europe, and engagement with international experts will support Ukraine's integration into the broader European ecological space. Joint projects focused on land reclamation or the modernisation of wastewater treatment plants could be financed through instruments provided by the European Bank for Reconstruction and Development. In conclusion, overcoming environmental threats is a complex, multifaceted process that demands not only technological solutions, but also public awareness, political commitment, and international solidarity. The results of this study demonstrate that the integration of science, practical implementation, and civic engagement can form a robust foundation for effective, lasting environmental change aimed at safeguarding both ecosystems and public health.

Discussion

The results of the study indicate that there are significant differences in the effectiveness of environmental risk management between cities in Ukraine and Germany. This highlights the need to adapt European approaches to national conditions. Air pollution indicators in Poltava – particularly the elevated concentrations of fine particulate matter $PM_{2.5}$ (45 μg/m^3) and nitrogen dioxide NO_2 (50 μg/m^3) – exceed EU standards by 1.8 and 1.25 times, respectively. These figures point to serious technological and managerial shortcomings in the field of environmental safety. The primary causes of this situation include the deterioration of industrial equipment, insufficient automation of monitoring systems, and limited funding for environmental protection measures at the local level (Vasyutynska & Barbashev, 2024; Grodz, 2024).

Research into modern approaches to air quality monitoring shows significant progress due to the integration of low-cost sensors, remote sensing technologies, and advanced analytical methods. H.A.D. Nguyen *et al.* (2024) demonstrated that combining low-cost sensor networks with traditional monitoring systems enhances the accuracy of $PM_{2.5}$ and other pollutant measurements, contributing to the timely forecasting of air quality changes. According to O.E. Rowland (2024), meteorological parameters have a substantial impact on the concentrations of NO_2, PM_{10}, $PM_{2.5}$, and O_3 in major cities such as Kraków, Paris, and Milan. This underscores the importance of incorporating climate factors into the development of air quality forecasting models.

T. Saeed *et al.* (2024) highlighted the technical challenges associated with maintaining low-cost monitoring networks in South Asia, pointing to the need for regional adaptation and the assurance of stable system performance. L. Mamić *et al.* (2023) developed models for predicting $PM_{2.5}$ and PM_{10} concentrations at national and regional levels using open-access remote sensing data, enabling high-precision air quality assessments and the monitoring of spatial pollution dynamics. A review by K. Okorn & L.T. Iraci (2024) examined current trends and limitations in the deployment of low-cost outdoor gas sensors, which is critical for understanding their potential role in long-term monitoring systems.

Finally, Q. Xiao *et al.* (2022) proposed a method for producing continuous daily estimates of $PM_{2.5}$ concentrations with high spatial resolution using the Tracking Air Pollution in China framework, thereby allowing effective monitoring of air quality changes with respect to seasonal and local variations. Thus, the integration of low-cost sensors, remote sensing technologies, and statistical methods offers a comprehensive approach to air pollution monitoring. This is essential for ensuring timely responses to environmental threats and for supporting informed decision-making in environmental management.

Similar issues are identified in the work of P. Pourhejazy *et al.* (2025), who emphasise the necessity of a structural transformation of urban infrastructure to achieve carbon neutrality goals. Unlike the aforementioned authors, who address challenges at the level of global supply chains, the findings of this study highlight the relevance of local sources of pollution, particularly the use of coal for individual heating and outdated industrial processes in production zones. This situation necessitates the development of regionally specific strategies aimed at reducing the technogenic burden on the environment.

The economic consequences of anthropogenic environmental threats are considerable. In Poltava, annual losses associated with the treatment of respiratory diseases are estimated at USD 2-3 million, confirming the link between environmental conditions and public health, as noted by U. Samarasekera (2024). While U. Samarasekera's study focuses on the direct effects of climate change on food security and health, the present analysis demonstrates an additional dimension of the issue – namely, the increase in economic losses resulting from rising morbidity rates and the migration of the working population from environmentally disadvantaged areas.

The study by I.P. Kovalenko (2021) confirms that implementing European Union standards within Ukraine's risk management system requires comprehensive reforms in both the legislative and educational spheres. This aligns with the findings of K.A. Vasyutynska & S.V. Barbashev (2024), who advocate for the deployment of IoT-based environmental monitoring systems in cities such as Kharkiv. The introduction of such technologies is equally applicable to Poltava; however, an analysis of available financial and human resources indicates that additional investments and the training of qualified specialists are essential (Voloshyna, 2021).

Within the framework of assessing regional ecological safety, particular attention is drawn to the study by

Ye.M. Bezsonov (2018), who substantiated the use of biotic indicators for analysing the condition of aquatic ecosystems. This supports the effectiveness of biological methods for diagnosing soil conditions in areas with active mining operations, particularly in Kryvyi Rih, where a significant level of land resource degradation has been recorded (Tykhenko, 2015). Existing risk assessment models proposed by V.I. Sovych (2021) and Y.I. Rudyk (2021), based on the international standard ISO 31010, are not well-suited to small Ukrainian cities due to limited resources and the absence of a comprehensive monitoring infrastructure. M.K. Signaevsky & K.I. Kazhan (2020), in their work, present an example of risk-based approaches in the context of urban air mobility. However, such models remain in the pilot stage and do not account for the specific requirements of ecological safety in urbanised environments.

In the context of environmental safety management at the enterprise level, the experience of S. Vlasova (2025) is particularly relevant. In their study on the application of risk management methodology at PJSC SVC "Borshchahivskyi HFZ", the researcher demonstrates the effectiveness of a systemic approach to risk control in industrial companies. However, for small enterprises and municipal institutions, these models remain challenging to implement due to the lack of necessary infrastructure (Koshevyi, 2024). The development of standardised environmental safety indicators for Ukrainian municipalities should therefore be based on international standards, while incorporating local specificities (Sumriy, 2024). In addition, S. Bilan & Y.V. Polyakova (2021) underline the impact of regulatory policy on the innovative activity of enterprises, particularly in the field of environmental technologies, which could form the basis for implementing new approaches to environmental monitoring.

Promising areas of international cooperation include the development of joint projects on phytoremediation of contaminated lands and the creation of sensor networks for air and water quality monitoring (Remeshevska *et al.*, 2021; Kulova *et al.*, 2023). Another key factor in enhancing the effectiveness of environmental monitoring is public engagement, as highlighted by M.D. Voloshyna (2021), who emphasises the importance of improving specialist competence through the accreditation of laboratories in accordance with international standards. The analysis also confirmed that the organisational and economic support for environmental project management systems remains insufficiently developed. V.S. Tykhenko (2015) proposes comprehensive approaches for integrating national and supranational mechanisms to finance environmental initiatives but notes that Ukraine faces a range of challenges in their practical implementation.

Thus, the results of the study indicate that effective management of environmental safety in Ukrainian cities requires not only technological solutions, but also systemic reforms in the regulatory and legal spheres, as well as the development of human capital. A comparison with the German experience demonstrates that a stable legislative framework, well-developed infrastructure, and a high level of specialist training are key success factors for environmental policy. For instance, the implementation of automated monitoring systems in Leipzig was facilitated by a comprehensive development programme that incorporated both financial investment and educational initiatives (Pourhejazy *et al.*, 2025). In light of the above, it is essential to pursue continued interdisciplinary research in the field of environmental safety. Such research will enable the integration of environmental, economic, and social dimensions into a unified risk management system tailored to the specific conditions of Ukraine.

Conclusions

The study has shown that environmental safety in Ukrainian cities – particularly in Poltava and Kryvyi Rih – is in a critical condition that requires urgent systemic change. A key finding was the identification of significant disparities in pollution levels compared to cities in the European Union. Specifically, the average annual concentration of $PM_{2.5}$ particulate matter in Poltava is 45 μg/m^3, which is 2.5 times higher than the equivalent value in Leipzig (18 μg/m^3). The nitrogen dioxide (NO_2) level in Poltava reaches 50 μg/m^3, almost double that recorded in comparable European cities. In Kryvyi Rih, approximately 40% of the territory exhibits signs of soil degradation, while concentrations of heavy metals in water resources exceed permissible limits by two to three times. These quantitative indicators point to the critical condition of urban ecosystems and confirm their direct impact on public health, particularly the increase in respiratory diseases, which affect 60% of residents in industrial areas.

The qualitative analysis conducted confirmed that combining geoinformation modelling with expert assessments and SWOT analysis enables the identification of the main threats and weaknesses within environmental safety management systems. The study revealed issues such as the lack of modern automated environmental monitoring systems, which hinders timely responses to ecological threats. It also established that the socio-economic consequences of air and water pollution are significant, with annual losses associated with the treatment of chronic respiratory diseases estimated at between two and three million US dollars. This demonstrates a direct link between environmental conditions and regional economic performance. The results support the feasibility of implementing automated environmental pollution monitoring systems in Poltava and Kryvyi Rih, following the Leipzig model. The use of IoT technologies – specifically, real-time sensors for $PM_{2.5}$ and NO_2 – can improve the effectiveness of environmental monitoring. The introduction of phytoremediation technologies for restoring contaminated soils, particularly through the use of hyperaccumulator plants such as white mustard, is considered an effective strategy for reducing pressure on degraded areas. Additional emphasis should be placed on the development of public platforms, such as Eco-Patrol, to raise public awareness of environmental risks and encourage citizen involvement in monitoring and control efforts.

A number of limitations were identified in the study. The focus on only two Ukrainian cities, while allowing for an in-depth regional analysis, does not permit generalisation of the findings to the entire country. Additionally, the limited availability of primary data – due to the lack of comprehensive automated monitoring systems in Ukraine – reduced the precision of comparisons with European cities. The expert survey, which involved only twenty specialists, may not fully capture the complexity of environmental issues at the local level. Promising directions for further research include the development of standardised indicators of environmental safety, which would integrate data on air, water, and soil pollution, public health, and the socio-economic consequences of environmental threats. The study also highlights the importance of expanding international cooperation with scientific institutions in the European Union, to facilitate the adaptation and implementation of advanced air and water purification technologies suitable for Ukrainian conditions. Research into the effectiveness of alternative energy sources – particularly solar panels and heat pumps – is regarded as an important element of the strategy to reduce coal dependency during the heating season.

In conclusion, the results underscore that overcoming environmental threats in Ukraine requires not only the introduction of technological innovations, but also profound reforms in environmental governance, increased funding for environmental protection, and enhanced public environmental awareness. The implementation of the proposed measures will contribute to the development of an effective model for the sustainable development of Ukrainian cities – aligned with European Union standards and adapted to the specific socio-economic and environmental conditions of the country. Future research should prioritise the development of standardised indicators of environmental safety that account for both global trends and local contexts. For instance, environmental indicators for Ukraine's industrial cities should include not only pollutant levels, but also social dimensions such as access to clean water, disease incidence, and the economic burden of healthcare. These indicators could serve as the foundation for sustainable development strategies that align with EU goals while being adapted to the Ukrainian context.

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Методологічні підходи до оцінки впливу загроз на екологічну безпеку

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Анотація. Метою цього дослідження було проведення комплексного аналізу методологічних підходів до оцінки впливу антропогенних загроз на екологічну безпеку, зокрема в міських умовах України та Німеччини. Дослідження базувалося на інтеграції кількісних методів, включаючи геоінформаційне моделювання просторового розподілу забруднюючих речовин та статистичний аналіз довгострокових даних, з якісними підходами, такими як SWOT-аналіз систем екологічного менеджменту та експертні оцінки. Результати виявили критичні відмінності між досліджуваними регіонами: у Полтаві (Україна) було зафіксовано стабільно високий рівень забруднення повітря (тверді частинки $(PM)_{2,5}$ – 45 мкг/м^3, NO2 – 50 мкг/м^3), що значно перевищує як показники Лейпцига (Німеччина) (відповідно 18 мкг/м^3 і 25 мкг/м^3), так і європейські стандарти. Особливо гострою була ситуація в Кривому Розі, де 40 % території міста показало ознаки деградації ґрунтів, а концентрація важких металів у водних ресурсах перевищувала допустимі рівні у два-три рази. У дослідженні також було кількісно оцінено соціально-економічні наслідки екологічних проблем; зокрема, щорічні збитки в Полтаві від лікування респіраторних захворювань оцінюються в 2-3 млн доларів США. Отримані дані підтвердили ефективність комплексного підходу до управління екологічними ризиками, який враховує як технічні аспекти моніторингу, так і соціальні фактори. Висновки дослідження підкреслили необхідність розробки стандартизованих показників екологічної безпеки, впровадження сучасних систем моніторингу в режимі реального часу в широкому масштабі та посилення міжнародного співробітництва з метою адаптації європейського досвіду до умов українських міст

Ключові слова: антропогенний вплив; моніторинг якості повітря; меліорація земель; управління екологічними ризиками; міська екологія

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Environmental risks of thermal waste management and prospects for sustainable remediation

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Abstract. The management of municipal solid waste remains one of the most urgent environmental challenges in Ukraine, particularly in the Kharkiv Region, where soil contamination and groundwater vulnerability intensify ecological risks. The study aimed to assess the environmental risks of thermal waste treatment technologies in the Kharkiv Region and evaluate their compatibility with ecosystem restoration strategies. The research applied a comparative analytical approach, integrating environmental impact assessment methods to analyse incineration, pyrolysis, and plasma gasification technologies. The assessment included estimation of pollutant emissions, energy efficiency, and secondary waste formation under regional conditions. It has been established that incineration, while effective at reducing waste volume, produces hazardous residues containing heavy metals and organic toxins. Pyrolysis demonstrates lower emissions and produces biochar capable of immobilising pollutants in soils, thereby enhancing its potential integration with phytoremediation practices. Plasma gasification provides nearly complete decomposition of complex waste streams, but it demands a high energy input and advanced technical infrastructure. The study identified that, under the post-conflict context of the Kharkiv Region, pyrolysis offers the best balance between environmental safety and resource efficiency. A framework for integrating thermal treatment residues into soil recovery strategies has been developed to support regional sustainability. The results can be applied by environmental engineers, municipal authorities, and policymakers to design sustainable waste-to-energy systems adapted to environmentally sensitive and post-conflict areas

Keywords: waste-to-energy technologies; pollutant emissions; soil and water protection; ecosystem restoration; resource efficiency; sustainable recovery

Introduction

The modern civilisational model of development is based on constant consumption growth, which inevitably leads to the accumulation of vast amounts of waste. Economic growth, urbanisation, and improvements in the standard of living are shaping a new ecological reality in which waste management is no longer only a technical but also a strategic task for states. The increase in the amount of solid household and industrial waste leads to soil, water, and atmospheric pollution, while traditional methods of disposal, particularly landfills, are reaching their limits. In this context, there is a need for technological solutions that strike a balance between processing efficiency and environmental safety. Thermal transformation of waste, including incineration, pyrolysis, and plasma gasification, is

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considered a promising direction; however, its application generates environmental risks associated with the formation of toxic emissions and ash. The issue of assessing these risks, as well as the possibilities of sustainable restoration of polluted ecosystems, is central to modern research and requires an integrated approach.

Y.A. Hajam *et al.* (2023) examined waste management through the lens of sustainable development, focusing on the environmental risks posed by traditional waste-disposal methods. Researchers demonstrated that environmental management strategies should be based on the principles of resource efficiency, specifically the transformation of organic waste into fertilisers or energy resources. The authors emphasised that without the development of closed waste management cycles, no management system can be considered sustainable. These findings emphasise the need to shift from the concept of "waste elimination" to "resource recovery". M. Bogusz *et al.* (2021) analysed the ideology of the concept of "zero waste" as a means of supporting the environmental awareness of consumers. They concluded that the environmental effectiveness of waste management policies largely depends on behavioural factors, including the willingness of the population to separate waste, reduce consumption, and recognise the value of resources. Although the authors worked in the context of European Union countries, their conclusions are of universal significance for Ukraine, where consumer culture is still in the process of formation.

In the national context, the monograph by N.S. Remez *et al.* (2023) made a significant contribution. The researchers developed a structural model of municipal waste management that takes into account technical, legal, and socio-economic factors. The authors emphasised that the lack of proper infrastructure and low level of control over waste movement create systemic environmental risks for Ukraine. They also noted that any utilisation technology should not be considered in isolation, but as an element of a holistic ecological cycle. Practical issues in implementing modern management strategies are discussed in the manual by M.O. Barinov *et al.* (2021), which investigated the mechanisms of separate collection, pre-sorting, and recycling of waste in Ukrainian communities. The authors highlighted the effectiveness of decentralised approaches but emphasised that, even with their implementation, a significant residual volume of waste remains, requiring additional thermal or biological treatment. Thus, these studies confirm the need to develop innovative thermal disposal technologies that minimise environmental impact.

From the standpoint of applied chemistry, the results of B.V. Korinenko *et al.* (2021), who studied the catalytic effect on low-temperature pyrolysis of polymer waste, are valuable. They proved that the use of catalysts allows for reducing the energy consumption of the process and improving the quality of the formed gas fractions, while reducing the formation of toxic residues. The authors also highlighted the potential for local implementation of such technologies in industrial regions, where polymer accumulation has become an environmental threat. Additionally, the Roadmap for the implementation of the Law of Ukraine "On Waste Management" (2022) summarises the strategic directions for implementing state policy in the field of waste management. The document emphasises the importance of integrating scientific developments into municipal management and of creating a system to monitor the impact of waste on environmental components. This allows consideration of the problem of waste management not only within the framework of technological processes, but also in terms of environmental safety and sustainable development of territories.

Despite the availability of modern research, a significant portion of scientific work focuses on individual aspects of the problem, such as the technological efficiency of thermal treatment, consumer behavioural factors, or phytoremediation processes. The relationship between thermal waste utilisation products and changes in soil ecosystems remains insufficiently studied, especially in post-conflict regions. There is also a lack of integrated research that combines environmental risk assessment with the development of mechanisms for the biological restoration of contaminated areas. Based on this, the purpose of the study was to analyse the ecological risks of thermal waste management and to determine the prospects for applying phytoremediation technologies for the sustainable restoration of degraded ecosystems.

Materials and Methods

The methodological basis of the study combines systemic, analytical, and comparative methods, which enabled the identification of logical connections between theoretical provisions of waste management and practical approaches to minimising their environmental impact. The search strategy was built on the principles of transparency, reproducibility and scientific validity. The information sample was compiled based on leading international databases, including Scopus, Web of Science, and Google Scholar, as well as national sources such as Scientific Periodicals of Ukraine (URAN) and the National Repository of Academic Texts. The time frame covered publications from 2020 to 2025, which ensures the relevance and modernity of the analysed results. Language restrictions applied to English- and Ukrainian-language works that contained empirical or conceptual data on the topic of environmental assessment of thermal waste management.

Search queries were formed by a combination of keywords: "municipal solid waste", "thermal treatment", "waste-to-energy", "incineration", "pyrolysis", "plasma gasification", "environmental impact", "phytoremediation", "soil restoration". For Ukrainian-language sources, the following queries were used: "thermal waste processing", "pyrolysis", "ecological risks", "phytoremediation". At the initial stage, more than 400 works were identified. After a phased selection based on thematic relevance, source reliability and methodological quality, the 31 most representative publications were included in the final analysis.

The inclusion criteria required that the study contained an analytical or experimental evaluation of the environmental impacts of thermal waste processing, provided a clear and explicit description of the applied technologies, such as combustion, pyrolysis, or plasma gasification, and demonstrated a direct link between energy recovery processes and ecosystem restoration. Review materials without scientific analysis, as well as outdated sources or publications lacking data on the environmental impact of technologies, were excluded.

The theoretical framework of the study was based on the concept of sustainable ecosystem restoration, combined with the principles of a circular economy and reducing carbon footprints. Within this paradigm, a logical analysis was conducted to assess the compatibility of thermal processing technologies with environmental protection strategies. To assess ecological risks, content analysis of publications was used, which enabled to identify key impact indicators. The method of systematisation and generalisation enabled the comparison of approaches from different authors, the identification of scientific gaps, and the detection of trends in the development of the direction. A separate analysis of official documents and statistical materials was conducted – in particular, the Roadmap for the implementation of the Law of Ukraine "On Waste Management" (2022), state reports on household waste generation, which allowed to assess the scale of the problem quantitatively. The results obtained formed the basis for further comparative analysis of risks and the potential of environmentally friendly solutions.

Graphical visualisation of comparative data was performed using analytical generalisation of literature and statistical sources, with figures constructed to illustrate technological process flows and cause-and-effect relationships between waste treatment stages and environmental impacts. Schematic diagrams of incineration, pyrolysis, and plasma gasification were developed as conceptual models based on published technological descriptions and engineering principles, with the aim of standardising process representation rather than simulating operational parameters. All visual materials were used as supporting analytical tools to improve the clarity and interpretability of the results and do not represent experimental modelling or primary numerical simulations.

Results and Discussion

Waste thermal processing technologies

Thermal treatment technologies, including incineration, pyrolysis, gasification, and plasma gasification, are key components in modern waste management strategies in Ukraine. Their environmental efficiency and energy potential vary significantly depending on process parameters, waste composition, and regional conditions. Waste incineration is the most common method, capable of reducing waste volume by 85-90% and generating heat or electricity. The process is presented in Figure 1.

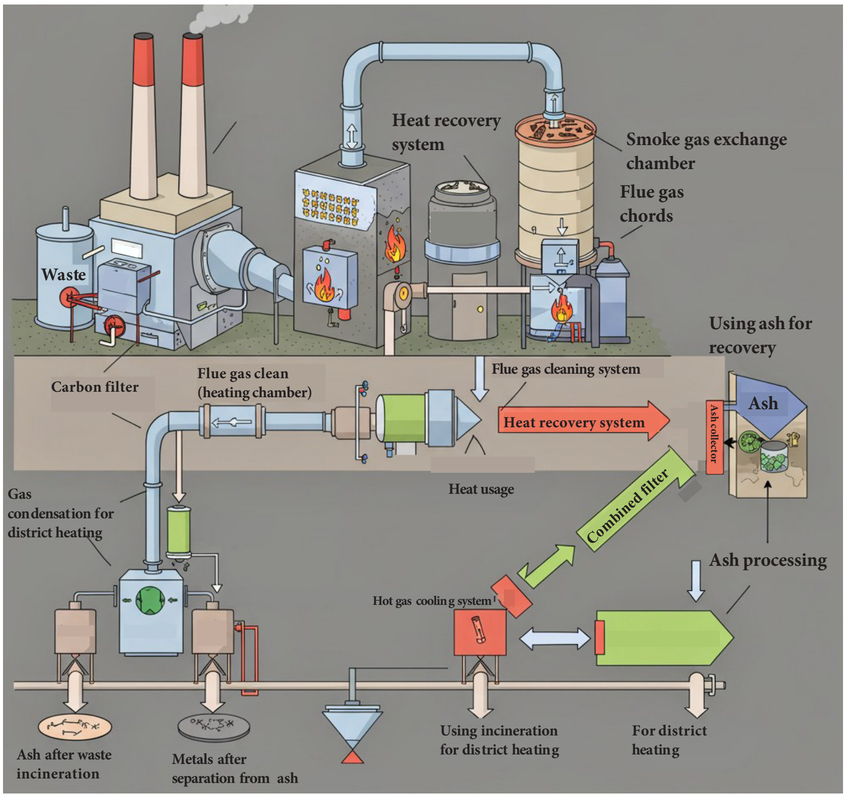

Figure 1. Incineration process

Source: made by the authors

The data indicate that while incineration provides the highest waste reduction, it generates the largest volume of hazardous residues. Pyrolysis offers a compromise between energy recovery and environmental safety. Gasification and plasma technologies ensure the lowest emissions but require a stable energy supply and advanced control systems (Table 1).

Table 1. Comparison of waste-to-energy technologies – efficiency, outputs, and environmental impact

Technology	Waste reduction (%)	Energy output	Major pollutants	Residue characteristics	Key advantages	Main limitations	References
Incineration	85-90	Heat, electricity	Dioxins, SO_x, NO_x, heavy metals	Toxic ash (10-15% of input)	Established technology; energy recovery	Toxic emissions; ash disposal risk	M. Niu *et al.* (2014), I. Cañete Vela *et al.* (2019)
Pyrolysis	70-80	Syngas, biochar, oil	VOCs, hydrocarbons	Biochar is suitable for soil application	Lower dioxin emissions; reuse potential	Energy-intensive; requires segregation	G. Özsin & A.E. Pütün (2022), J. Joo *et al.* (2022), C. Li *et al.* (2022)
Gasification	80-90	Syngas	CO, tar, trace metals	Inert slag	Efficient energy conversion; low emissions	Complex control; tar formation	S. Yasin *et al.* (2020), M. Dudyński *et al.* (2021)
Plasma gasification	90-95	High-quality syngas	Minimal (dioxins < 0.01 ng/m³)	Glassy inert slag	Near-zero pollution; hazardous waste treatment	High cost; up to 1 MW/t energy need	V.Ya. Kozhukhar *et al.* (2021),V. Vashchenko *et al.* (2024), G. Cornelissen *et al.* (2025)

Source: compiled by the authors

The Kharkiv Region presents specific environmental conditions that strongly influence the mobility of contaminants. Soils are primarily chernozems with high humus content (4-6%), pH levels of 6.0-7.0, and shallow groundwater levels (2-10 m). These properties reduce the migration of Pb and As but promote accumulation in the upper soil horizon during atmospheric deposition. Annual precipitation ranges from 600 to 700 mm, with spring floods intensifying the leaching of nitrates and metals into groundwater, according to a statement by L. Di Stasio *et al.* (2025). Toxic ash from incineration poses a significant risk of secondary contamination under flood conditions. Pyrolysis and plasma gasification generate smaller, more stable residues; however, their reuse as construction materials requires detoxification, as stated in the National Report on the State of the Environment in Ukraine (Ministry of Environmental Protection and Natural Resources of Ukraine, 2018) and supported by data from R. Mallick & P. Vairakannu (2025). Regional adaptation of technologies must therefore include strict emission control, safe residue management, and integration with renewable energy. The pyrolysis process (Fig. 2), as explained by I. Zyma *et al.* (2024), which occurs at temperatures of 400-800°C in an oxygen-free environment, produces biochar, synthesis gas, and liquid fractions that can be used as fuel or to stabilise contaminants in soils.

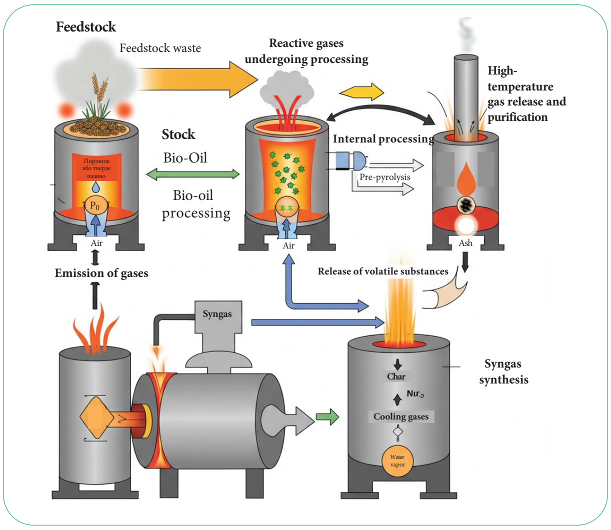

Figure 2. Pyrolysis process

Source: made by the authors

This technology reduces dioxin emissions compared to incineration, but its effectiveness depends on waste sorting and process stability. Studies show that pyrolysis biochar can bind Pb and Cd in chernozems (humus 4-6%), increasing the effectiveness of phytoremediation (*Brassica juncea* accumulates up to 1,000 mg/kg Pb). However, pyrolysis requires a significant energy input, which increases the carbon footprint if the energy is not renewable, and poses the risk of volatile organic compound formation during plastic recycling (Talwar *et al.*, 2025). Plasma gasification, which operates at temperatures ranging from 3,000 to 6,000°C, converts waste into synthesis gas and a glassy slag with minimal ash (Sanjaya & Abbas, 2023; Galaly *et al.*, 2024; Panwar *et al.*, 2025). This technology is effective for treating hazardous waste, such as medical or industrial waste, and reduces dioxin emissions to 0.01 ng/m^3 (Fig. 3).

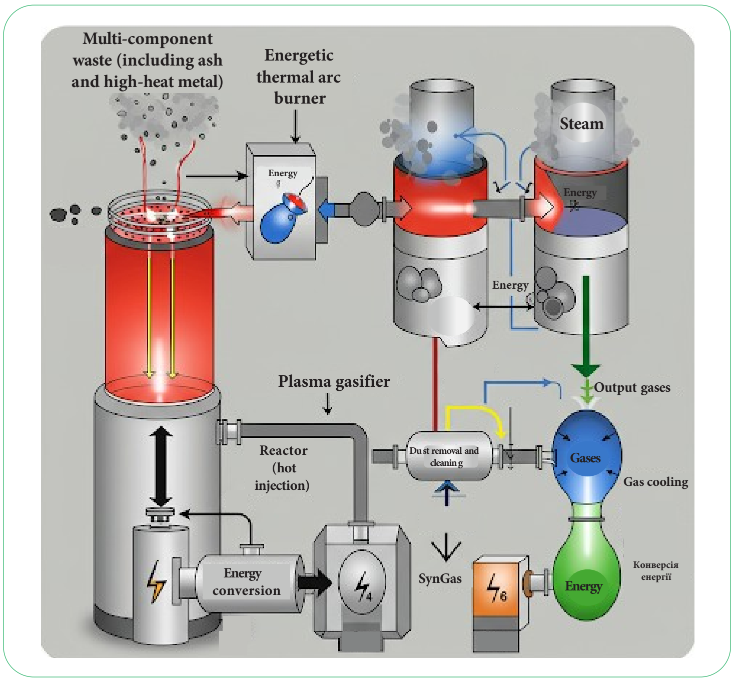

Figure 3. Schematic process of plasma gasification

Source: made by the authors

However, its high energy intensity, which can reach up to 1 MW per ton of waste, and the technological complexity of the equipment significantly limit its applicability in post-conflict regions such as the Kharkiv Region, where critical infrastructure remains constrained. Although the resulting slag is generally less toxic, the potential presence of heavy metal residues necessitates mandatory compliance with national regulatory requirements, in particular DSTU 7856:2015 (2015) and DSTU ISO 14001:2015 (2015), which governs its assessment prior to disposal. Overall, these factors indicate that plasma gasification in such conditions should be regarded as a technologically promising but currently constrained option that requires additional technical, economic, and environmental justification before large-scale implementation.

The environmental risks of thermal waste processing include air, soil and water pollution, which is especially relevant for the Kharkiv Region, where black soils with pH 6.0-7.0 and high humus content complicate the mobility of Pb and As, but increase the risk of their accumulation during the deposition of emissions (Solokha *et al.*, 2025). Emissions of dioxins and heavy metals from incineration can reduce the effectiveness of phytoremediation, as plants are sensitive to atmospheric pollution, which in turn reduces their ability to absorb nitrates (Di Stasio *et al.*, 2025). Studies show that protective strips of *Phalaris arundinacea* can retain up to 70% of atmospheric particles, but require regular monitoring, as specified in DSTU EN ISO 5667-1:2025 (2025). Toxic ash from incineration poses a threat to groundwater (2-10 m) in the Kharkiv Region, particularly during floods (600-700 mm of precipitation, with a peak in March-April), which can lead to secondary pollution as stated in the National Report on the State of the Environment in Ukraine (Ministry of Environmental Protection and Natural Resources of Ukraine, 2018). Pyrolysis and plasma gasification reduce the volume of ash, but its utilisation as a building material requires prior detoxification, which increases costs (Cornelissen *et al.*, 2025). The integration of thermal processing with phytoremediation requires spatial planning, as plants should be located at a distance from phytoremediation sites to prevent sedimentation of emissions.

Research gaps and regional context

The current literature primarily focuses on the industrial aspects of thermal processing, while its impact on agricultural regions, such as the Kharkiv Region, remains poorly understood. Most studies analyse the short-term effects of emissions, but the long-term impact on soil ecosystems, especially in combination with phytoremediation, remains poorly understood (Lackner & Besharati, 2025). For example, there is a lack of data on how Pb and Cd deposition from ash affects plants used for phytoremediation in conditions of high humus chernozems (4-6%). Additionally, limited studies have considered the energy intensity of technologies in post-conflict regions where access to renewable energy is challenging.

According to official statistical data and analytical reports, the scale of municipal solid waste generation in the Kharkiv Region is quantitatively significant and confirms the relevance of the problem stated in the methodology (Kharkiv Regional State Administration, 2024). In 2022, the total amount of waste generated in hazard classes I-IV in the Kharkiv Region was approximately 142,000 t, of which only 16.4 per cent was utilised, and approximately 13,875 t was treated by incineration or thermal recovery. At the same time, more than 27,000 t of municipal solid waste were disposed of in landfills, indicating a steady accumulation of waste and limited regional processing capacity. These figures reflect structural imbalances in the waste management system, in which disposal predominates over recovery and energy use. In addition, wartime conditions led to incomplete statistical reporting in 2022-2023, which constrains a full assessment of temporal dynamics but does not alter the overall conclusion about the critical scale of waste accumulation in the region. The regional data are consistent with national estimates, according to which Ukraine generates about 11-13 million tons of municipal solid waste annually, with more than 95% directed to landfills. This quantitative evidence substantiates the need to assess thermal waste treatment technologies in the Kharkiv Region not only from an environmental perspective but also in response to the objectively large and growing volume of municipal solid waste.

In the Kharkiv Region, where the climate (600-700 mm of precipitation) and hydrology (groundwater 2-10 m) favour nitrate leaching, thermal processing may complicate remediation due to secondary contamination. Studies recommend using renewable energy sources for pyrolysis and plasma gasification, as well as implementing remote monitoring (NDVI, drones) to assess the impact of emissions on phytoremediation sites (Ivanova & Kaverda, 2019; Petrushka & Volivach, 2024). However, the lack of standardised protocols for integrating these technologies with phytoremediation remains a challenge. Gasification, pyrolysis, and plasma gasification have significant potential for waste management, but are accompanied by environmental risks, including dioxin emissions, toxic ash formation, and high energy intensity. In the context of the Kharkiv Region, these risks may complicate phytoremediation, reducing the effectiveness of soil remediation for Pb, As, Cd, and nitrates. To minimise the impact, researchers Ya.H. Tsytsyura *et al.* (2022) suggested using modern filtration systems, buffer strips, monitoring, and renewable energy sources. However, gaps in the study of long-term effects and regional specificities indicate the need for further research that would combine thermal processing with phytoremediation in post-conflict settings.

The results obtained indicate that thermochemical waste processing methods, particularly pyrolysis, gasification, and plasma gasification, have significant potential for improving the efficiency of managing complex waste streams, such as textiles. The analysis confirms that the choice of temperature regime, the presence of catalysts and the design of the reactor determine the energy efficiency and yield of target products. Increasing the temperature leads to an increase in the yield of synthesis gas. At the same time, catalysts contribute to optimising the quality of liquid fractions, which is consistent with the results of modern research. In particular, N.L. Panwar *et al.* (2025) demonstrated that plasma gasification enables the reduction of CO_2 emissions and the complete elimination of dioxin formation, while maintaining a high calorific value in the resulting gas. Similar conclusions are presented in the work of E. Sanjaya & A. Abbas (2023), who emphasised that the introduction of plasma technologies into a closed-loop economy enables the combination of energy efficiency and environmental safety. A.R. Galaly *et al.* (2024) reported that plasma gasification of plastics provides minimal residual products and meets modern sustainability requirements. These results confirm the environmental advantage of the technology over classical combustion methods.

In the context of pyrolysis, the results are consistent with those of K. Sharma *et al.* (2022), G. Özsin & A.E. Pütün (2022), B.Y. Lamba (2025), who found that a temperature range of 600-800°C provides an optimal balance between the formation of gaseous and liquid fractions. I. Zyma *et al.* (2024) confirmed the importance of temperature control for stabilising the thermal decomposition of organic matter, while I. Petrushka & T. Volivach (2024) emphasised the role of catalysts in reducing the toxicity of the final products. Thus, an approach based on adapting the process parameters to the composition of the feedstock is crucial to achieve high energy performance and minimise harmful emissions.

Regarding gasification, analysis confirms the trends identified in V.V. Ivanova & L.O. Kaverda (2019), M. Lackner & M. Besharati (2025), and B. Hamidinasab & A. Nabavi-Pelesaraei (2025). The authors showed that at temperatures above 900°C, the content of CO and H_2 in the syngas increases significantly, while the formation of tars and ash decreases. However, as noted by N.L. Panwar *et al.* (2025), for the stable operation of such systems, preliminary preparation of the feedstock is necessary, in particular, the removal of flame retardants and impurities that reduce reactivity. Results of the current study confirm that differences in the composition of textile waste (cellulosic vs. synthetic) directly affect the gasification efficiency, which is consistent with the findings of A.R. Galaly *et al.* (2024) on the role of chemical heterogeneity in product formation.

A comparison of pyrolysis and gasification shows that both processes have the potential for fuel production, but gasification provides a cleaner energy product with lower residue content. However, as E. Sanjaya & A. Abbas (2023) point out, the formation of CO_2 and resins remains a problem, which reduces the efficiency of syngas use without additional purification. The results confirm these conclusions: even with optimisation of the temperature regime, a significant number of by-products is formed that require post-purification. Plasma gasification, on the other hand, demonstrates fundamentally different properties. As shown in the studies by N.L. Panwar *et al.* (2025) and A.R. Galaly *et al.* (2024), the use of plasma arc systems ensures the destruction of complex polymers and eliminates toxic emissions. Theoretical analysis confirms that extremely high temperatures (>2,000°C) contribute to the formation of clean syngas with high H_2 and CO content and virtually no tars, making the technology suitable for producing clean energy carriers. These results correlate with the conclusions of I. Zyma *et al.* (2024) on the need for innovative solutions in the field of emission control in high-temperature processes.

However, plasma technology has limitations, including high energy consumption and significant capital costs, as noted by E. Sanjaya & A. Abbas (2023) and N.L. Panwar *et al.* (2025). However, A.R. Galaly *et al.* (2024) and others believe that integrating plasma gasification with heat recovery and syngas reuse technologies can compensate for energy losses and improve overall profitability. A comparative analysis of literature sources reveals that over the past five years, there has been a noticeable increase in research interest in plasma technologies for waste management. This trend is observed in both domestic (Ivanova & Kaverda, 2019; Lackner & Besharati, 2025) and international publications (Sanjaya & Abbas, 2023; Galaly *et al.*, 2024; Panwar *et al.*, 2025), indicating the relevance of the topic. In general, it can be stated that plasma gasification is the most promising in terms of environmental safety and energy efficiency. At the same time, further research is needed to optimise balance, improve plasma burners, and scale the technology for industrial applications.

The assessment of thermal waste treatment technologies was refined with explicit consideration of the environmental conditions of the Kharkiv Region. Chernozem soils with high humus content and shallow groundwater increase the risk of secondary contamination from toxic residues generated during waste processing. Under these conditions, incineration poses a high environmental risk due to the formation of hazardous ash and its limited compatibility with ecosystem restoration measures. Pyrolysis demonstrates the highest regional suitability, as its biochar residues can reduce the mobility of heavy metals in soils and support phytoremediation practices. Plasma gasification provides low emission levels but is constrained by high energy demand and limited post-conflict infrastructure. Overall, the results indicate that pyrolysis is the most compatible thermal technology for the Kharkiv Region, combining waste treatment efficiency with practical integration into soil and ecosystem restoration strategies. Thus, the theoretical analysis conducted confirms that the transition from traditional incineration to high-temperature thermochemical conversion methods not only reduces environmental risks but also contributes to achieving sustainable development goals by converting waste into valuable energy sources.

Based on a comparative analysis of thermal waste treatment technologies, phytoremediation is not considered a stand-alone solution, but rather a complementary recovery stage following controlled thermal processing. In the conditions of the Kharkiv Region, the direct application of phytoremediation without prior stabilisation of pollutants is ineffective due to the presence of heavy metals and persistent toxic compounds in the soil. The results indicate that pyrolysis creates the most favourable conditions for subsequent phytoremediation. The application of pyrolysis-derived biochar reduces the bioavailability of Pb, Cd, and As, stabilises the upper soil horizon, and improves conditions for plant-based remediation. This allows phytoremediation to function as a targeted ecological recovery tool rather than a passive natural process. From an applied perspective, phytoremediation should be implemented in spatially separated zones, following residue characterisation and detoxification. Plant systems should be selected based on the type of contaminant and soil properties, and their performance must be supported by long-term monitoring. Under these conditions, phytoremediation becomes a practical component of an integrated waste management and ecosystem restoration strategy rather than an insufficiently explored concept.

Conclusions

The analysis revealed that thermal waste processing technologies, including incineration, pyrolysis, and plasma gasification, are key directions for transforming Ukraine's solid waste management system. Each of these methods has the potential to significantly reduce waste volumes and obtain secondary energy resources, but their implementation requires a balanced approach that considers potential environmental risks. Incineration remains the most common technology that significantly reduces waste volumes and energy generation. At the same time, its environmental safety is limited by the formation of toxic ash and emissions of harmful compounds, which requires highly efficient systems for cleaning, monitoring and disposal of by-products. Pyrolysis is a more environmentally balanced alternative, as it allows for the production of biochar, synthesis gas, and liquid fuel under conditions of limited oxygen access. The ability of biochar to fix heavy metals in the soil emphasises the dual effect of this process – energy and environmental protection. At the same time, the efficiency of pyrolysis largely depends on the quality of waste sorting and the stability of energy supply. Plasma gasification is the most technologically advanced method for processing hazardous or mixed waste streams. It provides the formation of synthesis gas and inert slag with minimal toxicity but requires significant energy resources and complex operational infrastructure.

The environmental consequences of thermal waste treatment are particularly important for the Kharkiv Region, where soil contamination with heavy metals and high groundwater vulnerability are observed. The success of such projects is possible only under the conditions of an integrated approach, which involves modern emission cleaning technologies, safe management of ash and slags, and the use of renewable energy sources to reduce the carbon footprint. For the Kharkiv Region, the study demonstrated that incineration and pyrolysis can significantly reduce waste volume and generate energy. At the same time, pyrolysis also provides additional heavy metal fixation in soils through the production of biochar. Plasma gasification is effective for mixed and hazardous waste, minimising the toxicity of slag, but it requires significant energy resources. The success of implementing these technologies in the region is possible only through an integrated approach, which includes modern emission treatment systems, safe management of residues, and the use of renewable energy. Further studies should assess the long-term impact of residues on soil and water ecosystems of the Kharkiv Region and determine the effectiveness of combining thermal technologies with phytosanitary measures. Such research will provide a scientific basis for combining technological innovations with ecological security and regional recovery objectives.

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Conflict of Interest

None.

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Екологічні ризики термічного управління відходами та перспективи сталого відновлення

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Анотація. Управління твердими побутовими відходами залишається однією з найгостріших екологічних проблем в Україні, особливо в Харківській області, де забруднення ґрунтів і вразливість підземних вод посилюють екологічні ризики. Метою дослідження було оцінити екологічні ризики технологій термічної обробки відходів у Харківській області та визначити їхню сумісність зі стратегіями відновлення екосистем. У роботі застосовано порівняльний аналітичний підхід із інтеграцією методів оцінки впливу на довкілля для аналізу технологій спалювання, піролізу та плазмової газифікації. Оцінювання включало визначення викидів забруднювальних речовин, енергоефективності та утворення вторинних відходів з урахуванням регіональних умов. Встановлено, що спалювання, хоча й ефективно зменшує об'єм відходів, утворює небезпечні залишки, які містять важкі метали та органічні токсини. Піроліз характеризується нижчими рівнями викидів і утворенням біочару, здатного іммобілізувати забруднювачі в ґрунтах, що підвищує його потенціал інтеграції з практиками фіторемедіації. Плазмова газифікація забезпечує майже повне розкладання складних потоків відходів, однак потребує значних енергетичних витрат і розвиненої технічної інфраструктури. Дослідження показало, що в умовах післяконфліктного контексту Харківської області піроліз забезпечує найкращий баланс між екологічною безпекою та ресурсною ефективністю. Розроблено підхід до інтеграції залишків термічної обробки у стратегії відновлення ґрунтів з метою підтримки регіональної сталості. Отримані результати можуть бути використані інженерами-екологами, органами місцевого самоврядування та політиками для проєктування сталих систем перетворення відходів на енергію, адаптованих до екологічно чутливих і післяконфліктних територій

Ключові слова: технології перетворення відходів на енергію; викиди забруднювальних речовин; охорона ґрунтів і вод; відновлення екосистем; ресурсна ефективність; сталий розвиток

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Integrated aerial and ground unmanned systems for assessing war-induced forest ecosystem damage

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Abstract. Armed conflicts pose severe and multidimensional threats to forest ecosystems, including large-scale fires, mechanical destruction of vegetation, soil degradation, chemical contamination, and biodiversity loss. The aim of this study was to theoretically substantiate the use of integrated aerial and ground unmanned systems for monitoring war-induced forest ecosystem damage under limited-access conditions. The study used a theoretical-analytical approach combining systematic literature review, comparative analysis, and conceptual synthesis of remote forest monitoring methods based on aerial and ground unmanned systems. It was established that traditional methods for monitoring forest damage, despite the high accuracy and comprehensiveness, were ineffective under armed conflict conditions due to physical danger, labour intensity, and limited access to affected areas. This determined the need to transition to innovative remote technologies to ensure continuous and accurate observation of forest ecosystem conditions. According to data from specialised studies and open environmental sources, unmanned aerial vehicles

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and ground platforms demonstrated high efficiency in conducting rapid monitoring of forest ecosystems in combat zones, particularly under conditions of restricted access. The methods considered make it possible to promptly detect manifestations of natural area degradation and assess the scale of tree stand damage both in Ukraine and beyond its borders. The practical significance of the study lay in the use of unmanned systems for environmental monitoring, damage assessment, and support of forest restoration in combat zones

Keywords: remote sensing; multispectral camera; drone; aerial photography; satellite image; multicopter

Introduction

One of the main environmental challenges for Ukraine was the problem of mass forest destruction due to fires, particularly those caused by hostilities. Forest ecosystems suffered significant damage – loss of tree cover, soil degradation, and reduction of biodiversity – which complicated natural regeneration processes and posed a threat to the existence of many species. The relevance of the study was driven by the fact that forest ecosystems suffered extensive damage due to the armed conflict, while traditional monitoring methods proved ineffective under conditions of limited access, increased danger, and the need for rapid and reliable environmental information. Therefore, the need for the use of advanced technologies increased. The research problem lay in the absence of methods adapted to wartime conditions for comprehensive monitoring capable of promptly and accurately detecting environmental damage. An analysis of modern publications revealed insufficient application of an integrated approach using ground and aerial unmanned systems to assess the condition of forests in hazardous areas.

The destruction of tree vegetation, changes in soil structure, and the reduction of biodiversity in forests in armed conflict zones were studied by S.G. Chornyy (2023). According to the study, due to the decrease in the normalised difference vegetation index (NDVI) during the period of maximum photosynthetic activity – from June to July 2023 – partial destruction of both primary and secondary vegetation occurred, which negatively affected the soil-protection and windbreak functions of shelterbelts. Under conditions of limited access to combat zones, traditional methods for monitoring forest damage proved ineffective. The issue was studied by Y.B. Kyryliv *et al.* (2024). According to the study, the greatest advantage of unmanned aerial vehicles (UAVs) use during the war was the high response speed and reduced resource and personnel costs required for the operation.

The issue of shelterbelt degradation in Donetsk Region, where a significant portion of shelterbelt plantations was damaged by fires between 2021 and 2025, was studied by S. Popov & O. Orechov (2024). The research involved the development of intelligent forest fire monitoring systems using swarms of UAVs. The researchers identified the need for comprehensive monitoring of the state of protective forest plantations and the development of effective measures for the conservation and restoration using geodetic methods and UAVs. Research in this field was conducted by S.G. Mohylnyi *et al.* (2023). The authors' findings indicated that the condition of protective forest plantations required constant monitoring, as these plantations were subject to degradation from both anthropogenic and natural factors. Notably, the greatest losses of field shelterbelts were recorded in Kherson (3,271.2 ha) and Zaporizhzhia regions (2,266.4 ha), due to extensive illegal logging.

In parallel, the study of changes in urban forests due to military actions emerged as an important issue for modern ecologists. The matter attracted the attention of M. Seneta *et al.* (2024). In the work, the authors proposed using quadcopters for environmental monitoring, particularly in urban forests, which enabled effective tracking of vegetation degradation in occupied territories and active combat zones. The research highlighted the importance of improving monitoring methods for urban forests, especially through the use of high-precision UAVs. Special attention was given to the use of advanced UAV technologies in forest fire protection. This issue was studied by B. Kozka & V.-P.O. Parkhomenko (2023). The authors explored the possibilities of using UAVs for reconnaissance and monitoring of forest fires, including the detection of fire outbreaks and assessment of extinguishing effectiveness. The issue of UAV use due to the ongoing war since February 2022 was studied by V.H. Shpyrna (2023). According to the author's research, effective use of UAVs in land management and environmental monitoring during the war enabled the prompt collection of spatial data, assessment of land condition, and detection of anthropogenic impacts on the environment. The significant environmental damage inflicted on Ukraine's forests by hostilities highlighted the need for forest ecosystem restoration and the implementation of effective rehabilitation measures, particularly using modern monitoring technologies such as UAVs.

The issue of the deterioration of coniferous forests in the Tukhlianske Forestry of the Prykarpattia Region due to fires was studied using UAV imagery, with proposed solutions offered by Kh. Burshchynska & Y. Dekalyuk (2021). The researchers proposed a method for assessing the condition of coniferous forests based on high-resolution imagery and UAV data. The method could be applied across various forestry structures and adapted to combat conditions. The problem of forest damage assessment in Kharkiv Region under occupation or active combat conditions was studied by N.V. Maksymenko *et al.* (2023). Based on UAV data, the researchers identified 2.9 million hectares of damaged forests and noted that large-scale tree stand destruction and forest fragmentation required the implementation of systematic and technologically advanced monitoring. According to O.V. Rybalova *et al.* (2019), the importance of implementing environmental measures to reduce the impact of chemical pollutants on soil and public health after forest fires should be emphasised. The study showed that the integral indicator of soil chemical content (IPCS) corresponded to Class 2 (good condition) before the fire, and Class 4 (poor condition) afterwards.

These studies did not give sufficient attention to a comprehensive approach to examining the impact of warfare on the ecological state of forest ecosystems – particularly regarding forest degradation monitoring, biodiversity loss, and destruction of protective plantings in combat zones. The purpose of this study was to validate and assess the function of integrated aerial and ground unmanned systems as a conceptual framework for tracking damage to forest ecosystems caused by war in situations with restricted access and increased environmental risk. The study objectives were: to conceptualise an integrated unmanned monitoring framework, analyse key indicators of war-induced forest ecosystem damage, and assess the complementary roles of aerial and ground platforms under limited-access conditions.

Materials and Methods

This work is based on a theoretical-analytical research methodology that aims to conceptualise and systematise modern methods for monitoring forest ecosystems in the context of armed conflict. In line with the theoretical focus and the findings, the methodological framework integrates conceptual modelling, comparative analysis, and qualitative synthesis. Peer-reviewed scientific publications discussing forest damage, fire effects, vegetation stress, and the use of remote sensing in conflict and post-conflict settings made up the analytical corpus. Additionally, reports from national and international organisations devoted to environmental monitoring in war-affected areas were included. The use of unmanned aircraft and ground-based systems for forest evaluation in dangerous or inaccessible places was also investigated through case studies that were reported. All of the materials were chosen based on their applicability to forest ecosystems that have been impacted by military operations and their contribution to the methodological advancement of remote monitoring techniques. Materials that did not address remote or unmanned monitoring techniques, did not clearly focus on forest ecosystems impacted by military or high-risk conditions, or did not have methodological or analytical relevance to the study's aims were excluded from the analytical corpus.

To guarantee a logical interpretation of forest damage monitoring during armed conflict, the study used a variety of complimentary analytical techniques. To categorise and organise the various forms of forest damage linked to military operations, such as thermal, mechanical, chemical, and biological impacts, thematic analysis was used. The functional capabilities, data resolution, spatial coverage, operational dangers, and suitability for employment in combat scenarios of several kinds of unmanned systems, both aerial and ground-based, were assessed using comparative analysis. The integration of various data sources, sensor setups, and operating platforms allowed for the examination of forest monitoring through system analysis. Additionally, an integrated model of remote forest assessment during armed conflict was developed by using conceptual synthesis to identify dominant monitoring paradigms. Together, these techniques made sure that the monitoring technologies examined and the damage typologies mentioned were in line, which supported the comparative analyses shown in the Results section.

Unmanned monitoring systems were analysed within the analytical framework using a common set of evaluation criteria, which included platform type (differentiating between aerial and ground-based systems) and onboard sensor configuration (such as RGB, multispectral, thermal, and LiDAR instruments). Along with operational constraints related to weather, terrain complexity, and security threats in combat situations, consideration was also given to the degree of spatial and thematic information each system offered. Additionally, the suitability of various technologies for site-specific assessment versus large-scale monitoring was taken into account. The comparative features and performance metrics, such as resolution, coverage area, autonomy, and damage detection accuracy, discussed further were based on this analytical approach. Kharkiv Region is considered in this study as a representative case frequently documented in publications on war-induced forest ecosystem damage.

Results

Types of tree damage in forests due to military actions

Types of tree damage in forests as a result of military actions are classified as thermal, mechanical, chemical, and biological. The war has negatively affected forest ecosystems, as forests were used as natural shelters for military equipment and personnel, and were also subjected to armed attacks, which led to the damage. As a result of shelling with various types of weapons, trees were destroyed, soils degraded, chemical contamination occurred, and biodiversity was lost. In addition, explosions and fires disrupted the ecological balance, leading to changes in forest stand composition and causing long-term environmental consequences. In particular, there was mass tree death, which in turn led to the replacement of native species with less resilient ones. Craters formed due to explosions, and mechanical destruction of soil occurred due to military equipment digging trenches and foxholes.

Soils and groundwater were polluted with remnants of ammunition, fuels, and lubricants (petrol, liquefied natural gas, engine oils), heavy metals, and toxic chemicals. Explosions, fires, and mechanical damage resulted in the death of animals and plants, leading to forced migration of fauna. When trees were damaged or completely died, and dry biomass accumulated, forest fires spread. Explosions caused crater-like depressions in the ground and disrupted the plant cover, which altered the water balance of forests, contributing to either waterlogging or, conversely, drying out of forest areas. This reduced forest water availability due to the loss of natural vegetation layers that help retain moisture in the soil. Such changes led to quicker soil drying and increased erosion risk. The accumulation of dry biomass after fires contributed to greater fire spread, which also affected the water balance. After such fires, the soil surface lost its moisture retention ability, as organic matter layers were burned and high temperatures dried the soil. If these processes led to crater formation or significant damage to vegetation, water would accumulate in lower areas, raising the groundwater level.

The crash of aircraft, helicopters, missiles, and UAVs containing ammunition, explosives, and fuel caused significant damage to forest ecosystems. Shockwaves, shrapnel, and debris broke tree trunks, branches, and roots, resulting in mechanical plant damage and forest fires. Powerful explosions created craters, leading to tree falls, root damage, and soil layer disruption. Typical damage symptoms detectable remotely by UAVs or satellites include a decrease in NDVI, indicating reduced photosynthetic activity; canopy cover disruption, indicating mechanical or thermal damage; and reduced forest stand density, which may result from fires, logging, or vehicle movement.

Overview of modern remote forest monitoring methods during armed conflict in Ukraine

The following provides an overview of existing monitoring practices and technologies essential for understanding the context and comparing with obtained results. The collection and processing of environmental data using UAVs is a modern and effective method for monitoring forest ecosystem conditions, especially under limited access or high-risk conditions, such as mine-contaminated areas. During full-scale armed aggression, systemic deterioration of forest ecosystems was recorded in areas directly impacted by combat. Theoretical analysis identified several key environmental consequences: firstly, a significant increase in damaged forest cover area, particularly in riparian forests along the Dnipro Delta in the administrative district unit "Kherson", indicating natural barrier destruction and biodiversity loss; secondly, increased fire risk due to degraded firefighting infrastructure and inability to control fires in temporarily occupied areas. These processes pose risks of long-term environmental changes, especially prominent in Kyiv, Kharkiv, Donetsk, and Luhansk regions, where anthropogenic and military impacts intersect with environmental vulnerability (Matsala *et al*., 2024). In response to fire threats and limited access to parts of forest areas, a national remote forest resource monitoring system was developed and implemented. The theoretical foundation of this system was based on integrating data from various sources (satellite imagery, GIS, risk assessment models), enabling comprehensive forest condition assessment even in hard-to-reach zones. Thus, the theoretical concept of monitoring during armed conflict transformed into a practical environmental security tool at the state level (Myroniuk *et al*., 2024).

Satellite monitoring was another important source of forest condition information. The use of medium and high-resolution satellite imagery (e.g., Sentinel-2, Landsat 8) allowed large areas to be assessed in a short time. Spectral analysis enabled detection of burned areas, decreased leaf surface, reduced biomass, etc. However, satellite methods are limited by weather conditions (e.g., cloud cover), insufficient detail for small damage areas, and data update delays, which can hinder timely ecosystem response. Using ground photogrammetry and laser scanning (LiDAR), 3D models of forests can be created, and vegetation structure, tree and understorey damage levels can be accurately determined. Ground laser scanners are particularly effective for detailed site analysis, but the use is limited by high time costs, the need for physical personnel presence, and difficulty operating in dangerous or mine-contaminated zones.

The integration of aerial imaging, laser scanning (LiDAR), and satellite data has formed a modern paradigm of remote environmental monitoring, enabling not only rapid detection of structural changes in forest ecosystems but also dynamic modelling of the spatial-temporal development (Borghi *et al*., 2025; Dahan *et al*., 2025). A special role in this approach is played by the Pure Forest Index (PFI), which synthesises spectral characteristics from satellite and LiDAR data, allowing for continuous assessment of forest disturbance levels (Cai *et al*., 2023). Such approaches enabled an expanded range of ecological indicators for analysis and adapted monitoring systems to limited-access conditions, particularly in combat zones. Conceptually, this transforms remote sensing from a supplementary tool into a key component of environmental security strategy.

In armed conflict contexts, traditional monitoring methods proved ineffective due to high danger, difficult access to observation sites, and the need for timely information. Ukrainian forests have been affected by combat operations, including explosions, fires, contamination with heavy metals and ammunition remnants, leading to forest ecosystem degradation. To assess damage and plan restoration efforts, precise, timely, and safe monitoring methods should be prioritised. Hence, there was a need for innovative solutions, among which remote technologies using unmanned systems played a central role – combining mobility, safety, and high data resolution.

In current conditions, where traditional field monitoring methods were insufficient or even dangerous – especially in conflict zones – remote technologies were used as the main tool for forest ecosystem condition assessment. Scientific focus shifted to implementing autonomous UAV-based systems, which, due to the manoeuvrability and adaptability to complex landscapes, can perform high-precision mapping and dynamic monitoring. Robotic drones equipped with trajectory planners (e.g., EGO-Planner-v2) were particularly promising, capable of autonomously navigating complex environments – opening new possibilities for constructing spatial-temporal forest cover change models (Karjalainen *et al*., 2024). The proposed remote monitoring concept included not only prompt detection of vegetation changes, but also integration of high-resolution image time series to assess anthropogenic impact. This transforms the approach to studying protected areas: from static condition capture to real-time ecosystem dynamic analysis. Thus, UAV use became not only a technical advancement but also defined a new methodology for environmental monitoring under high ecological risk (Ancin-Murguzur *et al*., 2020).

Sensor systems played an important role in improving monitoring efficiency using aerial and ground unmanned platforms. These included: multispectral cameras to analyse vegetation via vegetation indices (e.g., NDVI) and detect tree stress; hyperspectral sensors providing highly detailed physiological plant condition and damage type data; laser scanners (LiDAR) enabling accurate 3D forest structure models, including tree height, canopy density, and biomass volume; thermal cameras for detecting fires, decay zones, or other thermal anomalies; and high-resolution visual cameras for identifying mechanical trunk damage, logging, and technogenic impact traces.

With the active implementation of aerial UAV platforms (quadcopters, planes, or hybrid systems) equipped with high-quality optical and multispectral cameras, it became possible to generate detailed orthophotomaps, analyse canopy condition, and detect signs of fires, diseases, or mechanical damage. Aerial UAV use in forest monitoring opened new possibilities for prompt ecosystem condition assessment across large areas (Wójcik *et al*., 2022). The ability to produce accurate orthophotomaps and 3D terrain models enabled not only identification of forest damage zones but also laid the foundation for spatial-temporal change analysis. In this context, particular attention was paid to implementing hyperspectral remote sensing systems capable of detecting subtle physiological and biochemical deviations in vegetation. Mounting a Hyspex VS-620 hyperspectral thermal imager on a DJI Agras T30 platform demonstrated the potential for developing specialised aerial systems for monitoring forest biogeocenoses. Despite technical limitations – such as vibrations at 9.6 Hz, limited flight time, and safety requirements for operating drones over 25 kg – this solution showed the feasibility of creating adaptive monitoring systems capable of autonomous operation in complex conditions (Arroyo-Mora *et al*., 2023). Conceptually, this marked a transition from general sensing to highly specific, targeted diagnostics of forest ecosystems, particularly relevant under ecological risk and natural disaster conditions.

In the structure of modern environmental monitoring, the application of ground-based unmanned platforms (Unmanned Ground Vehicles (UGVs)) gained particular importance. Unlike aerial systems, such vehicles provided high-precision point control of environmental parameters at soil and understorey levels (Bruno *et al*., 2019). The ability to measure physical, chemical, and biological characteristics enabled detailed spatial ecosystem structure analysis, including assessing litter condition, structural tree damage, and microclimatic changes (Segaran *et al*., 2023). At the same time, the application in hard-to-access or potentially dangerous (e.g., mined) areas required new adaptation and integration strategies. The "air-ground" collaborative robotic systems concept formed a new level of situational awareness, where the combination of UAV and ground platform advantages allowed improved environmental data collection accuracy, timely environmental response, and comprehensive monitoring of areas with varying accessibility (Shults & Annenkov, 2023; Zhang *et al*., 2024). This approach is reported to improve the accuracy of degradation, fire, or other threat detection and localisation in dynamic environments. Theoretically, integrating multi-level unmanned platforms could become the foundation for building a new generation of autonomous monitoring systems capable of functioning under high-risk conditions without compromising data quality.

A comprehensive assessment of forest ecosystems required integration of diverse information sources. Combining aerial photography, satellite monitoring, ground visual observation, GPS tracking, and LiDAR scanning enabled the construction of 3D models of territories and provided multi-level diagnosis of forest structure and dynamics. This approach realised the principle of multi-sensor data fusion, which could theoretically form the basis of a new forest monitoring paradigm – adaptive, spatially differentiated, and highly detailed. Applying artificial intelligence algorithms in image processing enabled automatic classification of damaged areas, identification of vegetation changes, and formulation of scenario forecasts for environmental consequences. Integrating LiDAR data with satellite, hyperspectral, and radar materials allowed for more accurate assessment of attributes such as tree stand height, species composition, biomass, and canopy density. Theoretically, such interdisciplinary technological synergy created the prerequisites for developing the concept of remote, risk-resilient environmental monitoring. It was especially relevant in regions with increased military risk, where direct access to territories was restricted. In this context, multi-sensor data fusion not only reduced anthropogenic burden and personnel life risks but also improved forest monitoring accuracy (Balestra *et al*., 2024).

The combination of aerial and ground-based unmanned platforms as part of integrated environmental monitoring systems proved particularly effective under current combat conditions. Aerial UAVs equipped with high-quality optical, multispectral, and hyperspectral sensors enabled rapid sensing of large areas with high resolution, as well as the creation of detailed orthophoto maps and 3D terrain models. The UAVs could detect signs of fires, diseases, and mechanical tree damage, and conduct spatial-temporal analysis of forest ecosystem changes. Meanwhile, the key advantage of ground-based unmanned platforms was the ability to perform point measurements of physical, chemical, and biological parameters, allowing for more detailed analysis of litter layer condition, tree damage structure, and soil changes. The use of "air-ground" collaborative robotic systems created a synergistic effect, improving data collection accuracy, response speed, and monitoring safety in high-risk zones such as combat areas. Theoretically, this model of UAV platform integration formed the basis for developing the next generation of autonomous adaptive monitoring systems capable of effective operation under restricted access and heightened threat conditions, ensuring continuous control and assessment of forest ecosystem condition.

Comparative analysis of unmanned system types in the context of forest monitoring

Modern forest ecosystem remote monitoring technologies involve the use of both aerial (aerospace) and ground-based unmanned platforms. In combat zones, where territorial access is difficult or dangerous, innovative UAVs (drones) are widely reported as crucial tools for detecting forest damage caused by fires, explosions, logging, and other anthropogenic impacts. In eastern Ukraine, including the de-occupied territories of Kharkiv Region, forest monitoring activities are significantly constrained by mine contamination, damaged infrastructure, and ongoing security risks, which makes remote sensing and unmanned monitoring approaches the primary sources of spatial information on forest ecosystem condition (Maksymenko *et al*., 2023; Myroniuk *et al*., 2024; State Agency of Forest Resources of Ukraine, 2024). Table 1 presents a comparative description of the main UAV types used for forest monitoring, synthesised from published studies.

Figure 1 shows a conceptual comparison of the level of data detail reported for different types of UAV platforms, synthesised from published studies and interpreted for forest monitoring in war-affected regions, including case evidence from the de-occupied territories of Kharkiv Region.

Table 1. Comparative characteristics of ground and air-based UAVs

Criterion	Ground-based UAVs (robot rovers)	Aerial UAVs (multicopters/aircraft)
Sensor type	RGB camera, thermal imagers, LiDAR, gas analysers	RGB camera, multispectral, LiDAR, thermal imagers
Level of detail	High (soil and undergrowth details)	Medium-high (covering crowns, large areas)
Coverage area	Limited (up to 1 ha per session)	Wide (up to 100 ha per flight)
Survey speed	Low (0.5-1 km/h)	High (10-40 km/h)
Weather restrictions	Limited (poorly performs on wet ground)	Dependent on wind, rain
Obstacle avoidance (trees, terrain)	High mobility in complex terrain	Low mobility, possible collisions
Sample collection/interaction with the environment	Possible	Not possible
Risk of loss/failure in the combat zone	Medium	High (due to air defence, radio interference)
Equipment cost	High (due to complex navigation systems)	Relatively available

Source: created by the authors

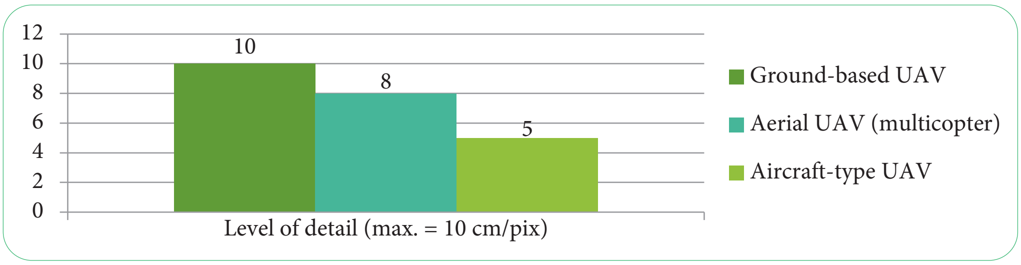

Figure 1. Comparison of the level of data detail reported for different types of UAVs within the deoccupied territories of Kharkiv Region

Source: compiled by the authors based on N.V. Maksymenko *et al.* (2023), V. Myroniuk *et al.* (2024), M. Matsala *et al.* (2024), State Agency of Forest Resources of Ukraine (2024)

The synthesis presented in Table 1 and Figure 1 indicates that, according to the reviewed literature, ground-based UAVs generally provide the highest level of data detail among the considered platform types. As for aerial multicopters, it should be noted that although the level of detail is somewhat lower, these multicopters remained effective for rapid mapping of large damaged areas, particularly burn zones, logging, or shelling, mainly through tree crown analysis and detection of localised damage. The lowest level of spatial detail is typically associated with fixed-wing aerial UAVs, which, although capable of covering vast areas, are reported as less suitable for fine-scale damage assessment. The comparative synthesis of data detail levels reported for different UAV types supports the feasibility of a combined approach, in which aerial systems are used for general surveys, while ground-based are applied for detailed analysis of key areas. Figure 2 presents a comparison of reported ranges of resolution (cm/pixel), flight altitude (m), autonomous operation time (min), and task-dependent damage detection accuracy for different types of UAV platforms.

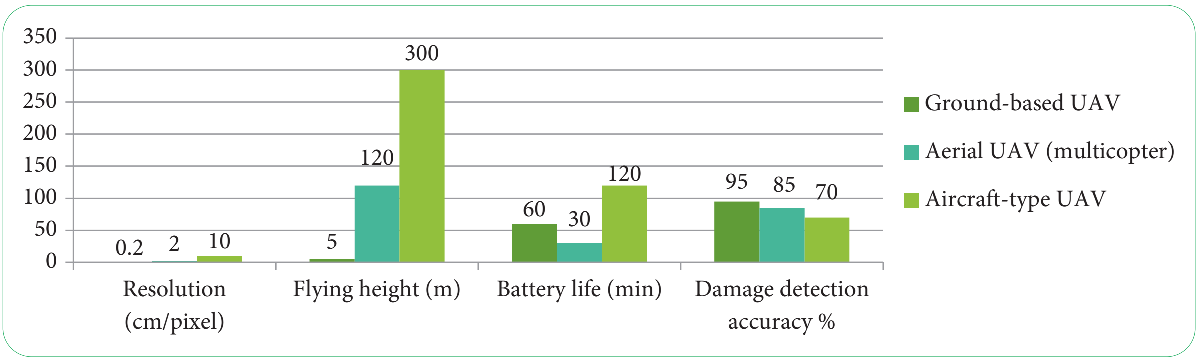

Figure 2. Comparison of reported ranges of spatial resolution, flight altitude, autonomous operation time, and task-dependent damage detection accuracy for different types of UAVs in war-affected forest regions, including the de-occupied territories of Kharkiv Region

Source: compiled by the authors based on S. Ecke *et al.* (2022), H. Zhang *et al.* (2023), N.V. Maksymenko *et al.* (2023), V. Myroniuk *et al.* (2024), State Agency of Forest Resources of Ukraine (2024)

According to the reviewed studies, ground-based UAVs are reported to achieve the highest spatial resolution and damage detection accuracy, making them particularly suitable for detailed analysis of individual trees or small forest plots with severe damage. However, this type of unmanned platform is characterised by limited operational range and low movement speed, which restricts its applicability for large-area surveys. Aerial UAVs of the multicopter type are widely described in the literature as offering balanced performance characteristics, combining relatively high spatial resolution with sufficient detection accuracy for medium-scale monitoring tasks, albeit with limited autonomous operation time and sensitivity to weather conditions (Seidaliyeva & Smailov, 2025). Multicopters are therefore considered effective tools for rapid monitoring of medium-sized areas, especially in challenging terrain or under limited-access conditions.

Fixed-wing UAVs are consistently reported as capable of operating at higher flight altitudes and maintaining longer autonomous flight durations, making them suitable for large-scale forest surveys and strategic planning. However, due to comparatively lower spatial resolution and task-dependent damage detection accuracy, these platforms are less effective for detecting minor damage or assessing the condition of individual trees and understorey layers. For detailed analysis of individual trees, understorey vegetation, soil structure, detection of explosive objects, and other small-scale damage, the use of ground-based UAVs (robotic rovers) is therefore considered advisable based on the reviewed literature. These platforms provide the highest level of data detail and enable interaction with the environment (e.g., sampling or identification of hazardous objects). However, the limited coverage area, low travel speed, and relatively high equipment cost due to complex navigation systems should be taken into account. For rapid assessment of medium-sized areas, including burn zones, logging, shelling, or local forest stand damage, the use of aerial multicopter UAVs is reported as an appropriate solution, offering a balance between spatial detail, mobility, and operational flexibility, despite constraints related to flight duration and weather dependence (DJI Enterprise, n.d.).

For large-scale monitoring of vast forest areas, strategic planning, and detection of large-scale changes in forest ecosystems, the use of fixed-wing aerial UAVs is widely described as appropriate. Their advantages include the ability to cover large territories within a single flight, operate at higher altitudes, and maintain longer autonomous flight times. At the same time, their lower spatial resolution and limited suitability for fine-scale damage assessment restrict their application for detailed forest diagnostics. Considering the above, the reviewed literature supports a combined application of different UAV types. Fixed-wing aerial systems can be used for general reconnaissance and preliminary detection of affected areas, multicopters can clarify the extent and spatial pattern of damage, and ground-based platforms can provide high-precision analysis and documentation of environmental threats in restricted or hazardous zones. Such an integrated approach is consistently associated with improved operational efficiency and monitoring reliability under conditions of increased risk and limited access (State Agency of Forest Resources of Ukraine, 2024). Overall, the synthesis of reported values for resolution, flight altitude, autonomous operation time, and damage detection accuracy indicates that UAV platform selection should align with specific monitoring objectives and spatial scales.

Innovative approach to monitoring under armed conflict conditions

In Ukraine, UAV use for environmental monitoring of forests in combat zones has been actively implemented since 2022. According to the State Agency of Forest Resources of Ukraine (2024), unmanned systems were used to inspect forest areas with dried-out stands. Due to the use of multispectral aerial imaging, forestry workers were able to promptly identify 194,000 hectares of forest lands damaged due to the drying out of forest trees and shrubs (due to military operations and temporary occupation of territories, the information is presented without data from Luhansk Region and parts of Donetsk, Zaporizhzhia, Kharkiv, Kherson regions and the Autonomous Republic of Crimea).

At the international level, examples of successful UAV use for forest damage assessment under limited access conditions were observed, notably in Syria and Iraq, where the humanitarian organisation UNOSAT (Fiol *et al*., 2021) used small-scale (mini) drones (e.g., DJI Phantom, DJI Matrice), multispectral drones (e.g., SenseFly eBee, Parrot Anafi USA), hexacopters and octocopters (e.g., DJI Matrice 300 RTK, Quantum Systems Trinity F90+), large drones (transport UAVs, e.g. Lockheed Martin Indago, AeroVironment Raven), and thermal drones (e.g., DJI Matrice 210 RTK, FLIR SkyRanger R70) for monitoring the degradation of natural areas in conflict zones, including UNESCO World Heritage Sites. Small (mini) drones were used to collect high-quality photos and videos in limited-access conditions. Multispectral drones equipped with sensors were used to monitor vegetation health, analyse landscape and ecosystem changes. Hexacopters and octocopters enabled lifting of heavy sensors, including LiDAR, multispectral cameras, and high-quality photo cameras. Large drones (transport UAVs) were capable of transporting heavy sensors and cameras, particularly for extended missions in low-visibility and adverse weather. Thermal drones with thermal imaging cameras were used to detect fires or heat anomalies in the area.

A case study of the Global Forest Watch (2025) project demonstrated the effectiveness of using satellite data combined with UAV-collected data for monitoring changes in forest cover in tropical regions affected by military action or illegal logging. Using multisource data allowed rapid detection and localisation of forest loss areas, assessing the scale and pace of ecosystem degradation, as well as tracking vegetation recovery. This approach improved the accuracy and speed of threat response, enhanced natural resource use control, and supported informed decision-making in complex ecological and social conditions. The main technical advantages of UAVs and ground-based unmanned platforms included mobility, enabling rapid deployment in any conditions, including rugged terrain and damaged infrastructure; autonomy of modern platforms that could perform flight missions on pre-set routes without direct operator involvement, reducing human risk; data collection speed, as UAVs could survey hundreds of hectares within hours – crucial for rapid response; and high resolution, allowing for detailed images and 3D models to accurately assess damage even at the level of individual trees.

The application of artificial intelligence (AI) methods is reported to improve the efficiency of processing data obtained from unmanned systems. Modern deep learning algorithms can automatically classify types of tree cover damage (e.g., fires, mechanical damage, diseases); detect changes in vegetation cover by analysing image series; create risk maps for further forest recovery planning; and generate forecasts of ecosystem degradation development based on trend models. AI-based solutions were actively implemented in Ukraine, for example, projects based on UAV-LiDAR technologies with automatic data processing through neural networks for detecting changes in forest stand structures.

Since 2022, UAVs and ground-based unmanned platforms have been actively used in Ukraine for environmental monitoring of forests in combat zones. According to the Forest Agency, multispectral aerial imaging enabled prompt detection of large areas of damaged forest lands despite restricted access to some regions. Domestic developments, such as the "Skif" UAV and the automated network system "Menatir", enabled highly accurate real-time data collection and processing, significantly improving monitoring responsiveness. Internationally, similar technologies were used in conflict zones in Syria and Iraq, employing various types of drones – from miniature to large transport ones – with multispectral, thermal, and LiDAR sensors. These multifunctional systems enabled assessment of vegetation conditions, forest damage detection, and environmental monitoring even in hard-to-access conditions. The main advantages of UAVs and ground-based unmanned platforms are mobility, autonomy, data collection speed, and high resolution, ensuring detailed damage assessment. The use of artificial intelligence, especially deep learning algorithms, improved the quality of analysis and automated damage type classification, risk map creation, and ecological forecasting, which was actively introduced in domestic projects.

Practical significance for forestry and management

The use of UAVs in forestry plays an important role in restoring natural resources after the end of military actions. The UAVs are an effective tool for identifying priority forest plots requiring urgent restoration. Multispectral analysis, NDVI index, LiDAR imaging, and RGB photogrammetry allow identification of the most degraded zones: completely burned areas, clear-cut zones, plots with disease spread or mechanical damage. Multispectral photography helps collect data on soil condition and crop health using UAV-mounted multispectral sensors. With the collected data, it became possible to determine vegetation dynamics, chlorophyll content, fungal outbreaks, frost damage, and seedling unevenness (Multispectral mapping with MENATIR…, 2022).

The data obtained through multispectral imaging form the basis for creating NDVI maps, which allow for comparisons of seedling conditions at different growth stages and across study areas. Since NDVI map data is processed quickly, it helps forestry workers save time and money by implementing efficient fertiliser and plant protection application technologies. Indicators obtained through multispectral mapping with MENATIR allow farmers to identify problem areas at early stages from the air without damaging crops, detect pests, diseases, and weeds, as well as nutrient deficiencies, and optimise the use of plant protection products (Multispectral mapping with MENATIR…, 2022).

Data from UAVs are used to plan reforestation activities. Digital terrain models, tree height inventory, canopy density and vegetation type allow identification of the most suitable forest recovery areas, selection of tree species, and calculation of the required scope of silvicultural measures. Important is the assessment of losses in ecosystem services, such as reduction in carbon reserves, loss of soil protection or climate regulation functions of forests. The use of hyperspectral and LiDAR data allows quantitative assessment of biomass reduction, stand volume, and soil degradation degree. Moreover, the integration of UAV data into forest management practices holds significant potential for shaping the post-war bioeconomy, offering the opportunity to transition to fully digitised, precise, and resource-efficient forest management that includes not only recovery from losses but also the creation of sustainable development conditions for the sector. Thus, the use of innovative UAVs can facilitate the adaptation of forest policy to post-war conditions, enabling rapid response to environmental threats and the integration of natural recovery principles.

Discussion

Analysing the obtained research results, it can be concluded that effective monitoring of forest ecosystem damage in combat zones is possible through the combination of different types of UAVs – aerial ones for rapid coverage of large areas and identification of general damage, and ground ones for highly detailed recording of critical zones and data collection in hard-to-reach or potentially hazardous areas. In contrast to R. Ashari *et al.* (2021), who found that management and urban stressors led to slow losses in tree condition and diversity in urban green areas, the current study shows a qualitatively different pattern of armed conflict-induced forest degradation. The results here show sudden, extensive damage leading to quick canopy loss and dramatic NDVI reduction, observable only by integrated remote sensing methodologies, while physical condition assessments in Ternate support long-term urban greening initiatives. This contrast shows how forest monitoring goals change from routine diversity assessment to high-resolution, risk-resilient systems that may capture abrupt ecosystem shocks under acute disturbance.

The study of chlorosis of trees interested K. Mladenovic *et al.* (2020). Following the research, the authors presented results showing that certain tree species, such as maples (*Acer negundo, A. pseudoplatanus*), horse chestnut (*Aesculus hippocastanum*), linden, poplar, and plane tree were susceptible to pathogenic fungi and fungus-like organisms. The results of the conducted study did not correspond to the findings of K. Mladenovic *et al.*, since this work examined a non-infectious plant disease manifested as a disruption in chlorophyll formation in leaves, while the work of the aforementioned authors concerned an infectious disease caused by wood-decaying fungi.

Soil pollution negatively affected the root system of pines and reduced the efficiency of photosynthesis (Grinfelde *et al.*, 2017). This topic was studied by N. Tatuśko-Krygier *et al.* (2023). According to the research, bioactive concentrations of magnesium (Mg) and iron (Fe) can protect Scots pine needles from the toxic effects of heavy metals such as zinc (Zn), lead (Pb), copper (Cu), and cadmium (Cd). One can agree with the opinion of N. Tatuśko-Krygier *et al.*, as elevated concentrations of these elements indeed promote better needle survival, given that magnesium and iron are actively involved in photosynthesis and can provide effective resistance to the adverse effects of pollution. The deterioration and drying of pine trees in mixed forest stands is a consequence of soil pollution due to fires caused by military actions. A similar issue was studied by M. Peris-Llopis *et al.* (2024). According to this scientific research, higher mortality after fire was observed in mixed stands compared to pure stands. Agreeing with this statement, it should be noted that the opinion of M. Peris-Llopis *et al.* is accurate, since in mixed stands different tree species may have varying fire resistance.

It was established that the increasing intensity of forest fires and logging in temporarily occupied territories and combat zones during 2022-2024 had serious negative consequences for the ecosystem, particularly for landscapes, due to soil cover degradation, loss of biodiversity, changes in the hydrological regime, increased erosion processes, and accumulation of toxic substances. A similar issue was raised by M.M. Bennett *et al.* (2022). The authors found that open satellite data, despite lower spatial resolution compared to commercial sources, were extremely valuable for the prompt identification, documentation, and analysis of environmental changes caused by war, including population displacement, infrastructure destruction, and land cover transformation. Similar conclusions were obtained in the presented study, as the results showed that fires significantly degraded landscapes, reduced biodiversity, increased greenhouse gas emissions, and caused soil degradation, complicating the recovery in conditions of armed conflict.

Combining data from sources such as aerial and ground imagery, satellite images, GPS coordinates, and LiDAR scanning makes it possible to create 3D models of territories and conduct multi-level forest condition assessments. This topic was studied by C.J. Iheaturu *et al.* (2024). According to the researchers' work, the combination of LiDAR and multispectral UAV data allowed accurate mapping of forest damage levels, which could be useful for monitoring damage in combat zones. Similar conclusions were made in the completed study, as the application of a comprehensive approach using various spatial data sources, including aerial imagery, satellite images, GPS coordinates, and LiDAR scanning, also enabled detailed visualisation and spatial analysis of changes in the forest ecosystem.

According to the conclusions of the current work, it is known that the use of both ground and aerial UAVs in a comprehensive approach to forest ecosystem damage monitoring makes it possible to achieve high efficiency in spatial data collection, especially in conditions of limited access to territories in combat zones. A similar issue was studied by F. Afghah *et al.* (2019). The authors found that the use of autonomous UAVs significantly improved the efficiency of forest fire monitoring due to the drones' ability to adaptively change routes based on changing fire conditions and terrain topography. The approach proposed by F. Afghah *et al.* ensured rapid response, optimal coverage of the affected zone, and reduced energy consumption, making it promising for practical implementation in conditions of limited human access and high risks. Thus, a comparison of the results of this work with the research of F. Afghah *et al.* confirmed that the use of autonomous unmanned systems based on a distributed "leader-follower" model, which grouped a set of drones into several coalitions, proved to be an effective strategy for forest fire monitoring in remote regions.

It was noted that during 2022-2025 in Ukraine, there was active implementation of an innovative approach based on artificial intelligence, in particular, a project based on UAV-LiDAR technologies with automatic data processing via neural networks for detecting changes in forest stand structures. A similar issue was studied by J. Xiang *et al.* (2024). The researchers found that the use of a combination of UAV data, POS positioning systems, and artificial intelligence algorithms significantly improved the efficiency and accuracy of forest change monitoring, ensuring reliable detection of forest area reductions even in complex urbanised conditions. This statement is agreeable, as the integration of remote sensing technologies, artificial intelligence, and precise geospatial information indeed significantly enhances the efficiency of forest ecosystem change detection, minimises the human factor, shortens data processing time, and ensures high reliability of the obtained results.

Traditional fixed-wing UAVs proved ineffective for detecting minor damage or assessing the condition of individual trees due to low resolution and limited damage detection accuracy. A similar issue was raised by H. Sun *et al.* (2023). The authors obtained results showing that the use of UAVs had significant advantages compared to traditional approaches such as manned surveys, watchtower observations, and piloted operation. In particular, it improved the efficiency of forestry tasks due to high data collection accuracy, the possibility of frequent repeated flights, and adaptability to different environmental conditions. Thus, UAVs proved to be a promising tool for monitoring, managing, and conserving forest ecosystems. The statement by H. Sun *et al.* is agreeable, as the research confirmed that the use of UAVs in forestry contributes to obtaining more detailed, up-to-date, and large-scale information about forest ecosystem conditions, enables prompt detection of disease outbreaks, pests, or fires, and also ensures effective forest resource mapping and inventory with minimal environmental interference.

In 2024, it was established that aerial multicopters proved effective for prompt mapping of large damaged areas, particularly zones of burning, logging, or shelling. A similar issue was raised by L.K.B. Melhim *et al.* (2024). The researchers obtained results showing that the use of drones in combination with a developed set of advanced algorithms significantly improved forest monitoring efficiency, allowing timely threat detection and prompt response to forest fires and other incidents. The statement by L.K.B. Melhim *et al.* is agreeable, as the research truly confirmed that the implementation of intelligent drone-based systems significantly improves early detection of forest fires, reduces response time, and contributes to more effective resource use during emergencies.

It was found that fixed-wing aerial UAVs demonstrated a low level of detail. A similar issue was studied by F.C. Eugenio *et al.* (2020). In the course of the research, the authors found that remotely piloted aircraft systems (RPAS) can improve the process of obtaining aerial images and the quality of derived products in terms of spatial and temporal resolution, which, in turn, enhanced the accuracy of forest inventories, prompt detection of pests and diseases, and effective monitoring of dynamic changes in forest ecosystems. Thus, a comparison of the results of this work with those of F.C. Eugenio *et al.* did not confirm that fixed-wing aerial UAVs were optimal for tasks requiring a high level of detail. On the contrary, multirotor RPAS platforms demonstrated higher effectiveness in tasks related to accurate mapping and monitoring of short-term changes.

It is demonstrated that fixed-wing UAVs are capable of covering large damaged forest areas; however, the obtained images were characterised by a low level of detail. A similar study was conducted by K. Kokamägi *et al.* (2023). According to the researchers' work, the orthophotomap created from UAV images was not an effective tool for assessing large areas of forest damage caused by storms, as this method required significant time and technical resources. Instead, for such research, it is more effective to use a fixed-wing drone or, in the absence of suitable take-off and landing sites, a multirotor drone. This statement is agreeable, as the use of orthophotomaps may prove too labour-intensive: on average, data collection took 96 person-hours, and result processing could take four full working weeks, which is not always appropriate in the context of rapid response to natural disasters.

It was found that aerial multicopter UAVs were able to provide a medium level of resolution (up to 2 cm/pixel) and accuracy (up to 85%) under conditions of complex terrain or limited access. A similar issue was studied by M. Evita *et al.* (2021). According to the authors' research, the use of aerial UAV technology was an effective alternative for forest fire monitoring and early warning in Indonesia, as it allowed high-accuracy data collection on vegetation condition and potential ignition points, creation of detailed 2D and 3D maps with minimal error, and detection of moving objects. The conclusion of M. Evita *et al.* is agreeable, as the research results confirm the high effectiveness of aerial UAV use for forest observation and prompt fire source detection. This is especially relevant given the increasing number of fires in Indonesia, where timely detection and response can significantly reduce damage to ecosystems, public health, and the economy. The analysis of the considered research results showed that effective monitoring of forest ecosystem damage in combat zones was achieved through the combination of aerial and ground UAVs. Aerial UAVs were able to cover large territories, while ground UAVs provided detailed recording and data collection in hard-to-reach areas.

Conclusions

In the course of the analysis of published studies, it was found that ground-based UAVs are reported to provide the highest spatial resolution and damage detection accuracy, while being characterised by limited coverage area and reduced mobility in wet or obstructed environments. Aerial multicopters are consistently described in the literature as a balanced option for rapid monitoring of medium-sized areas, whereas fixed-wing UAVs are widely reported as effective platforms for large-scale forest surveys due to their long flight duration, although they are inferior in spatial detail and task-dependent detection accuracy. In general, aerial UAVs offer wide area coverage and high data collection speed, but are more vulnerable under combat conditions and have limited ability to interact with the physical environment. In contrast, ground-based platforms enable detailed on-site inspections, including interaction with environmental objects, but are constrained by smaller operational range and lower overall efficiency for large-area monitoring.

Therefore, the reviewed literature supports a combined monitoring strategy based on the complementary use of different UAV types: fixed-wing systems for general reconnaissance and large-scale overview, multicopters for rapid assessment of medium-sized areas, and ground-based platforms for in-depth analysis of critical zones. This integrated approach is particularly relevant for de-occupied territories, where territorial access is limited and the balance between monitoring accuracy and data acquisition speed is crucial for timely environmental assessment of the consequences of hostilities.

Several limitations frequently reported in studies of war-affected forest areas include uncertainty regarding the exact boundaries of fire-affected zones, limited availability of timely high-resolution satellite imagery during critical periods, and restricted access to forest territories due to mine contamination and the absence of safe routes for field observations. These constraints highlight the need for further methodological and technological development. Prospects for further research identified in the literature include the development of UAV platforms resistant to electronic warfare interference, improvement of autonomous control algorithms for operation in GPS-denied environments, implementation of artificial intelligence modules for automated forest damage detection based on multispectral and LiDAR data, enhanced assessment of explosion- and fire-induced structural changes in forest ecosystems, and adaptation of early warning systems for environmental change monitoring to conditions of armed conflict.

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Conflict of Interest

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Інтегровані повітряні та наземні безпілотні системи для оцінки шкоди, заподіяної лісовим екосистемам внаслідок військових дій

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Анотація. Збройні конфлікти становлять серйозну та багатовимірну загрозу для лісових екосистем, включаючи великомасштабні пожежі, механічне руйнування рослинності, деградацію ґрунтів, хімічне забруднення та втрату біорізноманіття. Метою цього дослідження було теоретичне обґрунтування використання інтегрованих повітряних та наземних безпілотних систем для моніторингу пошкоджень лісових екосистем, спричинених війною, в умовах обмеженого доступу. У дослідженні використовувався теоретико-аналітичний підхід, що поєднував систематичний огляд літератури, порівняльний аналіз та концептуальний синтез методів дистанційного моніторингу лісів на основі повітряних та наземних безпілотних систем. Було встановлено, що традиційні методи моніторингу пошкоджень лісів, незважаючи на високу точність та повноту, були неефективними в умовах збройного конфлікту через фізичну небезпеку, трудомісткість та обмежений доступ до уражених територій. Це зумовило необхідність переходу до інноваційних дистанційних технологій для забезпечення безперервного та точного спостереження за станом лісових екосистем. За даними спеціалізованих досліджень та відкритих екологічних джерел, безпілотні літальні апарати та наземні платформи продемонстрували високу ефективність у проведенні швидкого моніторингу лісових екосистем у зонах бойових дій, особливо в умовах обмеженого доступу. Розглянуті методи дозволяють оперативно виявляти прояви природної деградації територій та оцінювати масштаби пошкодження деревостану як в Україні, так і за її межами. Практичне значення дослідження полягало у використанні безпілотних систем для моніторингу навколишнього середовища, оцінки збитків та підтримки відновлення лісів у зонах бойових дій

Ключові слова: дистанційне зондування; мультиспектральна камера; дрон; аерофотозйомка; супутникове зображення; мультикоптер

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Determination of the ecological state of atmospheric air in the Ivano-Frankivsk territorial community

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Abstract. Anthropogenic activity affects the state of the environment and transforms it, disrupting the ecological balance. Its main unifying element is atmospheric air – monitoring its state serves as the basis for environmental assessment and forecasting future changes in the ecosystem. The aim of the work was to assess the state of atmospheric air in the Ivano-Frankivsk territorial community and its surroundings using geographic information systems in environmental monitoring. The study used: actual measurements on the ground with gas analysers CEM GD-3803 and CEM DT-9881M, a statistical method for collecting and analysing data on pollution of the components of the surface layer of air with solid particles of fine-grained dust PM2.5 and PM10, carbon monoxide CO, carbon dioxide CO2. Visualisations of the distribution of pollution components were created using mapping. For this, the collected field data were subjected to mathematical processing and interpolated using the Kriging method in the Surfer program, after which the results were transferred to MapInfo. As a result, maps of the distribution of chemical pollutants in the territory of the Ivano-Frankivsk territorial community were created, a variant of building an environmental monitoring system was proposed, and a project cartographic model was developed. This will allow for more effective environmental monitoring in the future and planning measures to improve the condition of the territory. Automation was used in the MapInfo software for detailed step-by-step analysis of the environment and environmental monitoring of the studied territory of the community. The results of the study have practical significance for environmental management and planning, for the sphere of state and local environmental management, public initiatives and educational programs

Keywords: mapping; PM2.5 and PM10 particulate matter; transport emissions; GIS technologies; automation

Introduction

The atmosphere can contain dust particles and aerosols from various natural processes as well as anthropogenic activities (Melnychenko *et al.*, 2024). Sometimes, changes in natural emission sources occur due to extreme weather events, such as forest fires and wind-borne dust storms (Adamenko *et al.*, 2024). The largest anthropogenic contribution to atmospheric emissions mainly comes from the energy sector and transport, two-thirds of which are mainly from fuel combustion. Intensive economic activity, in particular the development of transport infrastructure and industry, takes place in the territory of the Ivano-Frankivsk territorial community, which has led to an increase in emis-

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sions of pollutants into the atmospheric air. This causes the entry into the atmosphere of components that are not typical for natural conditions in their nature, concentration and volume. The criterion for the division of atmospheric air (as a natural object) and other air is the natural, inviolable connection of air with the environment.

Law of Ukraine No. 2707-XII (1992) does not regulate relations regarding the air of residential, industrial and other premises. PM2.5 and PM10 are dangerous for the human body due to their size and ability to absorb other harmful substances on their surface. Large particle sizes most often come from construction sites, motor vehicles, soil dust and industrial enterprises. Small particles are more often released into the air from combustion processes such as forest fires and the conversion of gaseous compounds (Bondar & Tsiupa, 2024). According to studies by R. Popek *et al.* (2024), the presence of plastic microparticles and harmful heavy metals was detected in solid particles of urban aerosols. In particular, the danger of urban dust pollution lies not only in the physical penetration of fine particles into the lung tissue, but also in their ability to accumulate ferromagnetic nanoparticles of magnetite, which, in combination with iron oxides and heavy metals, exhibit increased toxicity and pose a significant risk to human health, as noted by K.M. Bondar & I.V. Tsiupa (2024).

Atmospheric PM particles that are part of urban aerosols increase risks to human health. In 2013, they were classified as carcinogens by the International Agency for Research on Cancer (World Health Organization, 2013). PM is a global risk factor that contributes to and is associated with increased mortality from cardiovascular and respiratory diseases (Chen & Hoek, 2020). The chemical composition of PM is dominated by highly reactive organic compounds, toxic chemicals and metals, which lead to excessive formation of reactive oxygen species. PM solid particles have the ability to cause oxidative stress and inflammation. They provoke the development of respiratory, cardiovascular diseases and cancer. Particles smaller than 5 μm, which are able to penetrate the alveoli of the lungs and the systemic bloodstream, are of particular danger (Lim & Kim, 2024).

The presence of risks to public health due to atmospheric air pollution is confirmed by epidemiological studies I. Manisalidis *et al.* (2020). However, the quantitative effects of long-term exposure to pollutants still remain difficult to accurately assess, especially in conditions of chronic pollution, when the concentrations of impurities vary depending on weather conditions, topography, seasonality and the presence of emission sources. Air pollution with fine particles (PM10 and PM2.5) is a factor that causes or complicates the course of respiratory diseases, cardiovascular diseases, and may also be associated with the development of oncological pathologies, diabetes mellitus, and neurodegenerative conditions. Despite the introduction of state monitoring of atmospheric air quality since 2019, its implementation in many regions, including areas with high anthropogenic load, remains fragmented. As noted by C.A. Belis *et al.* (2025), a significant part of the requirements of this monitoring are not met due to a number of technical, regulatory, and organisational barriers. O. Rybalova *et al.* (2022) in their study assessed the risk to public health due to atmospheric air pollution in industrialised regions of Ukraine. The authors note the increase in the incidence of chronic respiratory and cardiovascular diseases, as well as a decrease in the birth rate and an increase in mortality as one of the manifestations of an unfavourable ecological situation.

Thus, the study of the state of atmospheric air and the impact of its pollution on demographic and medical and biological indicators of the population is one of the key tasks of modern environmental science, which requires consistent implementation of air basin protection policies. Ivano-Frankivsk territorial community as a territorial object of study is indicative from many points of view. On the one hand, it is not too small for studying the state of the atmosphere, as it contains rural and urban landscapes that are subject to anthropogenic influence. And from the point of view of physical geography, such objects as rivers, lakes, hills, plains, forests, roads, industrial areas of a technogenic nature and settlements of varying density are contained and interact here. All this in a complex of factors makes it possible to talk about the isolation and search for new factors of influence on the state of atmospheric air. Therefore, the purpose of this study was to assess the level of air pollution in Ivano-Frankivsk territorial community using GIS monitoring tools.

Materials and Methods

The study of the state of atmospheric air within the Ivano-Frankivsk territorial community was carried out using a comprehensive interdisciplinary approach in March 2025. It combined instrumental monitoring methods, statistical analysis and geoinformation technologies. The study area has an increased level of anthropogenic load, caused by intensive car traffic in the central part of the Ivano-Frankivsk, emissions from industrial enterprises located mainly on the periphery, among which enterprises of the processing industry, mechanical engineering and the energy sector dominate. Instrumental measurements were carried out using gas analysers of the CEM GD-3803 and CEM DT-9881M models (brand CEM Instruments, China), which provide a high level of accuracy in determining the concentrations of both gaseous and aerosol impurities in the air.

The selection of locations for forming the coverage grid (frequency of points on the map) was based on the criteria of traffic intensity in the road and transport network and dense development. This is due to the accumulation of the bulk of pollutants due to constant anthropogenic impact. A total of 142 representative points were measured (Fig. 1), where the content of the following air pollution indicators was recorded: carbon monoxide (CO), carbon dioxide (CO_2), as well as particulate matter of the PM10 and PM2.5 fractions. The determination of priority pollutants was carried out in accordance with Appendix 2 of the Resolution of the Cabinet of Ministers of Ukraine No. 827 (2019). This document defines a list of key chemical substances that are formed as a result of human production, transport and household activities. Particular attention was paid to identifying so-called "dynamic pipes" – areas where constant wind flows contribute to the active transfer of pollutants from emission sources to the boundaries of residential buildings (Hsu & Chang, 2024).

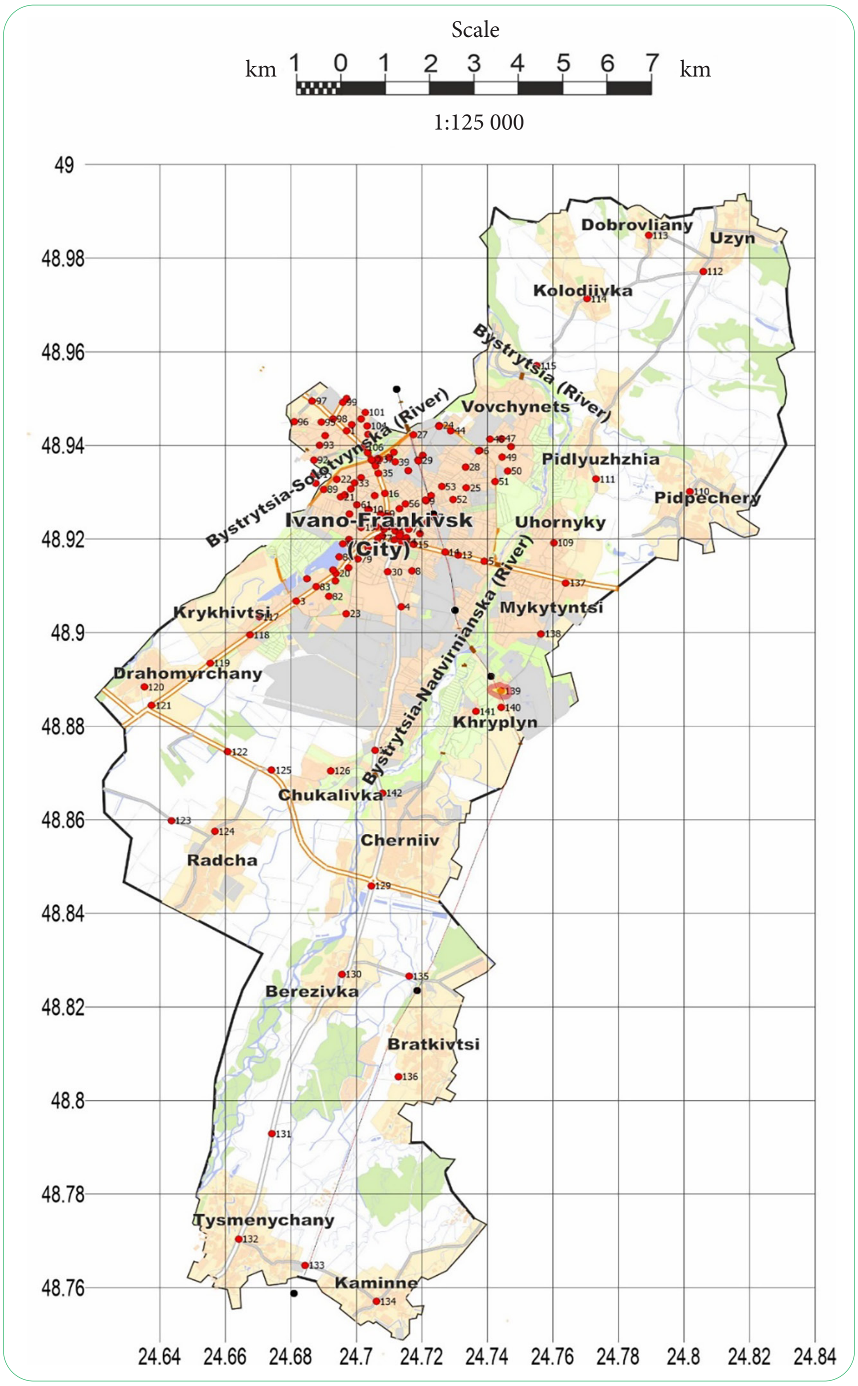

Figure 1. Map of factual material

Source: created by the authors

To process the obtained concentrations of pollutants, statistical methods were used, aimed at quantitatively assessing the spatial structure of the data and identifying deviations in concentration indicators. The value of the anomalous content was calculated by comparing the measured concentrations with the calculated background content indicator, i.e., selecting a group of indicators that is 2/3 and determining the average indicator for the group. The prepared data were used to construct a uniform grd-grid and perform interpolation using the Kriging method

(Salehi & Oral 2023) in the Surfer software environment, which ensured the formation of continuous concentrations within the polygons. To compare CO data, the maximum permissible concentrations (MPC) were taken as the average daily concentration of 3 mg/m^3, the maximum single MPC was 5 mg/m^3 (DSP-201-97, 1997) and the 8-hour MPC, the norm in accordance with the standards for monitoring atmospheric air in the EU, was 10 mg/m^3 (Directive of the European Parliament and of the Council No. 2024/2881, 2024).

To assess the spatial structure of pollution, GIS mapping was used in the MapInfo program. This made it possible to model concentration fields and determine the centres of formation of elevated pollution levels. To simplify and analyse routine monitoring and mapping processes, a functionality was created to display the environmental situation – this is a software module in MapInfo. The created function provided the opportunity to identify common pollution zones and divide them into categories for graphical display of the current state taking into account pollution data. This tool allowed to quickly and clearly depict the areas of overlap between two pollutants, while simultaneously identifying areas with anomalous pollution.

Results and Discussion

Based on the results of the study, a spatial-ecological database was created, which includes both numerical values of the content of chemical substances and geographical coordinates of each sampling point. The measured concentrations of carbon dioxide (CO_2) in the air were divided into intervals and calculations of the background and anomalous content of the substance in the air were performed (Table 1).

Table 1. Calculations of the background content (Cb) CO_2 (ppm)

Content intervals			
415	503	600	800
425	503	600	828
434	506	600	830
436	507	609	830
437	507	621	864
438	508	632	865
438	512	634	896
438	512	640	900
439	512	642	1,290
442	512	654	1,590
443	513	668	
444	514	685	
444	515	700	
444	521	700	
446	521	721	
448	521	731	
449	522	756	
451	522	762	
453	524	780	
455	528	794	
456	530		
457	532		
458	532		
458	532		
459	533		
460	533		
460	535		
460	535		
460	538		
462	540		
463	543		
465	547		
465	551		
466	557		
467	564		
468	566		
468	573		
469	580		
469	583		

Table 1. Continued

Content intervals			
470	585		
470	585		
470	590		
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499			
$\sum_{n=1}^{70} = 32,598$	$\sum_{n=1}^{42} = 22,447$	$\sum_{n=1}^{20} = 13,529$	$\sum_{n=1}^{10} = 9,693$
$\bar{x} = \frac{32,598}{70} = 465.6$	$\bar{x} = \frac{22,447}{42} = 534.4$	$\bar{x} = \frac{13,529}{20} = 676.4$	$\bar{x} = \frac{9,693}{10} = 969.3$
$I_c = 465.6$	$I_c = 534.4$	$I_c = 676.4$	$I_c = 969.3$
Backgrond (C_b) (96 samples from 142 samples (middle value) 2/3 a6o 66.6%) = 511.9896 Abnormal content (C_a) = 3 × C_b = 3 × 511.9896 = 1,535.969 Permissible concentrations CO_2 (ppm) = 600 Limited permissible concentrations CO_2 (ppm) = 1,000 Isoconcentrates (I_c) for the map $= \underset{Min}{415} - 465.6 - \underset{Background}{511.9} - 534.4 - \underset{Permissible}{600} - 676.4 - 969.3 - \underset{Limited}{1,000} - \underset{Abnormal}{1,535.9} - \underset{Max}{1,590}$			

Source: created by the authors

The carbon dioxide (CO_2) content was compared with the limited permissible and permissible values according to DBN V.2.5-67:2013 (2013) and rules were formed for constructing isoconcentrates for maps by interpolation method. According to Table 1, a visualisation map of the carbon dioxide content in the air of the Ivano-Frankivsk community was created (Fig. 2). The map shows that only two zones of overestimated CO_2 content were recorded at Nadrichna Street, 7, in the Ivano-Frankivsk, which is 1,590 ppm, and in the Khryplyn Village near the railway crossing, which is 1,290 ppm. Accordingly, the zones exceeding the limited permissible values of 600 ppm are located nearby and extend in space to the south of the community in the direction of the Kaminne Village. A separate zone has been allocated to the territory from the Bystrytsia River, the Kolodiivka Village in the direction of the Dobrovlyany Village, the concentration exceeds the permissible value and does not exceed the limited permissible value of 1,000 ppm. Considering the situation on the map, it can be concluded that the territory of the community in terms of CO_2 concentration is in a completely satisfactory state, but with local islands of abnormally high indicators.

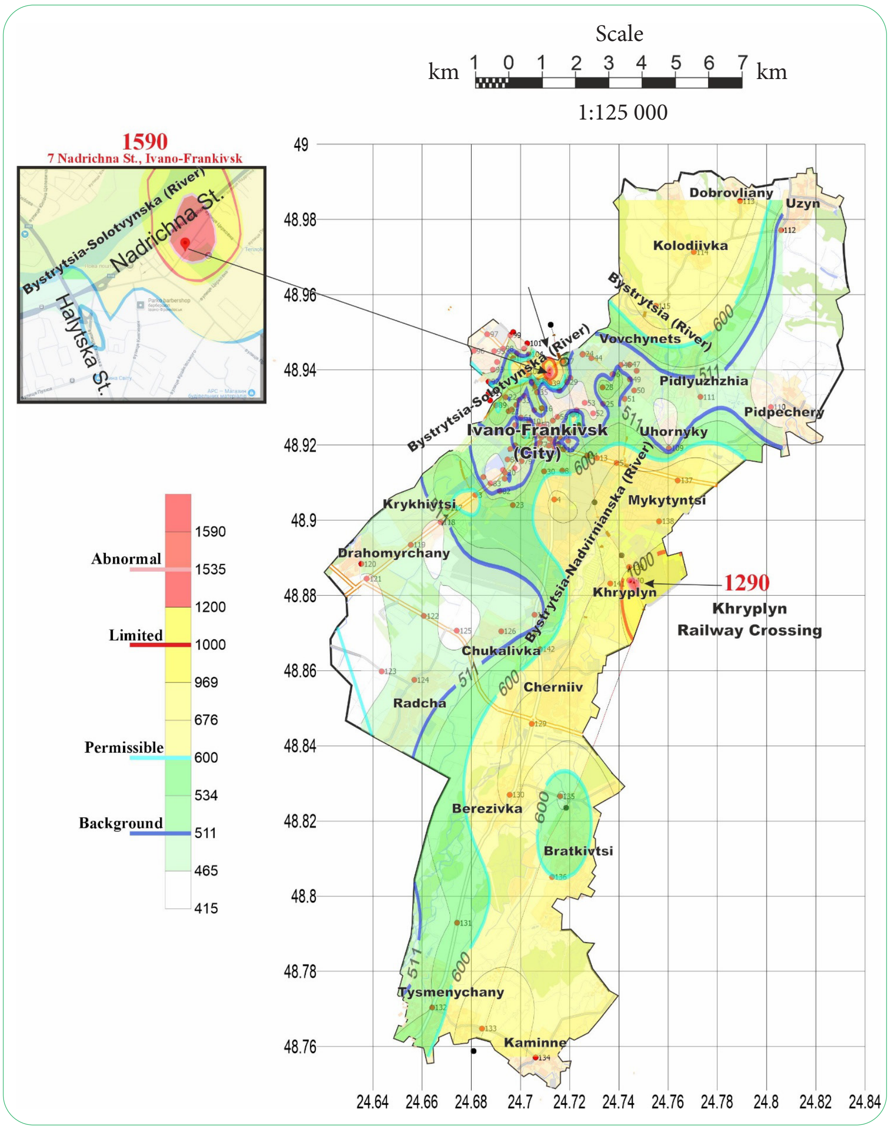

Figure 2. CO_2 concentration in the atmospheric air of Ivano-Frankivsk territorial community, 2025
Source: created by the authors

For carbon monoxide (CO), the obtained data were structured by dividing them into three analytical groups and calculations of the background and anomalous concentrations of the substance in the air were performed (Table 2).

Table 2. Calculations of the background content of CO (C_b)

Content intervals		
0	1	3
0	1	3
0	1	3
0	1	4
0	1	4
0	1	4
0	1	5
0	1	
0	1	
0	1	

Table 2. Continued

Content intervals		
0	2	
0	2	
0	2	
0	2	
0	2	
0	2	
0	2	
0	2	
0	2	
0	2	
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
$\sum_{n=1}^{36} = 0$	$\sum_{n=1}^{20} = 30$	$\sum_{n=1}^{7} = 26$
$\bar{x} = \frac{0}{36} = 0$	$\bar{x} = \frac{30}{20} = 1.5$	$\bar{x} = \frac{26}{7} = 3.7$
$I_c = 0$	$I_c = 1.5$	$I_c = 3.7$

Background (C_b) (43 samples from 63 samples 2/3 or 66.6%) = 0,55814
Abnormal content (C_a) = 3 × C_b = 3 × 35.7 = 1.674419
MPC (per day) – 3
MPC (one-time) – 5
MPC 8-hours, according to the atmosphere's monitoring norm, European Union Directions – 10
Isoconcentrates (I_c) for the map = $\underset{Min}{0} - \underset{Background}{0.55} - 1.5 - \underset{Abnormal}{1.6} - \underset{MPCper\text{-}day}{3} - 3.7 - \underset{MPCone\text{-}time}{5}$

Source: created by the authors

For carbon monoxide (CO), five zones exceeding the MPC of 3 mg/m^3 were recorded, namely an indicator of 5 mg/m^3 on the Vovchynetska-Zaliznychna ring road, and 4 mg/m^3 at the intersection of Tysmenytska-Mykytynetska streets, in the Khryplyn Village near the railway crossing, traffic rings on Konovaletsa Street, and on Nadrichna Street (Fig. 3). It is worth noting that the peak values of CO concentration (Fig. 3) coincide with the points of significant transport load, which directly indicates its dominant role in the formation of local pollution islands. The indicators of the content of fine-grained dust fraction PM2.5 are divided into three intervals (Table 3) and calculations of the background and anomalous content of PM2.5 concentration in the air environment are made.

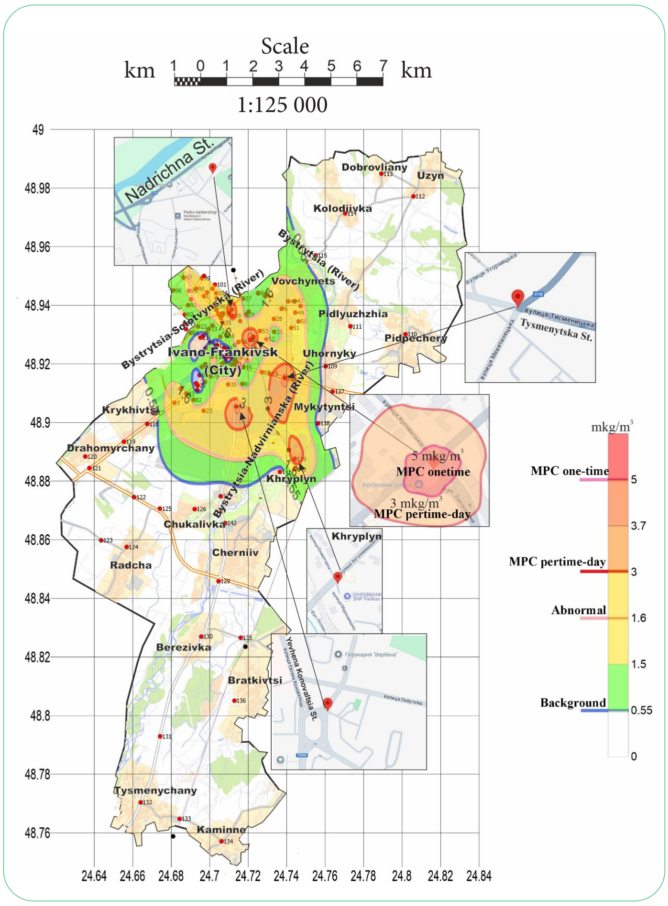

Figure 3. CO concentration in the atmospheric air of Ivano-Frankivsk territorial community, 2025
Source: created by the authors

Table 3. Calculations of the background content (C_b) PM2.5 ug/m

Content intervals		
2	11	21
2	11	21
2	11	21
2	11	22
3	12	26
3	12	27
3	12	31
4	13	37
5	13	38
5	14	42
6	14	61
6	15	209
6	15	
6	16	
7	17	
7	17	
7	18	
7	19	
7	19	
7	19	
7	19	
7		
7		
8		

Table 3. Continued

Content intervals		
9		
10		
10		
10		
10		
10		
10		
$\sum_{n=1}^{70} = 195$	$\sum_{n=1}^{70} = 308$	$\sum_{n=1}^{70} = 556$
$\bar{x} = \frac{195}{34} = 6.29$	$\bar{x} = \frac{308}{21} = 14.6$	$\bar{x} = \frac{556}{12} = 46.3$
$I_c = 6.29$	$I_c = 14.6$	$I_c = 46.3$
Background (C_b) (44 samples from 64, 2/3 or 66.6%) = 11.68182 Abnormal content (C_a) = 3 × C_b = 3 × 11.68182 = 35.04545 Safety levels (24 hours) 0-60mkg/m^3 Isoconcentrates (I_c) for the map = $\underset{Min}{2} - 6.29 - \underset{Background}{11.68} - 14.6 - \underset{Abnormal}{35} - 46.3 - \underset{\text{Safety level}}{50} - \underset{Max}{290}$		

Source: created by the authors

According to the results presented in Figure 4, one area with an elevated level of PM2.5 dust particles was identified. The safe level is considered to be between 0 and 50 μg/m^3 (US-EPA 2016 standard). The background dust content in the community is 11.68 μg/m^3, which can be considered a good value. For comparison, according to the standards for monitoring atmospheric air in the EU (Directive of the European Parliament and of the Council No. 2024/2881, 2024) where the value of 25 μg/m^3 is the limit for the protection of human health, and must be achieved by December 11, 2026.

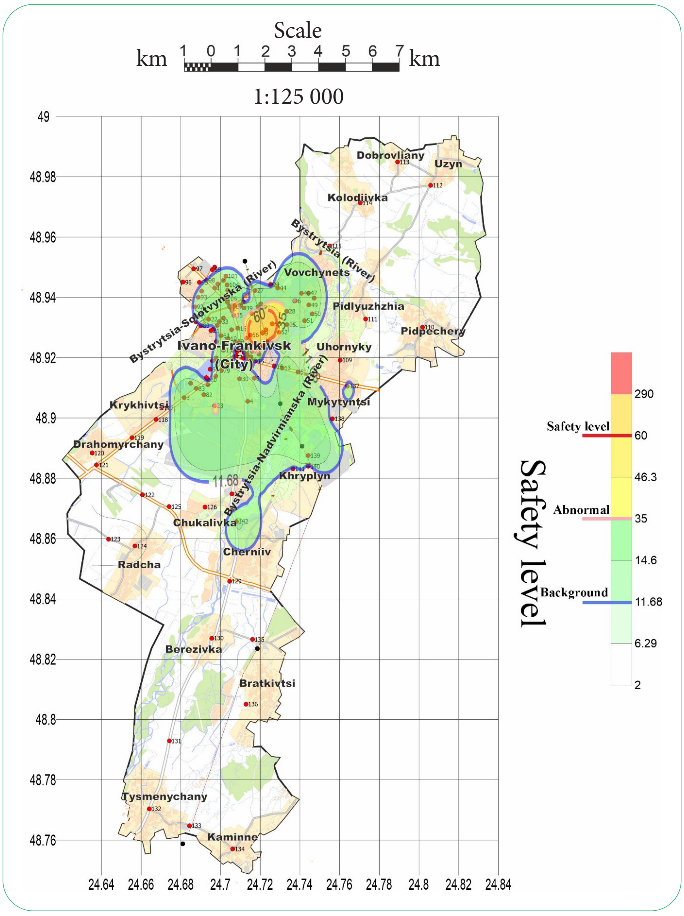

Figure 4. PM2.5 concentration in the atmospheric air of Ivano-Frankivsk territorial community, 2025
Source: created by the authors

Indicators of the content of fine-grained dust of the PM10 fraction were divided into three groups (Table 4) and calculations of the background and anomalous concentration content were carried out. For the PM10 fraction dust, one value exceeding the MPC was also recorded on Vovchynetska Street (Fig. 5)

Table 4. Calculations of the background content (C_b) PM10 ug/m

Content intervals		
3	22	76
5	23	76
6	23	79
10	23	79
11	24	84
11	26	88
12	26	91
12	28	94
14	28	97
15	29	98
15	29	100
15	29	111
15	31	151
15	31	775
17	32	
17	33	
18	33	
18	36	
18	38	
18	40	
18	43	
	43	
	45	
	54	
	55	
	56	
	64	
	66	
	67	
$\sum_{n=1}^{21} = 283$	$\sum_{n=1}^{29} = 1{,}077$	$\sum_{n=1}^{70} = 195$
$\bar{x} = \frac{283}{21} = 13.47$	$\bar{x} = \frac{1{,}077}{29} = 37.13$	$\bar{x} = \frac{1{,}999}{14} = 142.7$
$I_c = 13.47$	$I_c = 37.13$	$I_c = 142.7$

Background (C_b) (44 samples from 64, so 2/3 or 66.6%) = 35.7

Abnormal content (C_a) = $3 \times C_b = 3 \times 35.7 = 107.1$

Safety levels (24 hours) 0-100 mkg/m³

Isoconcentrates (I_c) for the map = $\underset{Min}{3} - 13.47 - \underset{Background}{35.7} - 37.13 - \underset{\text{Safety levels}}{100} - \underset{Abnormal}{107.1} - 142.7 - \underset{Max}{775}$

Source: created by the authors

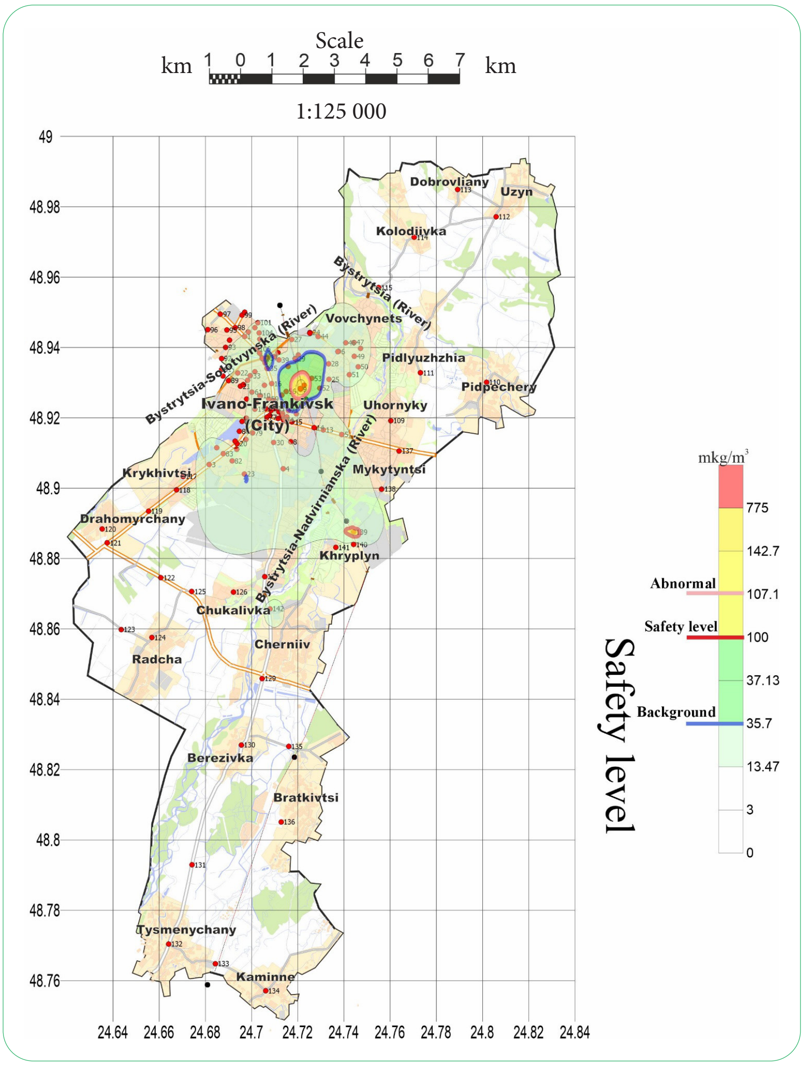

Figure 5. PM10 concentration in the air of Ivano-Frankivsk territorial community, 2025

Source: created by the authors

Using the MapInfo software module, a joint map of the overlap of the two pollutants CO and CO_2 was created (Fig. 6). The resulting map identifies four zones with an increased total level of pollution, which indicates the need for increased attention when planning environmental management measures.

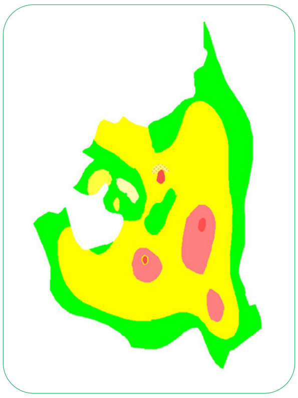

Figure 6. Map of CO and CO2 pollutants overlap

Source: created by the authors

According to the results of the study, several zones with exceeding the MPC for both small PM2.5 and large PM10 fractions were identified. These anomalous areas (central highways, railway crossings) are clearly visible on the maps, although there is a high but not 100% correspondence between the PM2.5 and PM10 maps. These facts suggest that there is a general pattern of dust distribution, while at the same time they indicate different mechanisms for retention and deposition of fractions in the air. Five zones of exceeding the single MPC of 3 mg/m^3 for carbon monoxide CO have been identified. Analysing the maps, it is worth noting that the peak values coincide with points of significant transport load, which directly indicates the dominant role in the formation of local islands of CO pollution. With carbon dioxide CO_2, the situation is similar, but it is worth noting that it is not identical, only two zones with increased anomalous air pollution were identified, this is in Khryplyna near the railway crossing and on Nadrichna Street 7 in the Ivano-Frankivsk. Despite the similar chemical composition, there are different factors for the accumulation of CO and CO_2 in the air.

The air of the Ivano-Frankivsk community is characterised by moderate pollution with a clear spatial connection to transport arteries and railway crossing points. This emphasises the need for environmental management, which consists in expanding green zones along the identified points near highways using plant species with a rough or hairy leaf surface (for example, maple, elm), which have the ability to accumulate solid particles well. It is also recommended to reduce the frequency of mowing grass along roads to increase the accumulation capacity of grassy barriers. Measures to limit peak hours by changing public transport routes in problem areas will also be effective. To control the situation, it is worth expanding the physical network of stationary monitoring to cover points with increased pollution levels.

A comparative analysis of the results of the study of atmospheric air within the Ivano-Frankivsk territorial community with similar works, in particular the study of Yamnytska UTC by scientists Y.O. Adamenko & T.B. Kachala (2022), dedicated to the analysis of the dispersion of PM10 and PM2.5 particles, allows to identify a number of common approaches and differences that have both scientific and practical significance for the development of an air pollution monitoring system in the region. Both studies use the CEM-DT-9881 device for field measurements of particulate matter (PM10 and PM2.5), which ensures methodological consistency and allows comparing the obtained data. In the work of Y.O. Adamenko & T.B. Kachala (2022) focused on modeling dust dispersion using EOL-PLUS software and further comparing theoretical calculations with actual measurement results. In the current study, the focus is shifted to real air quality indicators, geoinformation analysis of spatial pollution distribution, and calculation of total and anomalous pollution indices.

The advantage of the approach used in the study for Ivano-Frankivsk territorial community is the inclusion of a spectrum of impurities (CO, CO_2, PM10, PM2.5), which allows for a more comprehensive characterisation of the state of atmospheric air. While the study for Yamnytsia UTC focuses mainly on studying the dust load and spatial impact of a specific source (Private Joint-Stock Company "Ivano-Frankivsk Cement"), in the case of the current article, the general structure of pollution at the level of the urban community is studied – taking into account transport, residential development, industrial facilities and topographic features of the territory. It is worth noting that the study for Yamnytsia UTC pays special attention to comparing national and international legislation on permissible dust concentrations, which is an important contribution to the formation of the regulatory framework. The current work also mentions the action of Resolution of the Cabinet of Ministers of Ukraine No. 827 (2019).

Thus, the study of Yamnytsia territorial community is more highly specialised and technically oriented, while the study of Ivano-Frankivsk territorial community covers a wider range of environmental and socio-hygienic problems, demonstrating an integrated approach to assessing air quality and its impact on public health. Both approaches are complementary and can serve as the basis for creating a unified regional environmental monitoring system that will take into account both local emission sources and global atmospheric processes.

Compared to the study of N. Moskalchuk *et al.* (2022) of noise pollution in the suburban area of Ivano-Frankivsk, the author's study focuses on studying the chemical composition of atmospheric air within the Ivano-Frankivsk territorial community. Both works have common methodological approaches – a network of control points, experimental measurements, mapping of results. However, while the study of N. Moskalchuk *et al.* (2022) focuses on acoustic exposure, this work analyses the distribution of toxic substances that have a chronic impact on the health of the population. The key difference is the type of exposure assessed: noise – short-term and mainly localised, atmospheric – long-term, accumulative and more dangerous in terms of oncological and respiratory morbidity. Together, these studies complement each other, demonstrating the multifactorial nature of environmental risk for urban areas.

S.Y. Adamenko *et al.* (2024) analysed the temporal patterns of dust particle concentrations (PM2.5 and PM10) based on data from four stationary stations of the Ecocity system – in the centre of Ivano-Frankivsk, near the Burshtyn TPP, near the woodworking enterprise and in the recreational zone of the Mykulychyn Village. In the same case, mobile monitoring was used, which covers a slightly wider range of indicators (CO, CO_2, PM10, PM2.5) and provides high spatial resolution across the community. Common to both approaches is the use of local pollution measurements, which makes it possible to identify the impact of transport and industry on the urban area. In two works, data show an increase in pollution concentrations in areas of high anthropogenic load and may exceed permissible MPCs. Observational data confirm: near highways, emissions form local anomalous zones with elevated levels of PM and CO. In total, the combination of stationary and mobile observations creates a more complete picture of the situation: the former provide a reliable temporal context, the latter – high spatial detail. Such integrated information contributes to the justified placement of green infrastructure (Ferrini *et al*., 2020), the optimisation of transport flows and, in general, increasing the effectiveness of measures to improve air quality in the Ivano-Frankivsk community.

The study by K. Grygoriev (2023) used combined monitoring: data from the state system from 4 posts are supplemented with indicative measurements at compact public monitoring stations in the Mykolaiv. The current study was conducted using portable devices CEM-3803 and CEM-DT-9881, which provide high accuracy in determining pollutant concentrations, taking into account key areas of the Ivano-Frankivsk territorial community. The main differences are in the duration of observations: K. Grygoriev (2023) relied on multi-year state monitoring data (2016-2021) and selected indicative points (2021-2023), while the approach in the current work was based on specialised portable air quality gas analysers in short-term monitoring that can be used to supplement and verify the results of stationary stations. Both approaches assess pollutant concentrations relative to permissible pollution standards and calculate pollution indices. Both studies focus on the impact of transport emissions: due to intensive transit flows in the air, chronic excesses of pollutant concentrations are observed. Both analyses pay attention to particulate matter (PM2.5, PM10), noting their concentrations and excesses of the MPC. For example, in Mykolaiv, maximum PM10 concentrations reached 0.09 mg/m^3, which is consistent with monitoring observations in Ivano-Frankivsk, where elevated PM levels are recorded near highways.

Monitoring activities allow tracking changes over time, which may indicate both an improvement in the overall state of the environment and a deterioration in the state of things (Mora-Barrantes *et al*., 2021). Systematic monitoring of atmospheric air is a key element in assessing the level of pollution and developing scientifically sound environmental management measures. To increase the accuracy of such assessments, both remote sensing data, in particular satellite platforms (Badapalli *et al*., 2022), which provide large-scale spatial analysis of pollutants, as in the study by P. Gupta *et al*. (2020), and unmanned aerial systems capable of making local measurements with high resolution, as in T.F. Villa *et al*. (2016), are used. In addition, an important component is the results of ground-based measurements performed by certified instruments, which provide accurate reference concentrations of pollutants for calibration and validation of remote data.

Monitoring of the state of atmospheric air should be considered as the recording and analysis of current parameters of the atmospheric environment within a specified time interval. It provides the opportunity to objectively assess the effectiveness of measures aimed at preserving and improving air quality (Wang *et al*., 2021; Alolaiyan *et al*., 2024). The use of MapInfo and Surfer software is proposed for a detailed analysis of the environmental state, which will contribute to the adoption of effective management decisions to reduce pollution levels and improve the state of atmospheric air. In-depth analysis of pollutant concentrations in the urban atmosphere is key to making management decisions. Monitoring data allows you to identify locations with the highest levels of air pollution (in particular, near congested highways), which helps to optimise the placement of environmental posts and recreation areas.

Conclusions

Based on the results of the study, a comprehensive spatial and ecological database was formed, which combined the results of measurements of chemical concentrations with the geographical coordinates of sampling points. Analysis of the obtained data allowed to establish that the state of atmospheric air in the Ivano-Frankivsk territorial community is generally satisfactory, but is characterised by the presence of local zones of abnormally high pollution. In particular, two main zones of elevated CO_2 content (up to 1590 ppm) were identified in the area of Nadrichna Street and the Khryplyn Village, and the zones exceeding the limited permissible values extend to the south of the community. For carbon monoxide (CO), five zones of exceeding the MPC were recorded, the peak values of which (up to 5 mg/m^3) clearly coincide with key transport hubs and city rings. This directly indicates the dominant role of motor vehicles in the formation of local pollution centres.

The situation with the content of PM2.5 and PM10 fractions remains mostly within the normal range with a low background indicator of 11.68 μg/m^3, however, the detected point exceedances of the MPC on main streets confirm the common pattern of distribution of particulate matter along transport arteries. Summarising the results, it can be stated that the air environment of the community is moderately polluted with a pronounced spatial connection to the logistics infrastructure. The detected discrepancies in the localisation of peak values of various pollutants indicate different mechanisms of their accumulation and retention in the air. Taking into account the obtained maps of the superposition of indicators, the priority environmental management measures should be the expansion of the stationary monitoring network, optimisation of traffic during peak hours and the creation of protective green barriers using plants capable of intensive accumulation of particulate matter.

The results of the research emphasise the importance of monitoring of various types for the creation of regional plans for improving the quality of atmospheric air. The quality of monitoring data affects rational decision-making in environmental planning of the city and compliance with regulations. Further research involves expanding the functionality of the tool for calculating cartographic entropy, which will allow assessing the degree of separation of concentration zones from each other. This will provide the opportunity to identify common sources of pollution in different components of the environment, in particular in the atmosphere, soil and surface waters. In addition, it is planned to implement the function of automated calculation of background and anomalous levels of pollutants to improve environmental monitoring.

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Conflict of Interest

None.

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Визначення екологічного стану атмосферного повітря Івано-Франківської міської громади

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Анотація. Антропогенна діяльність впливає на стан довкілля і трансформує його порушуючи екологічну рівновагу. Її основним об'єднуючим елементом є атмосферне повітря – проведення моніторингу його стану служить основою для екологічної оцінки і прогнозування майбутніх змін екосистеми. Метою роботи було оцінити стан атмосферного повітря Івано-Франківської міської громади та її околиць із використання геоінформаційних систем в екологічному моніторингу. У дослідженні використовувалися: фактичні виміри на місцевості газоаналізаторами CEM GD-3803 та CEM DT-9881M, статистичний метод для збору та аналізу даних забруднення компонентів приземного шару повітря твердими частками дрібнозернистого пилу PM2,5 та PM10, оксидом вуглецю CO, діоксиду вуглецю CO_2. Створено візуалізації поширення компонентів забруднення за допомогою картографування. Для цього зібрані польові дані було піддано математичній обробці та проінтерпольовано з використанням методу Kriging в програмі Surfer, після чого результати було перенесено в MapInfo. У результаті було створено карти розповсюдження хімічних забруднювачів території Івано-Франківської міської об'єднаної територіальної громади, запропоновано варіант побудови системи екологічного моніторингу та розроблено проектну картографічну модель. Це в майбутньому дозволить ефективніше здійснювати екологічний моніторинг та планувати заходи покращення стану території. У програмному забезпеченні MapInfo використано автоматизацію для детального покрокового аналізу середовища і екологічного моніторингу досліджуваної території громади. Результати дослідження мають практичне значення для екологічного менеджменту і планування, для сфери державного та місцевого екологічного управління, громадських ініціатив та освітніх програм

Ключові слова: картографування; тверді частинки PM2,5 та PM10; транспортні викиди; гіс-технології; автоматизація

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Analysis of data on the generation of waste electrical and electronic equipment

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Abstract. The amount of waste electrical and electronic equipment (WEEE) is growing rapidly worldwide, outpacing the development of infrastructure for its collection and recycling. This aggravates environmental challenges and exacerbates the shortage of critical resources. The study aimed to conduct a comparative analysis of approaches to WEEE management in Ukraine, the European Union, Africa, Latin America, the United States, Australia and Brazil. The study emphasised the identification of differences in regulatory approaches, collection rates, recycling methods, and formulating recommendations for the implementation of effective practices in the Ukrainian context. The methodology included a systematic analysis of the legislative framework, statistical methods for assessing the dynamics of WEEE generation and collection, a comparative geographical analysis of national models, and a content analysis of regulatory documents. The study demonstrated that the EU has the most structured waste management model based on the principle of extended producer responsibility, but even with clear standards in place, collection rates are significantly lower than target values. In the US, WEEE management is fragmented and lacks uniform federal regulation, which makes it difficult to compile reliable statistics. Australia demonstrates the effectiveness of co-regulatory approaches, while Brazil demonstrates the unique integration of the informal sector into the official reverse logistics system. A comprehensive combination of legislative, infrastructural and behavioural dimensions of EPR management in five countries with different economic models is considered. The practical significance of the study is determined by the formulation of recommendations for Ukraine on the implementation of extended producer responsibility, the development of a monitoring system, increasing market transparency and adapting successful international instruments for the transition to a circular economy

Keywords: electronic waste; extended producer responsibility; circular economy; international management models; collection infrastructure; environmental policy

Introduction

Intensive digitisation and shorter lifespans of electrical and electronic devices have led to a sharp increase in the volume of related waste, making it one of the most challenging elements of global material circulation. Electronic waste contains high concentrations of strategically relevant metals and critical resources, but at the same time

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includes components that, in the absence of proper control, pose a serious threat to the environment and public health. Given that the scale of electrical and electronic equipment (WEEE) generation worldwide exceeds the capacity of existing collection and recycling systems to respond quickly to these changes, public policy should be based on accurate quantitative estimates, flow analysis and forecasting of the potential for material reuse within a circular economy.

During 2021-2024, the scientific community has paid significantly more attention to the dynamics of electronic waste generation and management. The latest global monitoring by WEEE shows record figures: in 2022 alone, 62 billion kg of electronic waste was generated worldwide, while the share of documented collection remains critically low (Baldé *et al.*, 2024). It is predicted that without changes to modern models, collection rates could decline to 20% by 2030, while generation rates will increase. The results of scientific research by M. Compagnoni (2022) show that improving the efficiency of waste management systems creates opportunities for significant economic benefits, in particular through the return of valuable materials to production cycles.

The issue of waste electrical and electronic equipment management is widely researched in contemporary scientific literature. S. Gulliani *et al.* (2023) conducted a critical review of existing technologies for extracting metals and valuable chemical compounds from electronic waste, noting significant potential for resource recovery when modern processing methods are used. According to D.D.S. Azizi *et al.* (2023), the material flow analysis (MFA) method is one of the leading analytical tools in the field of electronic waste management, but existing studies have significant limitations, including insufficient coverage of countries outside the OECD and limited use of dynamic models.

In a systematic review of the literature, M. Compagnoni (2022) analysed the effectiveness of the extended producer responsibility (EPR) mechanism in electronic waste management and concluded that, despite its prevalence, this tool does not always ensure that collection targets are met. According to N.M. Franz & C.L. Silva (2022), the traditional model of assessing collection relative to the volume of equipment placed on the market does not consider the unevenness of product life cycles, the accumulation of equipment in households, and the scale of informal flows. Among Ukrainian scientists, H. Yafen & T. Shevchenko (2021) significantly contributed to the study of this issue by analysing the mechanisms for promoting smart e-waste management systems in China and determining that small household electronics have the lowest return rates to collection systems. In addition, F. Mihai *et al.* (2024) investigated the characteristics of the circular economy and waste management in Eastern European countries.

In the European Union, concern regarding WEEE is reflected in the revision of the targets stipulated in Directive 2012/19/EU, as the traditional model of "collection relative to the volume of equipment placed on the market" does not cover the unevenness of life cycles, the accumulation of equipment in households and the scale of informal flows (Franz & Silva, 2022). In this regard, researchers highlight a need for a transition to more dynamic, material-specific indicators that are consistent with European aspirations for digital product passports and the recovery of critical raw materials (Kusch & Hills, 2017; Xavier *et al.*, 2021). The study aimed to conduct a comparative analysis of approaches to WEEE management in Ukraine, the European Union, the United States, Australia and Brazil, incorporating their legal framework, structural characteristics of waste, level of technological development and the effectiveness of existing collection and recycling models.

Materials and Methods

The study was conducted using a comprehensive combination of methods, which ensured a comprehensive coverage of the peculiarities of WEEE management in different regions and ensured the analytical consistency of the results obtained. Each method was selected, incorporating the specifics of the set goal and the nature of the available data. The system analysis method was used to consider national WEEE management systems as internally linked structures in which legislative requirements, infrastructure, economic incentives and behavioural factors form a common trajectory of efficiency. This method was used to track the impact of changes in one element (e.g., stricter ERP requirements) on collection rates or consumer behaviour. The relevance of the method is determined by the need to integrate diverse types of data, from legal provisions to statistical indicators, into a comprehensive picture of the system's functioning.

The comparative geographical method was used to identify differences and similarities between countries (the practices of the European Union, the United States, Australia, African countries, and Latin America) in terms of the regulatory framework, infrastructure organisation, level of technological development, and dynamics of WEEE flows. This identified both the structural advantages of individual regions and their characteristic problems. This method ensured the comparison of management models and the identification of the most effective practices for possible implementation in Ukraine. Statistical methods and Pearson's correlation coefficient were used to analyse quantitative indicators related to the generation, collection and processing of WEEE. The relationship between the volume of equipment placed on the market and the actual collection of its waste was analysed by constructing a linear regression. The study used dynamic series processing, calculation of intensive and relative indicators, as well as analysis of the relationship between the main variables of WEEE volumes on the market and the mass of officially collected waste. This ensured a transition from descriptive characteristics to quantitative conclusions and comparisons, which significantly increased the reliability and accuracy of the analytical part.

Synthesis was applied at the final stage of the research to combine the conclusions obtained using all previous methods. It was used to form a consistent model of the state of WEEE management in selected countries, identify general trends, characteristic problems and features of individual regions. The synthesis formulated balanced recommendations on adapting international experience to Ukrainian conditions. The study used data from the following groups of sources: international monitoring reports; peer-reviewed scientific publications presented in the international databases Scopus and Web of Science; official statistics from government and industry institutions. Their combined interpretation provided a broad view of the global context of WEEE management and enabled accurate cross-country comparisons. Content analysis and secondary processing of documents were the main tools used when working with regulatory acts, reports of international organisations, scientific publications and official statistics (Directive of the European Parliament and of the Council No. 2012/19/EU, 2012; Draft Law of Ukraine No. 2350, 2019; Hlavatska, 2021; Update of WEEE…, 2021; International Trade Administration, 2022; Baldé *et al.*, 2024; Clean Up Australia, 2024; Regulation of the European Parliament and of the Council No. 2024/1252, 2024; Eurostat, n.d.). This approach identified key legislative provisions and assessed performance indicators that shape the modern discourse in the field of WEEE management. In the context of the scale of the problem and the fragmentation of information, the decision to forego primary data collection in favour of a thorough analysis of authoritative sources ensured the high quality and validity of the results obtained.

Results and Discussion

The waste electrical and electronic equipment management system in the European Union was formed based on Directive of the European Parliament and of the Council No. 2012/19/EU (2012), which became a key regulation aimed at minimising environmental risks and implementing circularity principles. Its emergence was a response to the continuous growth of WEEE flows and the need to create mechanisms capable of ensuring control over the entire product life cycle. The Directive is based on the EPR approach, which places financial and organisational obligations for the collection, treatment and disposal of waste on electronic equipment manufacturers, rather than on municipalities or end users. As noted in several studies, this model forms the basis of EU policy on WEEE management and serves as a key prerequisite for the development of an economically efficient and sustainable collection infrastructure (Xavier *et al.*, 2021; Compagnoni, 2022; Zoka & Korez Vide, 2025).

The directive obliges Member States to establish national registers of EEE manufacturers and importers, to ensure that equipment can be returned free of charge at the end of the service term, and to prevent it from entering unsorted municipal waste. The "one-for-zero" and "one-for-one" principles, whereby retailers accept old equipment regardless of whether new equipment is purchased or sold, have become one of the key practices in EU countries (Kusch & Hills, 2017). The system of minimum targets is substantial: from 2019, EU countries must ensure a collection rate equivalent to 65% of the average weight of equipment placed on the market in the previous three years.

Despite the existence of a single regulatory framework, implementation varies significantly between countries (Grandhi *et al.*, 2024). Germany and Sweden demonstrate consistently high results, which are associated with the early introduction of EPR and a developed waste management infrastructure (Update of WEEE..., 2021). At the same time, publications note that a significant portion of WEEE still bypasses official collection channels, ending up in "grey" streams caused by exports, informal dismantling, or long-term storage in households (Serpe *et al.*, 2025). The data show contradictory dynamics: although the total volume of waste collected is growing in absolute terms, its share relative to the volume of EEE placed on the market is showing a downward trend (Directive of the European Parliament and of the Council No. 2012/19/EU, 2012). In 2022, the collection rate was only 40.06%, which is significantly below the regulatory benchmark. At the same time, the volume of EEE introduced into circulation has almost doubled compared to 2011, putting additional pressure on the collection and recycling system. Below is a summary of the dynamics for 2011-2022 (Table 1).

Table 1. Dynamics of EEE generation and collection in the EU (2011-2022)

Year	Volume of EEE on the market (million tonnes)	Collected WEEE (million tonnes)	Level of WEEE collection (%)
2011	7.65	3.04	37.44
2012	7.63	2.97	38.58
2013	7.76	2.97	38.38
2014	7.00	2.96	38.58
2015	8.04	3.23	41.54
2016	8.51	3.49	44.20
2017	9.07	3.76	46.12
2018	10.29	3.99	46.76
2019	11.21	4.52	48.61
2020	12.40	4.72	46.30
2021	13.74	5.06	44.76
2022	14.44	4.99	40.06

Source: compiled by the authors based on Eurostat (n.d.)

To quantitatively confirm the relationship between the main variables, a correlation analysis of data for the period 2011-2022 was performed. The results of the analysis are presented in Table 2.

Table 2. Results of correlation analysis of WEEE management indicators in the EU

Variable pair	Pearson's correlation coefficient (*r*)	Significance (*p*)	Interpretation
EEE POM – Absolute volume of WEEE collection	0.94	<0.001	Strong positive correlation
EEE POM – Relative collection rate (%)	-0.21	>0.05	Weak negative correlation (statistically insignificant)
Year – EEE POM	0.98	<0.001	Strong positive correlation
Year – Absolute volume of WEEE collection	0.91	<0.001	Strong positive correlation

Note: EEE POM – electrical and electronic equipment placed on the market
Source: calculated by the authors based on Eurostat (n.d.)

The results obtained indicate a strong positive correlation ($r = 0.94$; $p < 0.001$) between the volume of electrical and electronic equipment placed on the market (EEE POM) and the absolute volume of waste collected. This means that as the number of products on the market increases, so does the absolute volume of WEEE collected. At the same time, the correlation between EEE POM volumes and the relative collection rate (in percent) is weak negative ($r = -0.21$) and statistically insignificant ($p > 0.05$). This confirms that the growth rate of the electronics market significantly outpaces the development of collection infrastructure, as a result of which the relative collection rate does not grow proportionally and has even shown a downward trend (Chu *et al.*, 2024). In addition, a linear regression analysis was performed to determine the dependence of the absolute volume of WEEE collection on the volume of EEE POM. The resulting regression equation is as follows:

$$Y = 0.31X + 0.77 \ (R^2 = 0.89), \qquad (1)$$

where Y – volume of collected WEEE (million tonnes); X – EEE POM volume (million tonnes); determination coefficient $R^2 = 0.89$, indicating that 89% of the variation in collection volumes is explained by changes in production volumes on the market. A regression coefficient of 0.31 means that an increase in EEE POM by 1 million tonnes is accompanied by an increase in absolute collection of only 0.31 million tonnes, which quantitatively confirms the insufficient adaptability of existing collection systems to the growing volumes of electronic products.

To quantitatively confirm the relationship between the volume of electrical and electronic equipment placed on the market (EEE POM) and the level of waste collection, a correlation analysis of data for the period 2011-2022 was performed. The Pearson correlation coefficient between EEE POM volumes and absolute waste collection volumes is $r = 0.94$ ($p < 0.001$), indicating a strong positive relationship. At the same time, the correlation between EEE POM volumes and the relative collection rate (in percent) is weak and negative ($r = -0.23$), confirming the growing gap between the rate of new product introduction and the capacity of the collection system.

The results of the study show that most European Union countries are taking consistent steps towards improving WEEE management systems. At the same time, the growth rate of new electronics entering the market significantly outpaces the development of the relevant infrastructure and the effectiveness of take-back mechanisms. A range of studies emphasise that even well-structured approaches, such as the European model, face challenges such as the existence of illegal or hidden flows, weak motivation among end consumers to participate in return systems, and the widespread use of small household appliances with particularly low return rates (Yafen & Shevchenko, 2021; Liu *et al.*, 2023). The figure below illustrates one of the most pressing challenges for the EU: the imbalance between the speed at which new equipment appears on the market and the speed at which old devices are returned to the collection and recycling system (Fig. 1).

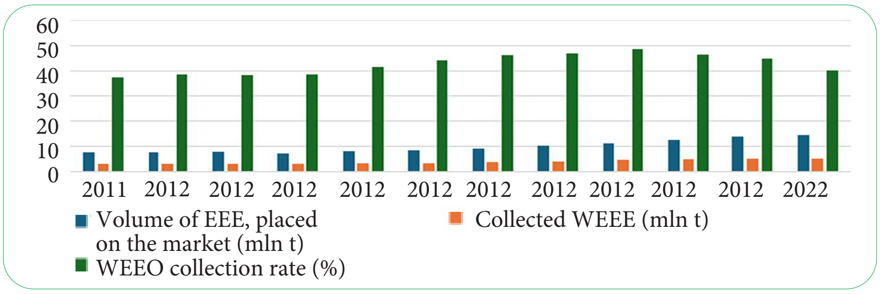

Figure 1. Dynamics of WEEE generation and collection in the EU (2011-2022)
Source: compiled by the authors based on Eurostat (n.d.)

Eurostat data (n.d.) shows rapid growth in the amount of electrical and electronic equipment entering the European Union market each year. Since 2015, this figure has increased by approximately 80% from 18 to 28 kg per capita. In contrast, the volume of officially collected WEEE during this period increased by only 54.7%, indicating a widening gap between the generation and actual return of products to the recycling system. This disproportion confirms that, despite the existence of European legislation and a formally developed infrastructure, the "take-make-waste" model continues to prevail. The reasons lie in the high dynamics of technological renewal, the growth in consumption of consumer electronics, limited repair options and the gradual reduction in product life cycles, trends that are noted in contemporary studies of the circular economy (Liu *et al.*, 2023).

Behavioural barriers are a substantial factor hindering the achievement of collection targets. A survey conducted in EU countries as part of the Global E-waste Monitor showed that a significant proportion of small electrical appliances and accessories are stored in households for years. Almost 13% of respondents admitted that they keep old phones, headphones, remote controls or chargers due to "emotional attachment", while the rest of the respondents stated they did not know where to properly dispose of such equipment. As a result, millions of electronic devices remain outside official collection streams, and valuable materials, including metals and critical raw materials, are effectively removed from economic circulation. According to Global E-waste Monitor estimates, this represents a loss of resources worth approximately 62 billion USD annually (Baldé et al., 2024).

The situation in Ukraine differs significantly in terms of scale, but the nature of the problem is similar. According to estimates by L. Hlavatska (2021), approximately 28,000 tonnes of WEEE are generated in the country annually. However, this figure is approximate, as Ukraine does not have a comprehensive system for monitoring and state accounting of electronic waste generation, especially in the household sector, where a significant portion of devices are retained by consumers or end up in mixed waste. The lack of reliable data creates a false impression of the scale of the problem and complicates the formation of effective state policy. Based on available estimates, a generalised component composition of WEEE in Ukraine has been formed (Table 3-4), which confirms the significant share of valuable metals, but also indicates significant volumes of hazardous components.

Table 3. Distribution of waste electrical and electronic equipment in Ukraine by category (2019)

Waste category	Approximate volume (thousand tonnes)	Share of total volume (%)
Technological devices	16.506	58.5
Batteries	5.934	21.0
Home and office appliances	3.637	12.9
Electronic components	1.196	4.2
Fluorescent lamps	0.564	2.0
Total	**~28.225**	**100**

Source: compiled by the authors based on L. Hlavatska (2021)

Table 4. Average material composition of waste electrical and electronic equipment in Ukraine

Material	Share by mass (%)	Note
Plastic	30.0	Cases, insulation
Copper	20.0	Wires, coils, printed circuit boards
Metal	8.0	Frames, mounts
Tin	4.0	Solder
Nickel	2.0	Batteries, coatings
Aluminium	2.0	Radiators, cases
Lead	2.0	Batteries, solder
Zink	1.0	Coatings
Silver	0.2	Contacts
Gold	0.1	Contacts, printed circuits
Other materials (glass, ceramics, etc.)	30.7	-
Total	**100**	-

Note: certain categories of WEEE (batteries, fluorescent lamps) contain hazardous substances such as lead, cadmium, mercury and arsenic, which require special handling conditions

Source: compiled by the authors based on L. Hlavatska (2021)

The state of WEEE management infrastructure in Ukraine remains fragmented. Although more than 1,500 companies are operating in the field of waste management in the country, only a small proportion of them have licences for WEEE collection and disposal operations. Of the 128 companies capable of accepting certain types of hazardous electronic waste, only 22 have the appropriate permits for its treatment, and only four are operating. This means that most electronic waste is either mixed with household waste or ends up in the informal sector, where it is dismantled without environmental control. Illegal imports of electronic waste from EU countries create an additional burden. According to the Global E-waste Monitor, it accounts for 14-18% of all WEEE generated in Ukraine (Baldé *et al.*, 2024). This situation makes Ukraine one of the destination countries for cross-border waste shipments, which is a serious problem in a global context. Weak control and the lack of specialised infrastructure contribute to the formation of a "shadow" market, which highlights the difference between formal obligations and actual practices.

In the context of reforms, one of the key areas is the introduction of EPR. Draft Law of Ukraine No. 2350 (2019) proposes to lay the foundations for a system that will provide for the financial and organisational participation of producers in the collection, processing and disposal of electronic waste (Table 5). It is expected that the introduction of EPR will not only align Ukrainian legislation with EU standards, but also stimulate changes in product design, increase its repairability and create conditions for the circular use of materials.

The integration of the RBB principle in Ukraine is viewed as one of the key steps on the path from a linear approach to resource management to a circular economy. In a situation where a significant portion of electronic waste is disposed of as general household waste or processed in the informal sector, the creation of a transparent, regulated system for WEEE management is critical. This approach will minimise environmental threats and facilitate the return of strategically relevant materials to production cycles.

Table 5. Comparison of key aspects of WEEE management systems in the EU and Ukraine

Characteristic	European Union	Ukraine (draft law)
Legal framework	Directive 2012/19/EU	Law of Ukraine "On Waste Management", draft Law "On WEEE"
Key principle	ERP	ERP
Goals	Prevention, reuse, recycling, and collection of 65% of EEE POM	Environmental safety, recycling of secondary raw materials, and introduction of RBB
Manufacturer responsibility	Financial and organisational responsibility for collection, processing and disposal	Financial responsibility, organisation of collection and recycling
Methods of fulfilling obligations	Individually or collectively (through producer responsibility organisations)	Individually or collectively (through ERP organisations)
Infrastructure	Developed, but with problems in achieving target indicators	Primitive, with low levels of licensing and control

Source: compiled by the authors based on Directive of the European Parliament and of the Council No. 2012/19/EU (2012) and Draft Law of Ukraine No. 2350 (2019)

European partner countries are substantial in supporting reforms aimed at modernising and developing the national waste management system. International technical assistance projects, in particular EU initiatives aimed at harmonising Ukrainian waste management legislation with the requirements of the European acquis, form the basis for the integration of modern approaches to WEEE management. Alongside regulatory support, investment programmes implemented with the participation of the European Investment Bank are significant. EIB financing is aimed at developing municipal infrastructure, including the modernisation or reclamation of waste disposal sites, which is critical in the context of the transition to a circular economy and overcoming the financial constraints characteristic of the Ukrainian waste management sector (Pan *et al.*, 2022; Baldé *et al.*, 2024).

The introduction of the EPR mechanism creates the basis for the development of a new economic direction, which covers enterprises specialising in the collection, sorting and processing of electronic waste. The practice of EU countries shows that such models stimulate the inflow of private capital and contribute to the modernisation of processing infrastructure (Xavier *et al.*, 2021; Compagnoni, 2022). In the Ukrainian context, this instrument can be strategic not only in increasing the collection rate of WEEE, but also in revitalising the industrial sector, creating new jobs, reducing dependence on imports of critical raw materials and deepening economic integration with the European Union.

At the same time, an analysis of electronic waste collection practices in the United States reveals significant discrepancies in statistical data, which can be explained by different reporting sources. The lack of a unified national accounting system means that different organisations use internal methods to estimate the volume of WEEE generated. Publications cite different figures for annual electronic waste generation: from 6.9 million tonnes to 9.9 million tonnes, which characterises the United States as one of the largest producers of electronic waste in the world. A similar situation is observed regarding the recycling rate, which ranges from 15.4% to 25%. This discrepancy in statistical data reflects a systemic problem: the lack of a comprehensive federal regulatory approach to WEEE accounting and management.

Due to the lack of uniform national standards, the United States operates a decentralised management model, within which each state adopts its own regulations on electronic waste. There are 25 states and the District of Columbia with separate laws in this area, most of which are based on the RBA approach, with the exception of the models used in

Utah and California. At the same time, the scope of state legislation varies significantly: some programmes apply exclusively to households, while others cover schools, commercial establishments or small businesses. The diversity of regulatory requirements creates a significant administrative burden on manufacturers and hinders the development of a coordinated recycling infrastructure (Liu *et al.*, 2023).

One of the most significant problems is the export of electronic waste to countries with less stringent environmental standards. Since the United States has not ratified the Basel Convention, it remains possible to legally export WEEE to countries where it is processed using primitive technologies that pose an increased risk to the health of workers and the environment. A systematic review of the risks of informal e-waste recycling in Africa and a review by P. Kumar *et al.* (2024) on the toxicological aspects of e-waste document the use of decomposition and metal extraction methods such as acid leaching and open burning, which are accompanied by emissions of lead, cadmium and mercury. These processes cause significant socio-environmental losses and highlight the need for the development of a comprehensive federal policy on WEEE management.

Australia also has high per capita e-waste generation rates. According to analytical estimates, the average amount of e-waste generated is 20-22 kg per person per year, while the global average is around 7 kg (Baldé *et al.*, 2024). In 2019, approximately 511,000 tonnes of electronic waste were generated, and this figure is projected to grow to 657,000 tonnes by 2030. A significant proportion of the value of materials in Australian WEEE remains unused: in 2019 alone, resources with an estimated value of 430 million USD were disposed of in landfills, which could have been returned to the production cycle (Xavier *et al.*, 2021).

The significant volumes of electronic waste generated in Australia are one of the factors stimulating national discussions on the need to transition to circular approaches to resource management. According to the Global E-waste Monitor, Australia is among the countries with the highest per capita e-waste generation, significantly exceeding the global average. This is influenced by the high frequency of electronics upgrades and the rapid obsolescence of technology. Despite this, a significant portion of valuable materials, particularly metals and plastics, are still not being returned to the production cycle, resulting in both economic losses and environmental risks (Xavier *et al.*, 2021; Liu *et al.*, 2023; Baldé *et al.*, 2024). EPR, widely implemented in EU countries, is considered in international reviews to be an effective tool for financing WEEE collection and recycling systems. The use of EPR involves manufacturers in managing the entire product life cycle and has demonstrated its ability to ensure steady growth in the collection of electronics and the return of secondary raw materials to production (Azizi *et al.*, 2023).

At the same time, fragmentation of regulation and the lack of mechanisms that integrate all categories of electronic waste into a single system remain key challenges in Australia. Policies focused on individual product groups do not provide comprehensive coverage of WEEE, making it difficult to achieve high material recovery rates (Liu *et al.*, 2023). As a result, a significant amount of resources end up in the informal sector or in landfills, hindering the implementation of the circular model. Brazil, which is the leader in e-waste generation in South America, also faces similar institutional constraints. The steady growth in e-waste volumes is linked to the spread of short-term use models for electronic devices and frequent replacement of equipment (Souza, 2020). Despite the presence of ERP elements in national legislation, their implementation remains limited, and most waste is processed outside formalised systems (Xavier *et al.*, 2021).

A distinctive feature of Latin America is the active role of the informal sector in the collection and dismantling of electronics. According to research, a significant portion of WEEE is handled by individual collectors or small businesses without compliance with technological and environmental standards (Issah *et al.*, 2022). This not only poses a threat to the health of people working with toxic substances but also reduces the efficiency of returning valuable components to production chains. However, as R.G. Souza (2020) highlighted, this sector is substantially linked to the actual extraction of metals, so effective policy should not exclude it, but rather gradually formalise its participation.

The challenges identified in Australia and Latin American countries demonstrate a common trend: WEEE management systems are unable to keep pace with the rate of technological renewal and growth in consumption. Studies show that even with formal infrastructure in place, a significant portion of waste ends up in mixed streams or is not registered at all (Liu *et al.*, 2023; Baldé *et al.*, 2024). This confirms the need for a comprehensive approach that combines strengthening the role of WEEE, developing infrastructure, information campaigns, and economic incentives for formalised resource recovery. A comparison of statistical estimates for the United States, Australia, and Brazil reveals notable differences, which are mainly due to the specifics of the regulatory environment. Australia and Brazil have national data collection systems in place, ensuring a more consistent WEEE accounting. However, rapid device upgrades and the availability of consumer electronics continue to place a burden on management systems, as confirmed by recent analytical materials (Xavier *et al.*, 2021; Liu *et al.*, 2023).

The situation in the United States is different. Due to the lack of a central federal accounting system and regulatory approach, data on the generation and processing of electronic waste is compiled by different institutions using different methodologies, which leads to significant discrepancies in the indicators. This complicates the construction of a unified national profile of WEEE flows and makes it impossible to assess the effectiveness of regulatory measures in a consistent manner (Kumar & Dixit, 2018; Baldé *et al.*, 2024). Overall, the comparison shows that the differences between countries are due not only to the scale of waste generation, but also to how statistics are collected and what tools are used to describe flows. Australia and Brazil provide more comprehensive data sets through national policies, while in the United States, the fragmentation of the regulatory framework creates structural gaps in accounting.

The analysis is based on a comparison of official statistics, international reports and scientific sources that reveal the peculiarities of the functioning of waste electrical and electronic equipment (WEEE) management systems in the European Union countries, as well as in Ukraine, the United States, Australia and Brazil. The summary data presented below provide an overview of the scale of electronic waste generation, the level of collection and the main institutional factors that influence the effectiveness of the relevant systems. According to Eurostat (n.d.), between 2011 and 2022, EU countries saw a steady increase in the volume of electrical and electronic equipment entering the market (EEE POM) (Fig. 2). While in 2011 this figure was 7.65 million tonnes, by 2022 it had increased to 14.44 million tonnes. The volumes of waste collected also showed growth, but lagged significantly behind the rate of increase in production. In 2022, only 4.99 million tonnes of WEEE were collected, which is 40.06% less than the 65% target set by Directive of the European Parliament and of the Council No. 2012/19/EU (2012).

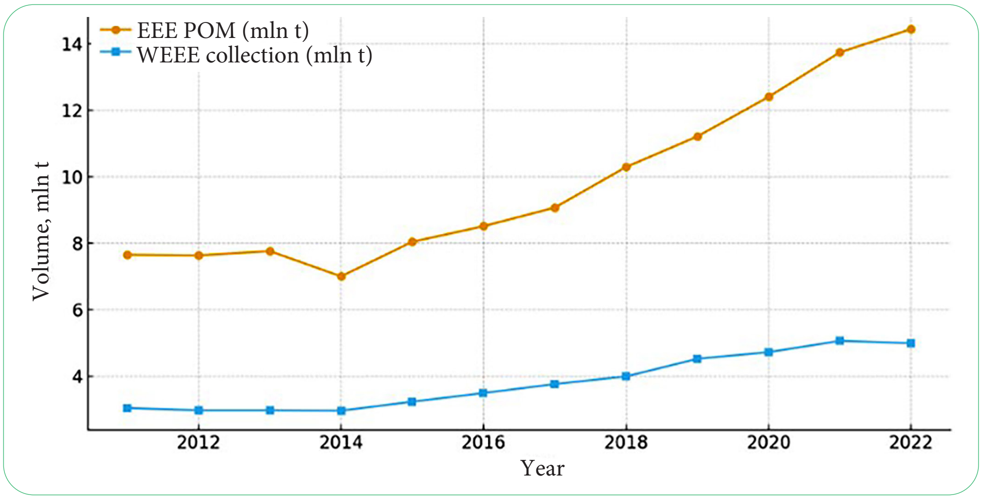

Figure 2. Generation and collection of WEEE in the EU (2011-2022)
Source: compiled by the authors based on Eurostat (n.d.)

The collection rate is presented separately as a percentage of the weight of electronic equipment placed on the market. From 2011 to 2019, this indicator showed an upward trend, reaching a maximum of 48.61%. However, after 2020, it began to decline, reaching 40.06% in 2022 (Fig. 3).

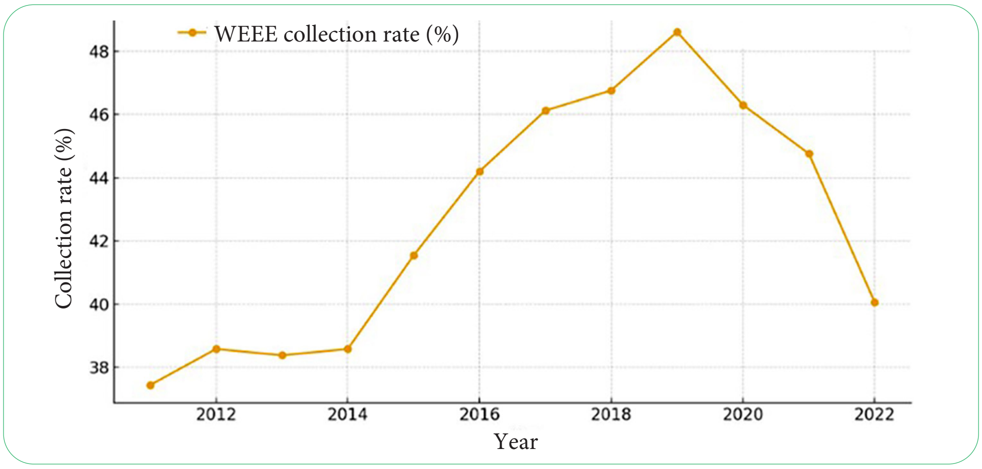

Figure 3. Dynamics of the level of WEEEE collection in the EU, 2011-2022
Source: compiled by the authors based on Eurostat (n.d.)

According to estimates by L. Hlavatska (2021), approximately 28,000 tonnes of WEEE are generated annually in Ukraine. At the same time, official statistics do not cover a significant part of the household sector, which leads to significant discrepancies between actual and documented volumes. The market has limited infrastructure: of the 128 enterprises capable of accepting hazardous waste, only 22 are licensed to process WEEE, and only 4 are operational. A major problem is the illegal import of electronic waste from EU countries, which, according to The Global E-waste Monitor, accounts for 14-18% of the total volume of WEEE generated in Ukraine. This further complicates the already inadequate infrastructure (Baldé *et al.*, 2024).

The United States is one of the world's largest producers of electronic waste. However, official data show significant differences depending on the methodology of the source. In 2021, the country generated 6.9-9.9 million tonnes of e-waste. The recycling rate fluctuates between 15.4 and 25%, which does not correspond to the scale of WEEE generation. A fragmented management system, with 25 states having their own e-waste laws, results in a lack of uniform national standards for collection and accounting. This complicates the creation of a reliable database and hinders the development of national infrastructure. Australia has one of the highest rates of e-waste generation per capita, at 20-22 kg per year (Clean Up Australia, 2024). In 2019, the total volume was 511,000 tonnes, and by 2030, it is expected to grow to 657,000 tonnes. The basis of the national collection system is the National Television and Computer Recycling Scheme (NTCRS), which aims to increase the collection rate to 80% and the material recovery rate to 90% by 2027. However, the scheme covers only certain product categories, which results in a significant portion of the WEEE stream remaining outside the formal system.

Brazil generates 2.1-2.4 million tonnes of electronic waste annually, which is 10.2 kg per capita (International Trade Administration, 2022; Vargas *et al.*, 2024). The recycling rate remains low at less than 3%. The National Solid Waste Policy (PNRS) sets a recycling target of 17% by 2025 and introduces reverse logistics for electronics. A significant element of the PNRS is the integration of informal collectors ("catadores") into the formal system, but uneven infrastructure development and low consumer participation remain key constraints. A comparison of per capita e-waste generation shows significant differences between the countries considered. Australia has the highest rate (over 20 kg/person), Brazil – approximately 10.2 kg, and the United States – approximately 7 kg (Fig. 4).

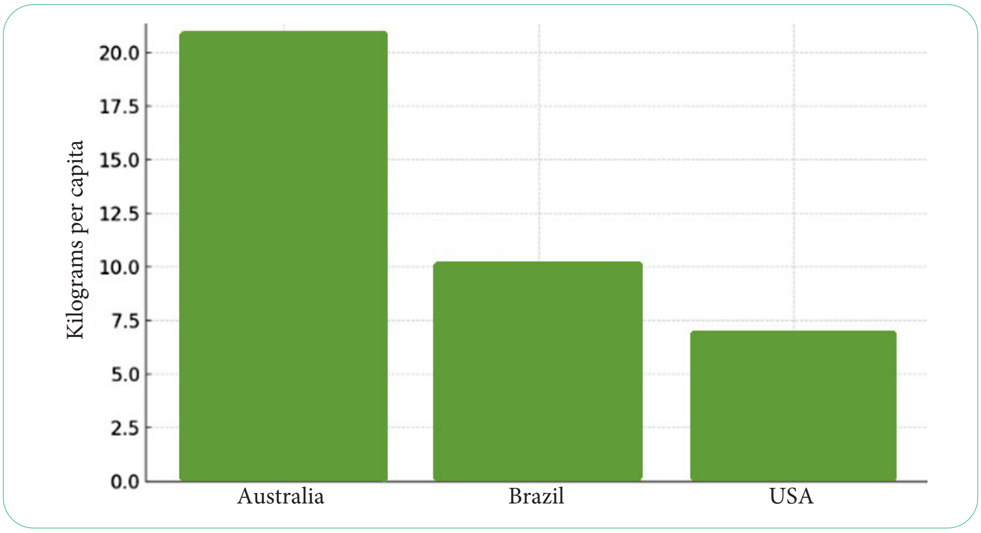

Figure 4. Comparison of e-waste generation per capita (Australia, Brazil, United States)
Source: compiled by the authors based on International Trade Administration (2022), C.P. Baldé *et al.* (2024)

A comparison of approaches to waste electrical and electronic equipment management in different countries covered by the study shows that the volume of electronic waste generation is on a steady upward trend. At the same time, existing institutional and infrastructural mechanisms are unable to keep pace with technological progress. According to analytical reports by international organisations, the scale of WEEE generation exceeds the capacity of official collection and recycling, which creates systemic pressure on resource turnover and the functioning of secondary raw material markets (Baldé *et al.*, 2024). Similar trends are also observed in individual regional analyses: researchers cite the short service life of electronic goods and the lack of a systematic approach to eco-design as key reasons for the increase in waste generation (Liu *et al.*, 2023; Kumar *et al.*, 2024).

The example of European Union countries shows a combination of a developed legislative framework with a range of structural challenges in policy implementation. Although the EPR principle is consistently applied and the collection infrastructure covers a significant part of the population, the actual achievement of WEEE treatment targets remains below the regulatory requirements. This is due, in particular, to the fact that some of the waste accumulates in the household sector, while the rest is diverted into illegal streams. Therefore, the effectiveness of EPR models in the European context is largely determined not only by regulatory policy, but also by consumer behaviour, the level of access to repair services and the quality of state control over the market.

The situation in Ukraine is characterised by a structural imbalance between the volumes generated and the capacity to process them. National data indicate approximately 28,000 tonnes of WEEE annually, but the actual volumes may be significantly higher due to the lack of systematic accounting. Limited infrastructure remains a key challenge: only a small proportion of existing enterprises have valid processing permits, leading to the dominance of mixed waste and the informal sector. Another barrier is the influx of illegal flows from the EU, which exacerbates the imbalance between the state's environmental obligations and its actual capabilities.

The experience of the United States shows that the fragmentation of the regulatory framework creates a systemic problem of reliability and comparability of statistical data. In contrast to the EU or Australia, where national accounting frameworks are in place, in the US, indicators are compiled by different agencies using different methods, leading to discrepancies in estimates of WEEE and recycling volumes (Kumar *et al.*, 2024). This approach complicates comparisons of trends and the development of long-term strategies.

Australia and Brazil, despite their different levels of economic development, demonstrate a significant impact of consumption patterns on the scale of e-waste generation. Australia is characterised by high per capita e-waste generation and the existence of national accounting and regulatory schemes (Liu *et al.*, 2023), while in Brazil, national policy focuses on developing reverse logistics and integrating the informal sector into waste management. However, even within a legally defined system, the actual recycling rate remains low, indicating a need to expand information campaigns and develop collection infrastructure.

A common conclusion for all countries analysed is the need to transition from quantity-oriented assessment models to systems capable of incorporating qualitative aspects of circularity, such as repairability, reusability, and preservation of material value. Academic reviews (Liu *et al.*, 2023; Mihai *et al.*, 2024) emphasise the need to introduce dynamic material flow analysis models focused on forecasting stocks and identifying priority fractions. For Ukraine, it is necessary to combine regulatory innovations with the development of applied mechanisms for creating a national EEE accounting system, strengthening control over cross-border flows, institutional support for the formal recycling sector, and stimulating eco-design. This will harmonise national policy with international practices and gradually transition to a functional circular economy model.

The results of the study can be used to conduct a comparative analysis with the conclusions of other researchers working in the field of waste electrical and electronic equipment management. The methodological approach to WEEE analysis is undergoing significant changes. Material flow analysis (MFA) is considered one of the leading analytical tools in this field, but existing reviews highlight a range of limitations, including a lack of research on countries outside the OECD and insufficient use of dynamic models and uncertainty accounting methods (Azizi *et al.*, 2023). The demand for more flexible approaches has led to the emergence of combined forecasting models that combine principal component analysis methods with neural network algorithms. Such solutions improve the reproduction of consumer behaviour patterns, which are a determining factor in the formation of WEEE flows (Guo & Zhong, 2021).

At the national level, the problem of e-waste management is complicated by both low recycling rates and the complex structure of the waste streams themselves. Studies show that small household electronics have the lowest return rates to collection systems, despite their significant share in the total volume of WEEE (Yafen & Shevchenko, 2021). At the same time, electronic waste is considered a valuable source of critically important raw materials. EU documents, including Regulation of the European Parliament and of the Council No. 2024/1252 (2024), emphasise the need to reduce the loss of such materials (Souza, 2020; Kumar *et al.*, 2024).

The observed decline in the relative level of WEEE collection in EU countries from 48.61% (2019) to 40.06% (2022), despite the growth in absolute volumes, is consistent with the conclusions of M. Compagnoni (2022), who stated in a systematic literature review that the ERP mechanism does not always ensure the achievement of targets. At the same time, the study supplements these conclusions with quantitative verification: a correlation analysis revealed a weak negative relationship ($r = -0.23$) between the volumes of products placed on the market and the relative collection rate, indicating a systemic inability of the infrastructure to adapt to the growth rate of electronics consumption. M. Compagnoni (2022) did not provide similar quantitative estimates, focusing mainly on qualitative policy analysis.

The results of a study by K. Liu *et al.* (2023), which emphasised the need to transition to dynamic material-specific indicators in a global review of electronic waste recycling, are confirmed by the analysis. Traditional collection indicators for EEE POM proved to be insufficiently sensitive to the actual effectiveness of management systems. However, in contrast to a study by K. Liu *et al.* (2023), which considered the problem mainly from a technological point of view, the presented study emphasised regulatory and institutional factors as determinants of effectiveness. Regarding methodological approaches, D.D.S. Azizi *et al.* (2023) highlighted in their content analysis of material flow analysis (MFA) applications the insufficient coverage of countries outside the OECD and the limited use of dynamic models. The presented study partially fills this gap by including Brazil and Ukraine in the analysis, but confirms the conclusion of D.D.S. Azizi *et al.* (2023) regarding the absence of dynamic models in the national monitoring systems of most of the countries studied.

The identified problem of illegal imports of electronic waste to Ukraine at a level of 14-18% expands on the conclusions of a study by F. Mihai *et al.* (2024) on waste management in Eastern European countries. The study noted common regional challenges but did not emphasise cross-border flows as a separate barrier to effective policy. Thus, the study complements the regional analysis with a specific quantitative measure of the problem. The results of the analysis of the situation in the United States are consistent with the findings of P. Kumar *et al.* (2024), emphasising the fragmentation of the regulatory system as a key obstacle. At the same time, the presented study adds a comparative dimension: the discrepancy in estimates of WEEE generation, ranging from 6.9 to 9.9 million tonnes, demonstrates the scale of statistical uncertainty, which significantly complicates international comparisons and prevents a correct assessment of the effectiveness of individual states' policies.

Of particular scientific interest is a comparison of the results with the study by R.G. Souza (2020) on the role of the informal sector in Brazil. The study described the participation of catadores in the reverse logistics system as a unique feature of the Brazilian model. The study confirms this conclusion, while noting that the low overall recycling rate (<3%) indicates the limited effectiveness of integrating the informal sector without the parallel development of formal infrastructure. This raises a substantial point for discussion: is the formalisation of the informal sector a sufficient condition for building an effective WEEE management system? The findings of L.H. Xavier *et al.* (2021) on the concept of urban metal mining as a promising direction for the circular economy are only partially confirmed in the current study. Although the potential for recovering valuable materials is undeniable, the analysis shows that realising this potential requires first addressing basic infrastructure issues, especially in transition economies such as Ukraine.

In contrast to a study by N.M. Franz & C.L. Silva (2022), which viewed e-waste primarily as a global production challenge, presented a study focusing on behavioural barriers. In particular, the study determined that a significant proportion of small electrical appliances are kept in households due to "emotional attachment", a factor that is not sufficiently considered in traditional management models and requires separate research in the field of consumer behaviour. Research by I. Issah *et al.* (2022) on the risks of informal recycling in Africa demonstrates problems similar to those identified in this study in the context of WEEE exports from developed countries. This confirms the global nature of the problem and the need for international policy coordination that goes beyond national regulatory systems.

In summary, the study confirms most of the conclusions of previous scientific works on challenges in the field of e-waste management, while supplementing them with quantitative assessments and comparative analysis between countries with different regulatory models. A key finding is that none of the models studied – neither the powerful European EPR system, nor the decentralised American approach, nor the co-regulatory models of Australia, nor the integrative Brazilian experience – provides an adequate response to the growth rate of e-waste. For Ukraine, this means the need to develop a comprehensive approach that takes into account both international experience and national specifics, in particular, the role of the informal sector, the problem of cross-border flows, and limited financial resources for infrastructure development. Promising areas for further research include analysing consumer behaviour factors, modelling material flow dynamics, and assessing the economic effectiveness of various EPR policy instruments in the Ukrainian context.

Conclusions

The study provided a comprehensive analysis of the characteristics of electrical and electronic equipment waste management in the EU, Ukraine, the United States, Australia, and Brazil. Official reports from international institutions, scientific sources, and national regulatory acts were used for the analysis. The results demonstrated that, despite the existence of regulatory frameworks and infrastructure development, none of the models studied currently provides a level of recycling that corresponds to the rapid growth in electronics consumption.

In European Union countries, despite a strong legal framework and the implementation of the EPR principle, there has been a decline in the collection of electronic waste, indicating a gap between targets and actual results. The situation in Ukraine is characterised by a lack of infrastructure and the significant influence of the informal sector, which significantly limits the coverage of waste by official channels in the context of growing shadow imports. In the United States, the lack of a unified regulatory approach and the fragmentation of the regulatory system lead to serious statistical discrepancies, which make it difficult to form a complete picture. Meanwhile, in Australia and Brazil, despite the existence of national systems and standardised accounting methods, there are difficulties associated with high per capita waste generation and limited consumer participation in return systems.

The uniqueness of the study is determined by the comparative analysis of regulatory approaches, infrastructure characteristics and statistical data in different countries within a single methodological framework. This identified common problems: weak use of material flow methods in planning, insufficient effectiveness of existing EPR instruments, underdeveloped monitoring systems, and a lack of incentives for reuse and repair of electronic equipment. The practical value of the study is determined by the identification of areas for improvement in the Ukrainian model of electronic waste management, incorporating international experience and the principles of the circular economy: in particular, the introduction of differentiated environmental rates, strengthening control over the movement of waste across borders, developing infrastructure for reverse logistics, and introducing new economic instruments to support product reuse.

Further research should emphasise modelling of waste flows using dynamic material flow analysis, studying the impact of the shadow sector on statistics, analysing consumer behaviour, and testing new approaches to implementing the EPR principle. Promising solutions include the introduction of digital product passports, environmentally oriented tax mechanisms, and repair incentive programmes. This will form the basis for the transition to a circular model of e-waste management and a reduction in the loss of strategically significant materials.

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Аналіз даних по утворенню відходів електричного та електронного обладнання

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Анотація. У світі спостерігається стрімке зростання обсягів відходів електричного та електронного обладнання (ВЕЕО), яке випереджає темпи розвитку інфраструктури для їх збирання й переробки. Це загострює екологічні виклики та поглиблює дефіцит критичних ресурсів. Метою дослідження було здійснення порівняльного аналізу підходів до управління відходами електричного та електронного обладнання в Україні, країнах Європейського Союзу, Африки, Латинської Америки, США, Австралії та Бразилії. Основна увага зосереджена на виявленні відмінностей у регуляторних підходах, показниках збору, методах переробки, а також на формуванні рекомендацій щодо впровадження ефективних практик в українських умовах. Методологія охоплювала системний аналіз законодавчих рамок, статистичні методи для оцінки динаміки обсягів утворення та збору ВЕЕО, порівняльно-географічний аналіз національних моделей та контент-аналіз нормативних документів. Дослідження показало, що ЄС має найбільш структуровану модель управління відходами, засновану на принципі розширеної відповідальності виробника, однак навіть за наявності чітких нормативів рівень збору суттєво нижчий за цільові значення. У США управління ВЕЕО характеризується фрагментованістю та відсутністю єдиного федерального регулювання, що ускладнює формування достовірної статистики. Австралія демонструє ефективність ко-регуляторних підходів, а Бразилія – унікальну інтеграцію неформального сектору до офіційної системи зворотної логістики. Розглянуто комплексне поєднання законодавчого, інфраструктурного та поведінкового вимірів управління ВЕЕО в п'яти країнах із різними економічними моделями. Практичне значення полягає у формуванні рекомендацій для України щодо імплементації розширеної відповідальності виробника розвитку системи моніторингу, підвищення прозорості ринку та адаптації успішних міжнародних інструментів для переходу до циркулярної економіки

Ключові слова: електронні відходи; розширена відповідальність виробника; циркулярна економіка; міжнародні моделі управління; інфраструктура збору; екологічна політика

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Predictive modelling of the movement of pollutants of the Naryn River using the SWAT+ model

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Abstract. The relevance of the study is conditioned by the need to assess the ecological state of the Naryn River basin under the influence of anthropogenic pollution and climatic changes caused by mining, agricultural runoff, urbanisation, and accumulation of sediments below hydroelectric power plants. The purpose of the study was to quantify the degradation of water quality and ecosystems in the Naryn River basin under the influence of anthropogenic pollutants and climate change. Methods of monitoring data analysis and mathematical modelling were used to achieve the goal. The results showed a significant decrease in biodiversity by 10-20% and water quality caused by an increase in concentrations of heavy metals – lead (up to 0.053 mg/l) and phosphorus (up to 0.48 mg/l) by 2050 under a high-emission climate scenario. It was found that erosion increased to 460 t/km2/year, and the productivity of the transboundary Syrdarya River decreased by 11%, which highlights the vulnerability of mountain and aquatic ecosystems. In addition, a decrease in the dissolved oxygen content to 4.7 mg/l was recorded, which increases the negative impact on aquatic biocoenoses. There was also an 18% decrease in the reproduction of fish populations, which indicates serious risks for their survival in conditions of habitat fragmentation below hydroelectric power plants. The practical significance of the study was to provide a framework for developing measures for monitoring and managing water resources in the region, which can be used by government authorities in Kyrgyzstan and neighbouring Central Asian countries, such as Kazakhstan and Uzbekistan, to coordinate transboundary water use, and environmental organisations and local communities for the conservation of biodiversity and sustainable development of the Naryn River basin

Keywords: anthropogenic impact; ecosystem degradation; transboundary river systems; climate change; water resources; biodiversity

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Introduction

Pollution of transboundary rivers in Central Asia, such as the Naryn, poses a threat to the region's water supply, irrigation, and ecosystems, which underscores the relevance of this study. Anthropogenic factors, including mining and agricultural runoff, combined with climate change, worsen the water quality of the Naryn River, affecting the sustainability of ecosystems and water users in Kyrgyzstan and neighbouring countries (Janybek kyzy, 2024). The problem lies in the lack of understanding of the long-term effects of Naryn pollution and the lack of predictive models that consider climate scenarios for this region.

M. Pamirbek kyzy *et al.* (2022) found that seasonal peaks in nitrogen and phosphorus concentrations in the middle reaches of the Naryn River reach 2.5 mg/l in summer due to agricultural runoff. Their analysis showed that melting snow and glaciers increases runoff by 10-12%, which contributes to the transport of pollutants downstream. However, their study did not consider long-term climate scenarios, but was limited to current observations. N. Degembaeva *et al.* (2024) found that lead concentrations in the upper Naryn River exceeded the maximum permissible limits by 1.5 times in June due to mining activities. They noted seasonal changes in water quality associated with increased erosion in mountainous areas. Their study highlighted the local contribution of anthropogenic sources, but did not include predictive models. F. Betz *et al.* (2023) showed that erosion in the Naryn Basin leads to a decrease in the vegetation cover of the basin by 15% due to hydromorphological changes. They used satellite data to analyse the interaction of vegetation and runoff, revealing the vulnerability of ecosystems to seasonal runoff peaks. L. Ma *et al.* (2020) investigated the hydrochemical composition of the transboundary Chu-Talas Basin in Kyrgyzstan. They found that arsenic concentrations in surface waters reached 10-15 mcg/l, exceeding the maximum permissible concentrations (MPC) by 1.5-2 times, due to natural weathering and anthropogenic emissions. These results indicate the risks of bioaccumulation in aquatic ecosystems and highlight the need for monitoring to prevent biota degradation.

In their research, N.A. Kaldybaev *et al.* (2024) conducted a geochemical assessment of the rivers of southern Kyrgyzstan, including the Kara Darya, a tributary of the Naryn Basin. Their analysis showed that the concentrations of lead and zinc in the sediments were up to 50 mg/kg and 120 mg/kg, respectively, which are lower than the MPC, but create cumulative risks for benthic organisms when resuspended during flood periods. These data highlight the importance of remediation to minimise trophic transfer of pollutants. M. Severinenko *et al.* (2024) investigated the impact of mining facilities in Kyrgyzstan on pollution of the Shu River. They found that the concentrations of uranium in irrigation channels reached 30 mcg/l, exceeding the MPC by 3 times, and molybdenum up to 20 mcg/l, which threatens agricultural ecosystems and increases soil erosion. Their findings highlighted the need for barriers to groundwater and strict control of tailings ponds.

A.D. Egemberdieva (2025) investigated anthropogenic and microbiological pollution in the Mailuu-Suu River Basin. The researcher found that the concentrations of mercury and cadmium in the water were up to 0.5 mcg/l and 1.2 mcg/l, respectively, exceeding the MPC by 2-3 times, which causes degradation of floodplain vegetation and microbial communities, increasing eutrophication. These results highlighted the need for advanced cleaning technologies to restore ecosystems. P. Kuznietsov & O. Biedunkova (2025) applied multidimensional statistical methods, including cluster analysis and principal component analysis, to assess heavy metal pollution in freshwater systems. They showed that the concentrations of copper and nickel in the sediments ranged from 40 to 100 mg/kg, which is associated with anthropogenic foci and leads to a decrease in species diversity by 15-20%. Their approaches confirmed the importance of statistical modelling for the development of adaptive protection measures.

Despite significant progress in the study of water pollution, gaps remain in understanding the dynamics of the spread of pollutants under climate change and anthropogenic pressure, especially in transboundary basins such as Naryn, where mining activities, such as the Kumtor mine, have led to the accumulation of more than 100 million tons of toxic waste since the 1990s. The lack of integrated models combining hydrochemical and climatic factors limits the accuracy of forecasts of environmental impacts. The purpose of the study was to numerically simulate the impact of anthropogenic pollutants and climate change on the deterioration of water resources and ecosystems in the Naryn River basin, including species diversity, hydrochemical characteristics, and sustainability of the transboundary water systems of the Syr Darya. The hypothesis was that anthropogenic pollutants, including heavy metals, significantly degrade water quality, increasing environmental risks such as loss of biodiversity and degradation of irrigation systems.

Materials and Methods

General characteristics of the method and research data

The study was conducted using the SWAT+ model, which integrates the hydrological cycle, sedimentation and transport of pollutants, to assess the impact of anthropogenic pollutants (heavy metals Pb, Cd, biogens N, P) and climatic changes on the ecosystems of the Naryn River basin. The model allowed quantifying the degradation of water quality and ecosystem functions (biodiversity, water regulation, biotreatment), considering mining runoff, agricultural activity (22% of the area) and climate scenarios RCP 4.5/8.5. Pollutants were modelled in the SWAT+ (n.d.) transportation module, considering both the dissolved and the fractions associated with the solid phase (suspended sediments). For heavy metals Pb and Cd, the distribution coefficients (K_d) 0.5-1.4 l/kg and 0.3-0.7 l/kg, respectively, were used, determining the proportion of metals adsorbed on suspended sediment particles according to the equation (1):

$$C_s = K_d \times C_d, \quad (1)$$

where C_s – concentration in the solid phase; C_d – dissolved phase; K_d – distribution coefficient. The model assumed a proportion of the bound form of 60-75% for Pb and 45-60% for Cd, depending on the granulometric composition of sediments. The deposition rate of pollutants was 0.01-0.04 m/day, and the resuspension rate was 0.005-0.015 m/day, which corresponds to the parameters of the sediment routing module in SWAT+. Concentrations of biogenic elements N (0.8-2.4 mg/l) and P (0.12-0.48 mg/l) were set in dissolved form, modelled through the mechanisms of surface and groundwater runoff. Thus, the model considered the combined transfer of metals in two phases – dissolved and solid (in suspended sediments), which provided a correct assessment of their migration and accumulation in bottom sediments. Calibration was performed according to Kyrgyzhydromet (n.d.). data (2020-2025) with the Nash-Sutcliffe index (NSE > 0.68 for runoff and > 0.65 for suspended sediment (SSC/SY)) and the balance deviation (PBIAS < 6.5%) for the flow variables (Q) and suspended sediment concentration (SSC). For the dissolved components (DO, Pb, Cd, N, P), the accuracy was estimated by the criteria $R^2 > 0.70$ and the mean absolute deviation ($MAD < 10\%$), which ensured consistency between the observed and modelled values in the space-time context.

In SWAT+, reservoirs (including the Kambarat hydroelectric power station) are defined as reservoirs with a seasonal operating curve (target volume/level by month) and throughput rules (average flow rate of 10-15 m^3/s). Sediment trapping is implemented through the RES_{SED} parameter (deposition coefficient 0.02-0.05 m/day) and PSE (delay efficiency 65-80%), which explains the sediment accumulation below the hydropower plant (HPP) (up to 5-10% decrease in efficiency). The input data included hydrometeorological parameters (runoff, suspended sediments, temperature, humidity) from Kyrgyzhydromet, and measurements of Pb, Cd, N, and P at the Uch-Terek (upper reaches), Naryn (middle reaches), and Bolshoy Naryn (lower reaches) posts. Complementary sources: Digital Elevation Model (DEM) SRTM (30 m) (Earth Resources Observation and Science Center, 2018), soil (Food and Agriculture Organization (n.d.) (FAO), land management Landsat 8/9 (U.S. Department of the Interior, 2025), which provided spatial and temporal representativeness for ecosystem impact analysis.

Sampling approach and modelling process

The methodology included a spatial sampling of a basin (59,100 km^2) divided into subbasins in ArcGIS Pro for accurate mapping of hydrological units (HRU) and assessment of the impact of pollutants on ecosystems (tugai forests, river biocoenoses, mountain meadows). The basin was divided into 128 sub-basins and 2,450 HRUs with thresholds: 5% land use, 10% soil, 15% slope. The time sample covered the years 2020-2025 with a forecast up to 2050. The modelling process in SWAT+ began with data entry (DEM SRTM, FAO soils, Landsat 8/9), calibration (NSE > 0.68 for runoff, > 0.65 for suspended sediment; PBIAS < 6.5%) and validation according to Kyrgyzhydromet data (2021-2025). Sensitivity analysis of the parameters (CN2 -0.20, $ALPHA_{BF}$ 0.18, SOL_{AWC} 0.22) in SWAT+ Toolbox optimised the assessment of the impact of pollutants on biodiversity (-20%), fish reproduction (-18%), and productivity of the Syr Darya (-11%). The RCP 4.5/8.5 scenarios (warming +1.7-2.4 °C, precipitation +8-11%) modelled changes in runoff (+12%), erosion (+11%, up to 510 t/km^2/year), and biogenic load (+18-22%), allowing long-term impacts on ecosystems and transboundary water resources to be estimated. Based on the results, recommendations have been developed to reduce anthropogenic impact and adapt to climate change. To assess the stability of the SWAT+ model and identify key parameters affecting the hydroecological parameters of the basin, a One-At-a-Time (OAT) sensitivity analysis was performed. Each parameter varied in the range of ±20% of the calibrated value, after which the normalised sensitivity was calculated (2):

$$S = (\Delta Y/Y0)/(\Delta p/p0), \quad (2)$$

where Y – response value (for example, Q, SY, DO, Pb, Cd); p – model parameter. Positive values of S reflect the direct effect of the parameter on the indicator, while negative values reflect the opposite.

Equipment and tools used

The equipment and tools used included SWAT+ 2024 software for performing calculations, ArcGIS Pro for spatial analysis, and SWAT+ Toolbox for evaluating parameter sensitivity, providing a high degree of automation and accuracy (SWAT+, n.d.). All the data involved in the study were publicly available, which contributed to the transparency and reproducibility of the results.

Results

Geoecological characteristics of the Naryn River basin and trends in ecosystem degradation

The Naryn River basin, 807 km long from the upper reaches of the Chon-Naryn to its confluence with the Karadarya River, covers an area of about 59,100 km^2 and is characterised by a complex mountainous terrain with heights from 1,500 to 5,135 m (SRTM 30 m DEM). The basin (59,100 km^2) is divided in SWAT+ into 128 sub-basins and 2,450 HRUs with thresholds: 5% land use, 10% soil, 15% slope. The main tributaries are At-Bashi and On-Archa. The climate of the region is continental, with an average annual precipitation of about 320 mm and a temperature range from -14 to +26°C, which forms pronounced seasonal fluctuations in runoff and water temperature. The average annual runoff in the upper reaches is 13.8 m^3/s with peaks in June and July up to 24.7 m^3/s, while 70% of the runoff is provided by glacial nutrition and 20% by precipitation, which causes intensive transfer of pollutants to the lower parts of the basin, affecting water users in Central Asia.

Anthropogenic load is manifested in high levels of erosion in mountain subbasins, reaching 460 t/km^2/year, the mass fraction of Pb+Cd in the total mass of pollutants in bottom sediments is approximately 26% (Food and Agriculture Organization, n.d.). The initial degradation of biotopes is observed in the lower reaches: a decrease in dissolved oxygen by 17% and a decrease in biodiversity by 10-20%, including fish species (osman, marinka) and bird populations (ducks, herons). The forecast scenarios of climate change (RCP 8.5) provide for an increase in runoff by 12% by 2050 (up to 15.5 m^3/s) due to increased glacier melting by 15% and precipitation growth by 8%, which increases the transport of pollutants.

From 2010 to 2015, metal concentrations in water and bottom sediments increased by an average of 30%, and erosion processes in mountain sub-basins contributed to the deepening degradation of coastal ecosystems. The ecosystems of the basin are represented by tugai forests (18%) and mountain meadows (42%), while protected areas (hotspot, 5% of the area) turned out to be particularly vulnerable to anthropogenic and climatic influences. SWAT+ modelling predicts a further loss of species diversity by 10-20%, with an index of 15% reduction in the number of species due to erosion and pollution.

Thus, the geo-ecological situation in the Naryn River basin demonstrates high seasonal and spatial variability of water resources, significant anthropogenic impact, and the threat of degradation of coastal and aquatic ecosystems. The combined effect of glacier melting, erosion processes, and metal pollution requires integrated water resources management and environmental monitoring, and the introduction of preventive measures to preserve biodiversity and stabilise the basin's water balance (De Serio & Mossa, 2016). An analysis of pollution in the Naryn River basin using the SWAT+ model revealed a variety of sources of anthropogenic and natural impacts that shape the current environmental situation presented in Table 1.

Table 1. Sources of pollution and their consequences in the Naryn River basin

Source of pollution	Effects
Mining activities (Kumtor mine)	Increased concentrations of lead (Pb) to 0.048 mg/l and cadmium (Cd) to 0.018 mg/l, exceeding the MPC by 1.5 times, degradation of aquatic ecosystems
Agricultural land (22% of the territory)	Increase of nitrogen (N) to 2.4 mg/l and phosphorus (P) to 0.48 mg/l, eutrophication and decrease of oxygen content by 12-16%
Urbanised areas (12% of the territory)	An increase in organic pollutants by 7.5%, an increase in biochemical oxygen demand (BOD), and a deterioration in water quality in the lower reaches
Erosion and snowmelt in mountainous areas	Increased transport of lead by 28% in June, removal of sediments (460 t/km^2) containing 26% by weight of pollutants to the downstream
Climate change (RCP 4.5/8.5)	Increase in runoff by 12% and concentrations of N, P by 18%, decrease in WQI by 11% by 2050, loss of 10% of vegetation cover of floodplain meadows

Source: calculated by the authors in the SWAT+ (n.d.) based on Food and Agriculture Organization (n.d.), Earth Resources Observation and Science Center (2018), U.S. Department of the Interior (2025)

The reasons for these indicators are related to intensive anthropogenic activity and changes in natural conditions. Mining activities, including the Kumtor mine, contribute to the accumulation of heavy metals due to waste leaching into watercourses. Agricultural runoff is enhanced by the use of fertilisers during the growing season, which leads to eutrophication. Urbanisation adds organic pollutants through wastewater, and erosion and snowmelt in mountainous areas, accelerated by climate change, increase the transport of pollutants downstream.

Scenario modelling: Climate and management scenarios

To assess the potential impact of climate change and management measures on the hydroecological indicators of the Naryn River basin, scenarios RCP4.5 and RCP8.5 for 2050, and three management measures (M1-M3) and their combined version (M4) were modelled. Stable hydrological observations by Kyrgyzhydromet (Janybek kyzy, 2024) with minimal climatic anomalies were used as the base period (2010-2015), which helped to calibrate the SWAT+ model and determine reference values of key indicators (average annual flow rate, erosion, dissolved oxygen, background concentrations of Pb and Cd in water and bottom sediments).

Climate change scenarios consider ensembles of CMIP6 models (ACCESS-ESM1-5, MIROC6, IPSL-CM6A-LR, GFDL-ESM4, NorESM2-MM) with a median and a range of 25-75 percentiles, adjusted using delta-change, and quantile matching techniques for forecasting for 2030 and 2050. Management measures have been implemented in SWAT+ through the reduction of erosion coefficients (USLE-C and USLE-P), the creation of coastal buffer strips 15-30 m wide and the modernisation of wastewater treatment plants. The combined M4 scenario allowed assessing how much a set of measures compensates for the increase in risks under the influence of climate change. The main modelling results for each scenario are presented in Table 2, including annual changes in key indicators, ensemble medians, and ranges of possible deviations.

Table 2. Changes in key indicators of the Naryn River basin by scenarios (2050, median of the ensemble±range)

Scenario	ΔQ (%)	Q (m^3/s)	ΔSY (%)	SY (t/km^2/year)	ΔDO (%)	DO (mg/l)	ΔPb (%)	Pb (mg/l)	ΔCd (%)	Cd (mg/l)
RCP4.5	+7 [4-10]	14.8	+9 [5-12]	500	-11 [-15-8]	5.0	+4	0.050	+6	0.019
RCP8.5	+12 [8-17]	15.5	+11 [8-15]	510	-16 [-20-12]	4.7	+10	0.053	+11	0.020

Table 2. Continued

Scenario	ΔQ (%)	Q (m^3/s)	ΔSY (%)	SY (t/km^2/year)	ΔDO (%)	DO (mg/l)	ΔPb (%)	Pb (mg/l)	ΔCd (%)	Cd (mg/l)
M1	-2 [-1 to -3]	15.2	-28 [-25 to -32]	395	+0.4 [0.2-0.6]	5.3	-16	0.044	-14	0.017
M2	-1 [0 to -2]	15.3	-22 [-18 to -26]	405	+0.3 [0.1-0.5]	5.2	-12	0.047	-10	0.018
M3	0 [-1 to 1]	15.5	-5 [-3 to -7]	485	+0.6 [0.4-0.8]	5.6	-18	0.043	-17	0.017
M4 (comb.)	-3 [-2 to -4]	15.0	-35 [-30 to -40]	330	+0.9 [0.7-1.1]	5.6	-22	0.037	-21	0.015

Source: compiled by the authors

As shown in Table 2, the RCP4.5 and RCP8.5 climate scenarios are characterised by an increase in mean annual discharge (up to 14.8-15.5 m^3/s), intensification of erosion processes, a decrease in dissolved oxygen concentration, and an increase in the content of heavy metals in water. Under the RCP8.5 scenario by 2050, discharge increases by 12% and erosion by 11%, while dissolved oxygen concentration decreases by 16%, indicating a substantial rise in hydroecological stress on the basin ecosystems. At the same time, Pb and Cd concentrations increase to 0.053 and 0.020 mg/l, respectively, approaching ecotoxicological threshold values and increasing risks to aquatic biocenoses.

The implementation of management measures (M1-M3) does not lead to abnormal changes in river discharge: ΔQ deviations remain within -2 to 0% relative to the baseline period, confirming the internal consistency of the SWAT+ hydrological module. The main effect of the management scenarios is associated with reductions in erosion and pollutant concentrations. Anti-erosion measures (M1, M2) reduce sediment yield by 22-28%, while modernisation of wastewater treatment facilities (M3) primarily improves the oxygen regime of the watercourse (+0.6 mg/l) and reduces Pb and Cd concentrations by 17-18%. The combined M4 scenario demonstrates the highest efficiency: erosion losses decrease by 35-40%, Pb and Cd concentrations by 21-22%, and dissolved oxygen stabilises at approximately 5.6 mg/l, creating favourable conditions for the functioning of aquatic organisms even under climate warming conditions. However, the annual average values do not fully reflect the seasonal dynamics of processes, on which the state of aquatic ecosystems significantly depends. To assess seasonal variability, an additional quarterly analysis was performed, considering changes in temperature, precipitation, runoff, dissolved oxygen concentration, and erosion losses. The main results are shown in Table 3.

Table 3. Seasonal changes in climatic and hydroecological indicators according to the RCP8.5 scenario by 2050 (median of the ensemble)

Indicator/Season	Winter	Spring	Summer	Autumn
ΔT (°C)	+1.9	+2.2	+2.4	+2.1
ΔP (%)	+7	+9	+11	+8
ΔQ (%)	+8	+11	+14	+9
ΔSY (%)	+7	+10	+13	+8
ΔDO (%)	-9	-13	-16	-11
ΔPb (%)	+6	+9	+12	+8
ΔCd (%)	+7	+10	+11	+9

Source: compiled by the authors based on SWAT+ (n.d.)

Seasonal analysis shows that the most pronounced changes are observed in the spring and summer period, when an increase in temperature and precipitation leads to an increase in runoff and increased erosion processes. During this period, the concentration of dissolved oxygen decreases to the minimum values (4.5-4.6 mg/l), which coincides with an increased intake of suspensions and metals. In winter and autumn, there is a moderate increase in water consumption with lower DO losses, but the effect of seasonal water quality degradation persists. These results emphasise the importance of a seasonal approach in assessing ecosystem risks, since it is the spring-summer extremes that have a key impact on the state of biota and the indicators of biodiversity (IBI). Combined management measures (M4) are particularly effective during the peak runoff season, reducing erosion by approximately 30-35% and increasing dissolved oxygen concentrations by about 0.9 mg/l during peak runoff periods. The OAT sensitivity analysis was performed. The most sensitive parameters were those related to surface runoff, moisture retention, and sedimentation (Table 4).

Table 4. Sensitivity of hydroecological parameters to the main parameters of the SWAT+ model (OAT method, range ±20%)

Parameter/Indicator	Q (Flow rate, m^3/s)	SY (Erosion, $t/km^2/year$)	DO (mg/l)	Pb (water, mg/l)	Cd (water, mg/l)
CN2 (Curve Number)	+0.48	+0.36	-0.22	+0.27	+0.29
$ALPHA_{BF}$ (Baseflow recession)	-0.21	-	+0.18	-	-
SOL_{AWC} (Soil moisture storage)	+0.19	+0.11	+0.25	+0.16	+0.18
$USLE_C$ (Cover ratio)	-	+0.52	-0.31	+0.41	+0.44
$USLE_P$ (Anti-erosion practices)	-	+0.47	-	+0.38	+0.35
LAT_{TTIME} (Lateral drain time)	+0.14	-	+0.12	-	-

Note: sensitivity range ±20% of the calibrated values
Source: calculated by the authors in the SWAT+ (n.d.)

The results of the sensitivity analysis allowed identifying the key parameters that were used in the development of management scenarios (M1-M4). In particular, the $USLE_C$ and $USLE_P$ parameters, which showed the greatest impact on erosion and transport of heavy metals, were directly considered when modelling environmental protection measures. The next stage of the analysis was aimed at quantifying the effectiveness of each management scenario in reducing erosion losses, Pb and Cd concentrations, and improving the oxygen regime of the watercourse without inducing significant changes in river discharge.

Four management scenarios were modelled to reduce the negative effects of climate change:

- M1 – implementation of anti-erosion practices (reduction of $USLE_P$ by 30%);
- M2 – improvement of vegetation cover ($USLE_C$↓ by 25%);
- M3 – modernisation of sewage treatment plants (BOD and metal removal efficiency +20%);
- M4 – combined scenario (M1+M2+M3).

The effectiveness was assessed by the relative changes in key indicators compared to the base period (2010-2015) and relative to the RCP8.5 climate background by 2050 (Table 5).

The combined M4 scenario compensates for approximately 35-40% of the climate-related increase in hydroecological risks, with the strongest effect observed for erosion control and heavy metal reduction. The main contribution to reducing erosion and metal pollution is provided by measures aimed at reducing $USLE_C$ and $USLE_P$. Improved wastewater treatment (M3) increases dissolved oxygen levels, while agrotechnical measures (M1-M2) stabilise runoff and reduce suspension.

A comparison of climate and management scenarios shows that even with the implementation of the set of measures (M4), part of the residual risk remains, mainly due to rising temperatures and reduced summer costs affecting oxygen saturation and metal mobility. To assess the environmental consequences of the residual risk and possible changes in the structure of aquatic communities, the obtained DO, Pb, and Cd values were compared with biotic thresholds and biodiversity indices. This analysis allows quantifying the sustainability of the basin ecosystem under various scenarios by 2050.

Table 5. Effects of management scenarios relative to RCP8.5 by 2050 (median of the ensemble)

Indicator/Scenario	M1	M2	M3	M4 (comb.)
ΔQ (%)	-2	-1	0	-3
ΔSY (%)	-28	-22	-5	-35
ΔDO (mg/l)	+0.4	+0.3	+0.6	+0.9
ΔPb (water, %)	-16	-12	-18	-22
ΔCd (water, %)	-14	-10	-17	-21
Residual risk (% of RCP8.5)	72	78	69	58

Source: calculated by the authors in the SWAT+ (n.d.)

Even with the implementation of a set of environmental protection measures, part of the climate-related risk to aquatic ecosystems remains (Shumka *et al.*, 2020; Hussain *et al.*, 2022). This is conditioned by an increase in summer extremes, an increase in temperature and a change in the flow regime, which affects the oxygen balance and migration of metals. The relative changes in key indicators (Q, SY, DO, Pb, Cd) compared to the baseline period (2010-2015) were used for the integral assessment of residual risk. The residual risk index characterises the proportion of unrealised negative changes after the application of management measures (Table 6).

Table 6. Changes in key indicators under different scenarios relative to the baseline

Indicator/Scenario	ΔRCP4.5 (%)	ΔRCP8.5 (%)	DM4 (comb.)	Residual risk (%)
Q (Consumption)	+7	+12	-3	+5
SY (Erosion)	+9	+11	-35	+1

Table 6. Continued

Indicator/Scenario	ΔRCP4.5 (%)	ΔRCP8.5 (%)	DM4 (comb.)	Residual risk (%)
DO (mg/l)	-11	-16	+0.9	-4
Pb (water)	+10	+14	-22	+3
Cd (water)	+9	+13	-21	+2

Source: calculated by the authors in the SWAT+ (n.d.), CMIP6 ensemble calculations

Combined measures (M4) significantly compensate for the climatic increase in risks: the erosion load decreases by about 35%, Pb and Cd concentrations by about 21-22%, and the dissolved oxygen content increases by approximately 0.9 mg/l (to about 5.6 mg/l). However, the residual risk (2-5%) remains due to incomplete levelling of extreme seasonal fluctuations and rising water temperatures. A comparison with biotic thresholds (DO < 5 mg/l, Pb > 0.05 mg/l, Cd > 0.02 mg/l) indicates a likely decrease in the biodiversity index (IBI) by 8-10% under the RCP8.5 scenario and only by 2-3% under the implementation of the package of measures (M4). Comparison with other landlocked countries (Ethiopia, Uganda, Algeria) showed similar trends in increased erosion and biogenic pollution under the RCP8.5 scenario. However, the Naryn Basin is characterised by a unique water supply structure (up to 70% of glacial runoff) and a pronounced transboundary nature, which increases the vulnerability of ecosystems (Table 7).

Table 7. Decline of ecosystem functions under RCP8.5 scenario by 2050, %

Component	Biodiversity	Water regulation	Bio-purification
Floodplain forests	17	11	19
River biocoenoses	20	14	17
Mountain meadows	10	9	11

Source: calculated by the authors in the SWAT+ (n.d.)

The decrease in ecosystem functions is associated with the combined influence of climatic and anthropogenic factors. Increasing concentrations of Pb and Cd, and erosion processes, accelerate the degradation of riverine biocoenoses and pasture ecosystems. Below the Kambarat hydroelectric power station, habitat fragmentation and a decrease in hydropower efficiency by 5-10% are observed due to sediment accumulation. Transboundary wetlands in the lower reaches of the Syr Darya are losing about 10% of their area due to eutrophication, which reduces the productivity and biodiversity of aquatic and coastal ecosystems (Table 8).

Table 8. Projected changes in ecosystem conditions under the RCP8.5 scenario (2020-2050)

Ecosystem	Indicator	2020-2025	2050 (RCP8.5)	Environmental impact
Tugai forests	DO (mg/l)	5.6	4.7 (-16%)	Increased eutrophication, degradation of flora and birds
	Pb (mg/l)	0.048	0.053 (+10%)	Toxic effects, reduction of species composition
Mountain meadows	Erosion (t/km^2/year)	460	510 (+11%)	Reduced pasture productivity and sustainability
River biocoenoses	Biodiversity (%)	100	80 (-20%)	Reduction of fish numbers (osman, marinka)
	Fish reproduction (%)	100	82 (-18%)	Disruption of migration and reproduction below the HPP

Source: calculated by the authors in the SWAT+ (n.d.)

The combined impact of climate change and anthropogenic stress leads to the loss of 10-20% of the ecosystem functions of the Naryn Basin by 2050. Riverine biocoenoses and floating ecosystems are the most vulnerable, where the combination of temperature rise, erosion, and heavy metal pollution increases the degradation of biodiversity (Bilyalov *et al.*, 2025). These processes have a transboundary effect, reducing the environmental sustainability of the lower reaches of the Syrdarya River and requiring the expansion of adaptation measures on a regional scale.

The results of scenario modelling confirmed the hypothesis that the introduction of management measures can significantly compensate for the climate-related risks of degradation of aquatic ecosystems in the Naryn Basin. Despite the expected increase in temperature and erosion activity under the RCP8.5 scenario by 2050, the integrated approach (M4) reduces erosion losses by 35%, reduces Pb and Cd concentrations by approximately 21-22% and increases dissolved oxygen by nearly 0.9 mg/l, confirming the effectiveness of integrated management measures under adverse climatic conditions. Thus, it is confirmed that the implementation of a set of environmental and engineering measures can slow down the degradation of ecosystem functions and stabilise hydroecological parameters even under adverse climatic conditions. The results highlight the need for adaptive water resources management and the integration of climate risks into regional sustainable development strategies.

Discussion

The study revealed a deterioration in water quality and biodiversity caused by anthropogenic pollution and climate change, which will lead to a decrease in the biodiversity and productivity of the Syr Darya by 2050. The results confirmed the hypothesis that a combination of anthropogenic and natural factors leads to degradation of the basin's ecosystems, emphasising the need for further monitoring and adaptation measures. The relevance of the study was to provide empirical data to assess the transboundary impact on Central Asia, especially for irrigation and energy, which was critical for regional environmental security.

A comparison with studies by other researchers has shown both similarities and differences. L. Yuan *et al.* (2020) in a review of watershed models, including SWAT, noted the effectiveness of modelling non-point sources of pollution, which corresponded to data on the prediction of concentrations of N (0.8-2.4 mg/l) and P (0.12-0.48 mg/l) in agricultural areas of Naryn. However, their analysis covered a wider range of watershed areas in the United States with a lower impact of erosion (200-300 t/km^2) compared to 460 t/km^2 in Naryn, which indicated more intense natural processes in the highlands, and also did not include RCP climate scenarios. Z. Hong *et al.* (2020) investigated heavy metal pollution along the Yellow River and found concentrations of Pb up to 0.05 mg/l, which coincided with the data for Naryn. Their impact on biodiversity (5-10%) turned out to be lower than 18-22% due to lower anthropogenic pressure and erosion in the study area, which could also be related to differences in water protection measures.

X. Zhang *et al.* (2025) revealed chemical characteristics of anthropogenic waters in the Jinji River Basin with Cd concentrations (0.01-0.03 mg/l) exceeding 0.005-0.02 mg/l in Naryn. This indicated a similar level of industrial pollution, but erosion in Naryn was more significant, increasing ecosystem degradation, and there was a lack of data on transboundary effects. S. Arora & A.K. Keshari (2021) applied cluster analysis in the Yamuna River study and identified seasonal pollution peaks similar to a 30% increase in Pb in Naryn in June. However, their water quality index (WQI) decreased by 8%, while Naryn was projected to decrease by 12% by 2050, reflecting a stronger impact of climatic factors and erosion in mountainous areas. S.H. Ewaid *et al.* (2020) developed a water quality index for Iraqi rivers, where an increase in salinity (up to 600 mg/l) corresponded to data on 500 mg/l in the lower reaches of the Naryn. Their analysis did not include climate scenarios, limiting comparison with RCP 8.5 forecasts, and also did not consider the effects of erosion and transboundary runoff, which distinguished the approach from this study.

W. Yang *et al.* (2020) applied the analysis of the main components in the Xinanjiang River Basin and revealed the effect of biogens on eutrophication, similar to the data on an 18% decrease in DO in Naryn. However, their DO decrease was only 10% at a concentration of P (0.3 mg/l), which was lower than 0.53 mg/l in Naryn, indicating more intense pollution, and there were no data on transboundary impacts. K. Kandel *et al.* (2024) found high concentrations of ions in the Himalayan rivers of Nepal, but their effect on biodiversity (5-7%) was less than 20% in the river biocoenoses of Naryn. This highlighted the high sensitivity of Naryn ecosystems to erosion and pollution, and the lack of analysis of the effect of heavy metals on fish reproduction in their study. D. Dimri *et al.* (2021) assessed the water quality of the Ganges River in the western Himalayas and showed the effect of erosion on biocoenoses similar to an 8% decrease in the coverage of mountain meadows in Naryn. Their decrease in productivity (5-8%) turned out to be lower than 10-15%, which could be conditioned by a lower anthropogenic load, and the cross-border aspects characteristic of Naryn were not considered.

X. Dong *et al.* (2022) in the Weihe Basin revealed spatial differences in hydrochemistry similar to seasonal pollution peaks in Naryn. However, their impact on transboundary ecosystems was less pronounced than the 12% loss of productivity in the Syr Darya, which highlighted the regional specifics of Naryn, and there was a lack of data on climate forecasts. K. Khatri *et al.* (2023) investigated the chemistry of snow and rain rivers in western Nepal and found a concentration of P (0.2 mg/l), which contrasted with 0.53 mg/l in Naryn. Their erosion data (400 t/km^2) was close to 460 t/km^2, but the transboundary effect remained less pronounced, and the analysis did not include impacts on fish biodiversity. G. Matta *et al.* (2022) assessed changes in water quality in the upper Ganges Basin and identified the effect of heavy metals on biodiversity (10-15%), which corresponded to part of the Naryn data. Their decrease in water regulation (5%) was less than 10-15%, which indicated differences in the intensity of climatic effects, and there were no data on transboundary water resources.

A. Bamal *et al.* (2025) in a global review showed that hydroclimatic factors increase pollution, which corresponded to the forecasts of a 10-15% increase in runoff under RCP 4.5 in this study. However, their analysis did not focus on transboundary ecosystems, unlike the data on the Syr Darya, nor did it include an assessment of the impact of erosion on biodiversity. M.T. Ejigu (2021) summarised water quality modelling and confirmed the effectiveness of SWAT+ for forecasts, which coincided with the approach to Naryn. The lack of a cross-border aspect and heavy metal analysis in their work limited direct comparison with Pb and Cd data. T.K. Karimov *et al.* (2024) identified problems with the safety of water supply in Kyrgyzstan, where mineralisation corresponded to Naryn data. Their focus on drinking water excluded ecosystem analysis, and also failed to consider climate scenarios, which distinguished the approach from this study.

A.F. Hill *et al.* (2017) investigated the socio-hydrological aspects of Naryn and identified vulnerability to flow changes, which corresponded to data on peaks of 25 m^3/s. Their analysis did not include heavy metals and erosion, limiting comparison with data on the degradation of biocoenoses, and there were no forecasts for 2050. A joint study by M.J. Nasir *et al.* (2023) in Pakistan evaluated the pollution index and identified the effect of Pb on precipitation, similar to the data from Naryn. Their concentrations (0.08 mg/l) exceeded 0.053 mg/l, indicating more intense local pollution, and cross-border aspects and climate forecasts were not considered. A. Nazir *et al.* (2022) revealed metal variations in the Ganges similar to seasonal changes in Naryn. Their decrease in biodiversity (8%) was less than 20%, which could be attributed to less erosion, and there was also a lack of data on transboundary water resources. I. Karaouzas *et al.* (2020) in Greece showed a higher level of heavy metal pollution than in Naryn, but the effect on biocoenoses was similar. Their analysis did not include climate scenarios and erosion, which limited comparison with data on mountain ecosystems.

D. Gupta *et al.* (2024) in Narmada identified health risks from Pb, which corresponded to a 20% decrease in fish reproduction in Naryn. Their research focused on human health rather than ecosystems, and did not include a cross-border context, which distinguished the approach in this study. M. Asim & K.N. Rao (2021) in Yamuna showed spatial differences similar to those in Naryn, but their WQI dropped by 10%, which was lower than the projected 12%. This indicated a less pronounced effect of climate change, and there was also no data on cross-border effects. F. Ustaoğlu *et al.* (2020) found a similar effect of mineralisation in Turkey, but the impact on biodiversity was less than in Naryn. Their analysis did not include erosion and forecasts for 2050, limiting comparison with data on ecosystem degradation. N. Sheripov *et al.* (2024) emphasised the need for legal reforms in Kyrgyzstan, which supported recommendations based on data on ecosystem degradation. Their study focused on legal aspects, not including direct environmental data, which made the comparison indirect. Thus, the results of the study corresponded to global trends in the deterioration of water quality and biodiversity due to anthropogenic impact and climate change, but were distinguished by a higher level of degradation due to the mountainous terrain and the transboundary context. These findings highlighted the importance of a regional approach to water resources management and moved on to the conclusions section for further recommendations.

Conclusions

The results of the study, obtained using the SWAT+ model based on empirical monitoring data, demonstrated a pronounced degradation of water quality and ecosystems in the Naryn River basin under the influence of anthropogenic pollution and climate change. It was found that concentrations of heavy metals such as lead (up to 0.053 mg/l by 2050) and phosphorus (up to 0.48 mg/l), and erosion (up to 510 $t/km^2/year$) led to a decrease in biodiversity by 10-20%, and dissolved oxygen content by 16% (up to 4.7 mg/l) and reproduction of fish populations by 18%, which confirms the hypothesis of the cumulative impact of anthropogenic factors, including mining and agricultural runoff, on the environmental sustainability of the region. The quantitative indicators obtained, including an 11% deterioration in the water quality index (WQI) and an 11% decrease in the productivity of the transboundary Syrdarya River by 2050 under the RCP 8.5 scenario, emphasise the increased risks for mountain meadows, floating forests and river biocoenoses, where habitat fragmentation below hydroelectric power plants reaches 18%. Qualitative results indicate systemic disruptions of ecosystem functions, such as water regulation (-9-14%) and biotreatment (-11-19%), which have long-term consequences for biodiversity and regional hydrological stability.

Based on the analysis, practical recommendations are proposed: strengthening pollution and erosion monitoring with the introduction of automated systems, reducing anthropogenic impact through the optimisation of agricultural practices and mining, and the development of cross-border cooperation for the management of Syrdarya water resources. For further research, it is recommended to expand the empirical base through long-term observations of runoff and biodiversity, integrate more detailed climate models, and apply machine learning to improve forecast accuracy. The limitations of the study are related to the lack of direct measurements for the Naryn Basin, which required the use of estimated data from adjacent regions, potentially affecting the accuracy of interpretation of some scenarios. Despite this, the study has laid the foundation for adaptation strategies in a changing climate, contributing to the sustainable development of the region's water resources.

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Conflict of Interest

None.

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Прогнозне моделювання руху забруднювачів річки Нарин із застосуванням SWAT+ моделі

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Анотація. Актуальність дослідження обумовлена необхідністю оцінки екологічного стану басейну річки Нарин під впливом антропогенного забруднення та кліматичних змін, викликаних гірничодобувною діяльністю, сільськогосподарськими стоками, урбанізацією та накопиченням седиментів нижче гідроелектростанцій. Метою дослідження була кількісна оцінка деградації якості води та екосистем басейну річки Нарин під впливом антропогенних забруднювачів та кліматичних змін. Для досягнення мети застосовувалися методи аналізу даних моніторингу та математичного моделювання. Результати показали значне зниження біорізноманіття на 10-20 % та якості води, викликане збільшенням концентрацій важких металів (до 0,053 міліграма на літр свинцю) та фосфору (до 0,48 міліграма на літр) до 2050 року за кліматичного сценарію. Встановлено, що ерозія збільшилася до 460 т/км^2/рік, а продуктивність транскордонної річки Сирдар'я знизилася на 11 %, що наголошує на вразливості гірських і водних екосистем. Крім того, зафіксовано зменшення вмісту розчиненого кисню до 4,7 міліграм на літр, що посилює негативний вплив на водні біоценози. Також зазначено зниження відтворення рибних популяцій на 18 %, що вказує на серйозні ризики для їх виживання в умовах фрагментації місцеперебування нижче гідроелектростанцій. Практична цінність роботи полягає в наданні основи для розробки заходів з моніторингу та управління водними ресурсами в регіоні, які можуть бути використані органами державної влади Киргизстану та сусідніх країн Центральної Азії, такими як Казахстан та Узбекистан, для координації транскордонного водокористування, а також екологічними організаціями та місцевими спільнотами для збереження

Ключові слова: антропогенний вплив; деградація екосистем; транскордонні річкові системи; кліматичні зміни; водні ресурси; біорізноманіття

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