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Methodological approaches to assessing the impact of threats on environmental safety

Nataliia Maksiuta*
PhD, Researcher
National University "Yuri Kondratyuk Poltava Polytechnic"
36011, 24 Vitaliia Hrytsaienka Ave., Poltava, Ukraine
https://orcid.org/0000-0002-0256-6986

Iryna Levchenko
PhD, Associate Professor
National University "Yuri Kondratyuk Poltava Polytechnic"
36011, 24 Vitaliia Hrytsaienka Ave., Poltava, Ukraine
https://orcid.org/0000-0001-7068-8320

Alona Buriak
PhD in Economics, Associate Professor
National University "Yuri Kondratyuk Poltava Polytechnic"
36011, 24 Vitaliia Hrytsaienka Ave., Poltava, Ukraine
https://orcid.org/0000-0002-0814-7459

Anna Cherviak
PhD, Researcher
National University "Yuri Kondratyuk Poltava Polytechnic"
36011, 24 Vitaliia Hrytsaienka Ave., Poltava, Ukraine
https://orcid.org/0000-0002-2747-4041

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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*Corresponding author

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/m^3, which is 40% higher than the standard limit (25 μg/m^3). In Leipzig, this indicator was significantly lower – 18 μg/m^3 – 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/m^3)	45	48	18
NO_2 (μg/m^3)	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/m^3)	Winter peak level (μg/m^3)	Summer minimum (μg/m^3)	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)

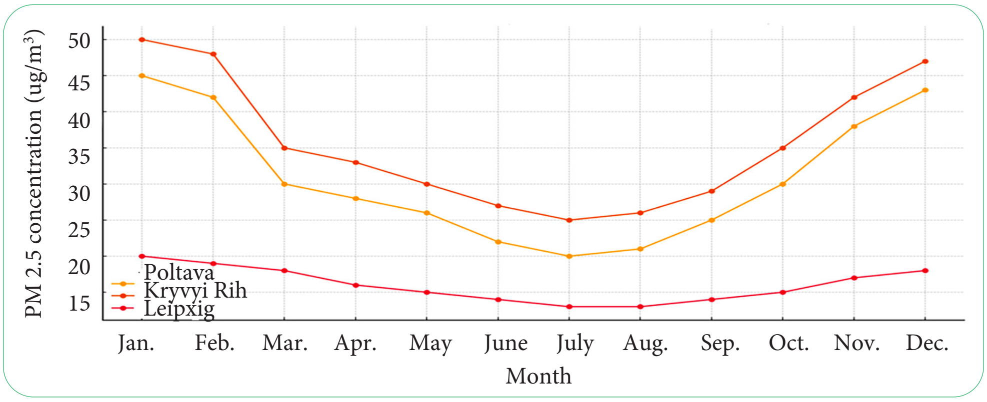

Figure 1. Seasonal fluctuations in PM2.5 concentrations in the air during 2024 in Poltava, Kryvyi Rih, Leipzig
Source: compiled by the authors based on Ukrainian Hydrometeorological Centre (2025), Air quality data access and tools (2025)

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 μg/m^3 – well above the norm of 40 μg/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 μg/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 μg/m^3) is more than twice as high as in Leipzig (18 μg/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 $\mu g/m^3$, with a standard deviation of approximately 7 $\mu g/m^3$, 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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Conflict of Interest

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Методологічні підходи до оцінки впливу загроз на екологічну безпеку

Наталія Максюта
Доктор філософії, науковий співробітник
Національний університет «Полтавська політехніка імені Юрія Кондратюка»
36011, просп. Віталія Грицаєнка, 24, м. Полтава, Україна
https://orcid.org/0000-0002-0256-6986

Ірина Левченко
Доктор філософії, доцент
Національний університет «Полтавська політехніка імені Юрія Кондратюка»
36011, просп. Віталія Грицаєнка, 24, м. Полтава, Україна
https://orcid.org/0000-0001-7068-8320

Альона Буряк
Кандидат економічних наук, доцент
Національний університет «Полтавська політехніка імені Юрія Кондратюка»
36011, просп. Віталія Грицаєнка, 24, м. Полтава, Україна
https://orcid.org/0000-0002-0814-7459

Анна Черв’як
Доктор філософії, науковий співробітник
Національний університет «Полтавська політехніка імені Юрія Кондратюка»
36011, просп. Віталія Грицаєнка, 24, м. Полтава, Україна
https://orcid.org/0000-0002-2747-4041

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